

Chapter 4

Hydrology of Mid-Atlantic Freshwater Wetlands

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Abstract Hydrology is a key variable in the structure and function of a wetland; it is a primary determinant of wetland type, and it drives many of the functions a wetland performs and in turn the services it provides. However, wetland hydrology has been understudied. Efforts by scientists from Riparia, a wetland and aquatic systems research center at Penn State University, have advanced the understanding of wetland hydrology in the Mid-Atlantic Region over the past two decades primarily through a series of studies at a set of long-term monitoring sites. This work contributed to four primary issues in wetland hydrology: validation of regional hydrogeomorphic classification schemes, establishment of reference criteria for monitoring and assessment, identification of targets for restoration or mitigation, and evaluation of the hydrologic behavior of created vs. non-created wetlands. This chapter (1) summarizes some of the key findings of hydrologic studies of wetlands from the published and non-published research of wetland scientists associated with Riparia and secondarily, (2) describes general, seasonal, and inter-annual hydrologic patterns of the water level data that has been collected at some of the long-term monitoring sites or “reference sites.”

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4.1 Introduction

Hydrology is a key variable in the structure and function of a wetland; it is a primary determinant of wetland type, and it drives many of the functions a wetland performs and in turn the services it provides. However, wetland hydrology has been understudied. Though there has been important work on understanding complete water budgets at a single wetland, there are fewer studies that look across a number of sites encompassing a range of wetland types under a range of human disturbance settings. And, there remains a major technical challenge “to determine an average or characteristic hydroperiod for sites on which there is no hydrologic data, or for which hydrologic data cover only a short period of time” (p. 91) (National Research Council 1995). This characteristic hydroperiod, or hydrologic regime, of a wetland can be characterized by the magnitude, frequency, duration, timing, and rate of change of hydrologic events such as inundation or soil saturation (Poff et al. 1997). Modifications to any aspect of this regime can have cascading effects on aquatic ecosystems (Karr 1991; Karr and Chu 1999). The timing and duration of inundation and saturation can influence recruitment from seedbanks (Seabloom et al. 1998) and survival of herbaceous and woody plant species (Harris and Marshall 1963; Mountford and Chapman 1993; Poiani and Johnson 1993; Miller and Zedler 2003; Magee and Kentula 2005). Reduction in the magnitude and dynamics of flooding can result in a reduction in the biophysical complexity of a wetland ecosystem (Richter et al. 2003), which in turn can shift the invertebrate communities both on the surface (Richards and Host 1994; Lammert and Allan 1999) and in hyporheic zones (Poole et al. 2006). Further, the timing, duration, and dynamics of the hydrologic regime influence the biogeochemical environment of wetland soils (Richardson and Vepraskas 2001).

Riparia, formerly the Cooperative Wetlands Center, is a wetland and aquatic systems research center at Penn State University. Efforts by Riparia scientists have advanced the understanding of wetland hydrology over the past two decades. The objectives of this chapter are (1) to summarize some of the key findings of hydrologic studies of wetlands in the Mid-Atlantic Region (MAR) from the published and non-published research of wetland scientists associated with Riparia and secondarily, (2) to describe general, seasonal, and inter-annual hydrologic patterns of the water level data that has been collected at some of the long-term monitoring sites or “reference sites.” The discussion and analysis in this chapter are focused on freshwater wetlands, which has been the primary focus of research within the MAR by researchers in Riparia.

4.2 Riparia’s Hydrologic Studies

Several long-term, regional, multi-wetland hydrologic studies began in the 1990s in the Pacific Northwest (Shaffer et al. 1999), North Carolina (Rheinhardt et al. 1999), Ohio (Fennessy et al. 2004), and in Delaware and Maryland (Weller et al. 2007;

Whigham et al. 2007) in order to better understand wetland hydrology across wetland types and disturbance conditions. In 1993 researchers from Riparia began to establish a network of monitoring sites in wetlands across types and across a range of land use settings to help to fill the knowledge gap about wetland hydrology in the MAR, particularly in the Appalachian Plateau and the Ridge and Valley Physiographic Provinces. The sites were classified following the hydrogeomorphic (HGM) approach, in which two of the key characteristics of the classification scheme are water source and hydrodynamics (Brinson 1993). All of the work at the reference sites contributed to four primary issues in wetland hydrology: validation of regional HGM classification schemes, establishment of reference criteria for monitoring and assessment, identification of targets for restoration or mitigation, and evaluation of the hydrologic behavior of created vs. non-created wetlands (Cole and Brooks 2000a). This section chronologically presents the goals and key findings of the hydrologic wetland studies that have been performed in Riparia and have contributed to the understanding of wetland hydrology in the four key areas mentioned above.

First, a note on wetland classification used in this chapter. During the period 1993 until the present, the regional HGM classification system has been modified as more was learned about these ecosystems. Although this book generally follows the most recent terminology (Brooks et al. 2011), in this chapter we refer to the original terms to facilitate continuity with most of the published papers on wetland hydrology. When first mentioned, both terms are provided. Readers can refer to Chap. 2 of this book for more details about changes in wetland classification.

Initial efforts confirmed the a priori HGM classification by finding differences between the classes particularly in terms of median duration of saturation in the root zone (upper 30 cm). Cole et al. (1997) instrumented 24 wetlands across four HGM subclasses: slope, depression (riparian depression as per Cole et al. 1997), riverine lower perennial (mainstem floodplain as per Cole et al. 1997), and riverine upper perennial (headwater floodplain as per Cole et al. 1997) with shallow water level monitoring wells and piezometers where monthly measurements were taken during the growing season (Cole et al. 1997). They found riparian depressions and slopes had more groundwater contribution than the floodplain classes and duration of saturation in the growing zone ranged across classes with the most saturation in riparian depressions, the least in the floodplain systems, and slopes in between. They also concluded that headwater floodplains were fed primarily through overland flow while mainstem floodplains were driven by overbank flooding. The next efforts continued to validate the regional HGM classification scheme, and built upon earlier findings by collecting data at more reference wetlands ($n=30$) in the same HGM subclasses as the previous study, collecting water level data outside the growing season, and looking at differences in disturbance across sites (Cole and Brooks 2000a). Automatic water-level recorders took measurements every 3–6 h throughout the year. There were similar differences between subclasses in terms of percent time of water in the root zone for the whole year and not just the growing season. Disturbance was also a key factor in wetland hydrology, and may override HGM subclass characteristics. For example, median water levels for moderately disturbed depressions

were standing water (8 cm) while low disturbance depressions were saturated (-7 cm). Using data from this study and a similar study of hydrology in Oregon wetlands, it was also determined that low frequency measurements (7 days or less) could accurately predict annual and monthly water level statistics (Shaffer et al. 2000).

Studies also investigated the differences in hydrology between natural and created systems in Pennsylvania (Cole and Brooks 2000b) and New York (Cole et al. 2006). In the Pennsylvania work, created mainstem floodplain systems had much higher median water depths, and most notably much more standing water throughout the year, than did natural systems. Similarly, in the New York study, created sites ($n = 5$) were generally wetter than comparable natural sites ($n = 3$), and, despite designing for saturated soils, many had open water habitats. These studies provide a particularly important contribution to the understanding of created wetlands, as some of the data were collected over a 10-year period. Most hydrologic monitoring of constructed wetlands does not extend beyond 1 year (Zedler 2000), while vegetation and hydric soil conditions may take several years to decades to establish and hydrologic data from any single year may not represent mean hydrologic behaviors because of inter-annual variation in weather conditions.

Comparisons of wetland hydrology data from Pennsylvania and Oregon were used to evaluate the transferability of HGM functional models across regions (Cole et al. 2002). Three years of hydrology data from wetlands ($n = 18$ in Pennsylvania and $n = 15$ in Oregon) in three HGM subclasses (slope, headwater floodplain, and mainstem floodplain) were compared across a range of disturbance levels. The hydrology was similar for the slope wetlands in terms of monthly median and inter-quartile range of depth of water, percent of time in the root zone, and the percent of time soils were saturated or inundated across regions, but not for the two riverine subclasses. Variation between years was relatively small, but did affect the percent of time the median water levels were in the root zone for the headwater subclasses. The wettest periods were in the spring (March–April) while the driest periods were in the late fall to early winter (November–December). Additionally, less standing water in Pennsylvania wetlands may be due to differences in soils, particularly higher percentages of fine sediments at the Oregon sites. Based on these data, HGM functional models were found to be robust across regions for the slope subclass but not for the riverine subclasses.

The transferability of HGM functional models was also evaluated through a study that took the HGM classification north and south along the Appalachians into the Catskills and Adirondacks of New York and northwestern Virginia (Cole et al. 2008; Peterson-Smith et al. 2009). Water level data were collected at 6-h increments for up to 3 years at 53 minimally disturbed wetlands in three HGM subclasses (headwater floodplain, slope, and riparian depression). They found that headwater floodplains and slope wetlands were hydrologically similar by subclass between Pennsylvania and Virginia, but different in New York, while riparian depressions were similar throughout. Hydrologic differences were attributed to high beaver activity and snow cover in the New York sites. Again, even within the MAR some of the HGM functional models are robust and others are not based on HGM subclass.

Hydrology has played a key role in a number of other studies performed by Riparia researchers, even if it was not the primary focus of study. One such study

identified plant species that are indicators of groundwater contribution to a wetland (Goslee et al. 1997). Another study, done in collaboration with the USGS, used hydrology to help explain amphibian breeding in small, isolated wetlands in the Delaware Water Gap (Julian 2009). Julian assessed both the connectivity of wetlands to surface water bodies (strictly isolated, seasonally isolated, or permanently connected) and hydrologic stability (the proportion of wetland area inundated in June relative to the high water period (mid-April)) based on visual surveys of 125 wetlands. One wetland biogeochemical study used hydrology to characterize wetlands in looking at decomposition in 12 headwater complex wetlands across a range of disturbance (Ryan 2005). The hydrologic regime was characterized as moderately inundated, saturated, moderately saturated, or dry based on a clustering of temperature and hydrologic metrics generated from 1 year of water level data (percent time inundated or saturated and the number of flooding events in three duration categories: less than or equal to 1 day, 1–2, 2–7 days, and greater than 1 week). Continuing work is also contributing to the understanding of wetlands as part of the larger riverine landscape, which is an important interdisciplinary problem in achieving integrated water resources management (Ward 1989; Thorp et al. 2006). Researchers in Riparia have contributed to the integration of wetland and riverine studies in some of the work outlined above, but also in other efforts with aquatic invertebrates (Laubscher et al. 2004) and with the development of integrated rapid assessment techniques (Brooks et al. 2009). Finally, there is on-going work quantifying the ecosystem services provided by wetlands including provision of habitat, flood storage, and nitrogen attenuation and how these services relate to hydrology in the face of land use and climate change (Shortle et al. 2009; Hychka 2010; Yetter et al. 2011; Hychka et al. *in prep*).

4.3 Water Level Patterns by Type and Disturbance

In this section we will present some of the hydrologic data collected through Riparia and associated researchers in order to build upon the analyses in the literature presented above. Specifically, we will discuss some of the hydrologic behaviors of the wetlands across wetland types and disturbance in relation to seasonal and inter-annual response to climatic drivers. The relationship between wetland hydrology and climatic drivers has not been studied extensively by Riparia researchers and is important particularly in the face of forecasted climatic changes.

4.3.1 Sites

Data are presented for a subset of wetlands that have been monitored by Riparia as part of a reference collection (www.riparia.psu.edu). The subset was selected to cover a range of wetland types and disturbance levels. Sites were excluded if the records spanned less than 40% of the study period, if site-level disturbances were so

unique that the water level information might not be generalizable, or if they were constructed wetlands. The coarse condition classes used (reference standard, least disturbed, and disturbed) are based on landscape and site-level characteristics of the wetlands, where reference standard sites were chosen to represent high ecological integrity. The sites include depressions (reference standard $n=4$, disturbed $n=2$), riverine upper perennial or headwater (reference standard $n=3$, disturbed $n=3$), riverine lower perennial or mainstem (least disturbed $n=1$, disturbed $n=2$), and slope (reference standard $n=2$, disturbed $n=4$) (Table 4.1). Water levels were recorded using automatic recording devices installed in shallow, slotted, PVC well casings (Cole and Brooks 2000a). Water levels were recorded every 4 h over a 13-year period (1996–2009) with individual well records covering 43–89% of that time. The gaps in the data are not random and are more likely to occur during winter months and extreme events where the water levels may have gone above or below the measurement interval for the instrument.

This dataset is unique and highly valuable in the region for providing information about wetland hydrology over multiple years and across wetland types and disturbance levels. The discontinuous nature of the data does make it difficult to perform certain statistical analysis; even means may not be representative and many time series analyses require complete or nearly complete series. However, there is a lot to be learned from exploratory statistics and visualizations, which is the approach that will be taken in this chapter.

4.3.2 *Climate*

Seasonal: Temperature and evapotranspiration (ET) patterns of the MAR of the USA have a strong seasonal signal with warm summers with high ET and cool or cold winters with very low ET. Precipitation, on the other hand, does not show a strong annual cycle (Najjar 1999). More specifically, the Köppen climate regions in the Mid-Atlantic are all Mid-Latitude Humid with the north and the spine of the Appalachians in Severe Mid-Latitude Humid continental with a severe winter, no dry season, and either a hot (Dfa) or warm (Dfb) summer (Godfrey 1999) (Fig. 4.1). Most of the non-Appalachian portions of Virginia, southern Maryland, and the Delmarva Peninsula are Mild Mid-Latitude Humid subtropical with a mild winter, no dry season, and either a hot (Cfa) or warm summer (Cfb). The result of the seasonal patterns of temperature, evaporation, and precipitation on the region's hydrology is that typically spring has higher levels of soil moisture and stream flows, while the summers have lower soil moisture and mean stream flows (Fig. 4.2) (Pennsylvania NRCS 2000). And, though the region has a humid climate, the late fall and early spring are the only periods of recharge in the hydrologic cycle when the soils are not frozen and there is low ET demand from plants (Swistock 2007).

Inter-annual: There is also a wide range in the inter-annual climatic conditions in the region. Precipitation and temperature vary on a roughly decadal cycle, which may be driven by the North Atlantic Decadal Oscillation (NAO) with winter

Table 4.1 Sites with hydrologic data used for exploring freshwater wetland hydrology in this chapter

Class	Disturbance	Site name	Site #	Start	End	Days with records	n	% Total period with data
Depression	Ref std	Clarks Trail	13	10/22/96	03/09/08	2840.50	11,362	0.61
Depression	Ref std	McCall Dam	5	12/07/96	05/15/08	2941.75	11,767	0.63
Depression	Ref std	Sand Spring	6	10/22/96	07/20/07	3454.25	13,817	0.74
Depression	Ref std	Whipple Dam	10	09/05/97	01/09/08	3024.50	12,098	0.65
Depression	Disturbed	Canoe Creek	7	10/23/96	06/11/09	3910.00	15,640	0.84
Depression	Disturbed	Tadpole	52	06/17/97	06/27/08	3238.75	12,955	0.70
Riverine Upper Perennial	Ref std	Laurel Run	60	10/09/97	10/31/07	3079.50	12,318	0.66
Riverine Upper Perennial	Ref std	Tuscarora	87	06/28/00	12/20/08	2956.25	11,825	0.64
Riverine Upper Perennial	Disturbed	Buffalo Run	18	06/11/97	07/10/09	3949.00	15,796	0.85
Riverine Upper Perennial	Disturbed	Nittany B&B	53	02/20/98	06/27/08	3205.00	12,820	0.69
Riverine Upper Perennial	Disturbed	Thompson Run	57	07/22/97	04/15/08	3313.00	13,252	0.71
Riverine Upper Perennial	Disturbed	Water Authority	26	12/08/96	03/12/04	2296.75	9,187	0.49
Riverine Lower Perennial	Least dist	Bald Eagle Creek	3	10/19/96	05/15/08	3901.50	15,606	0.84
Riverine Lower Perennial	Disturbed	Fravel	32	11/06/96	07/02/09	4125.25	16,501	0.89
Riverine Lower Perennial	Disturbed	Lock Haven	58	07/31/97	07/02/09	3655.75	14,623	0.79
Slope	Ref std	McGuire Rd	24	09/18/97	06/10/08	2975.25	11,910	0.64
Slope	Ref std	Swamp White Oak	55	07/11/97	03/16/08	3146.00	12,584	0.68
Slope	Disturbed	BESP PEM	2	12/08/96	01/06/03	2006.50	8,026	0.43
Slope	Disturbed	Cumberland Valley	67	06/17/98	05/13/05	2279.75	9,119	0.49
Slope	Disturbed	Shavers Creek	23	11/02/96	06/10/08	3428.50	13,714	0.74
Slope	Disturbed	Windy Hill Farm	23	11/02/96	04/21/05	2923.75	11,695	0.63

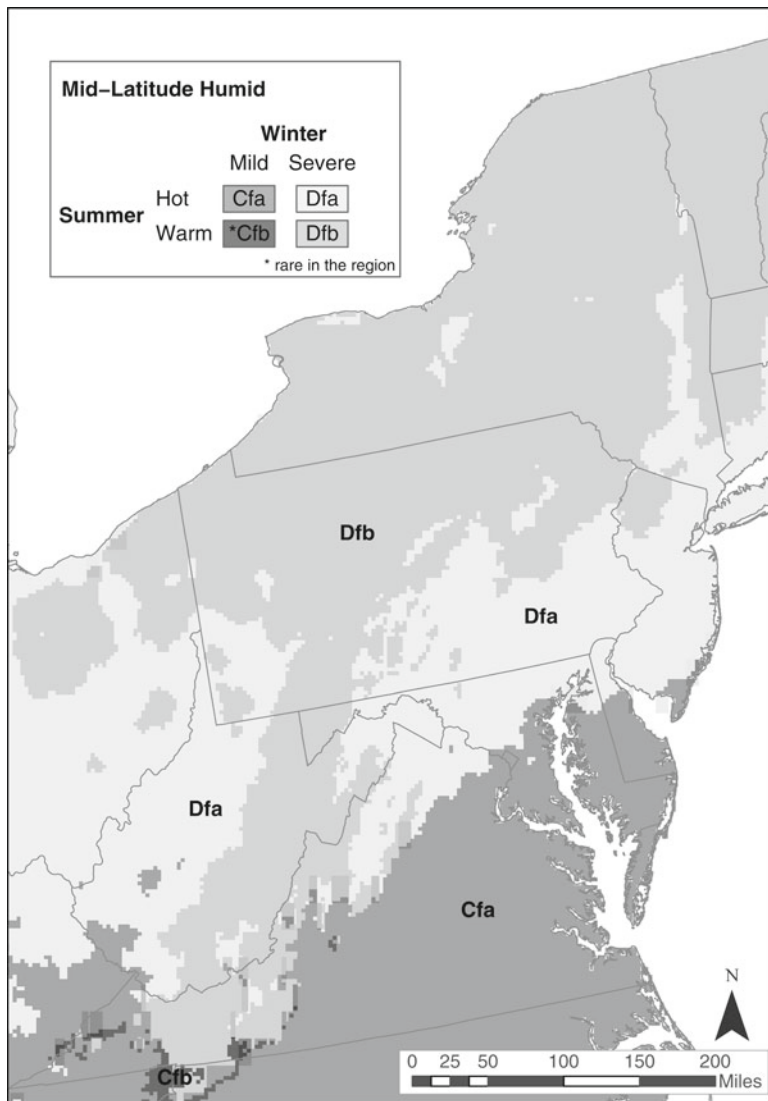


Fig. 4.1 Köppen climatic regions for the Mid-Atlantic Region

precipitation at Pennsylvania study climate stations showing an inverse relationship with the NAO (Willard and Cronin 2007; Ning et al. 2012). During the period of study there were periods of both extremely moist conditions (Palmer Drought Hydrologic Index (PDHI) +4.0 and above) and extreme drought (PDHI -4.0 and below) (Palmer 1968) (Fig. 4.3).

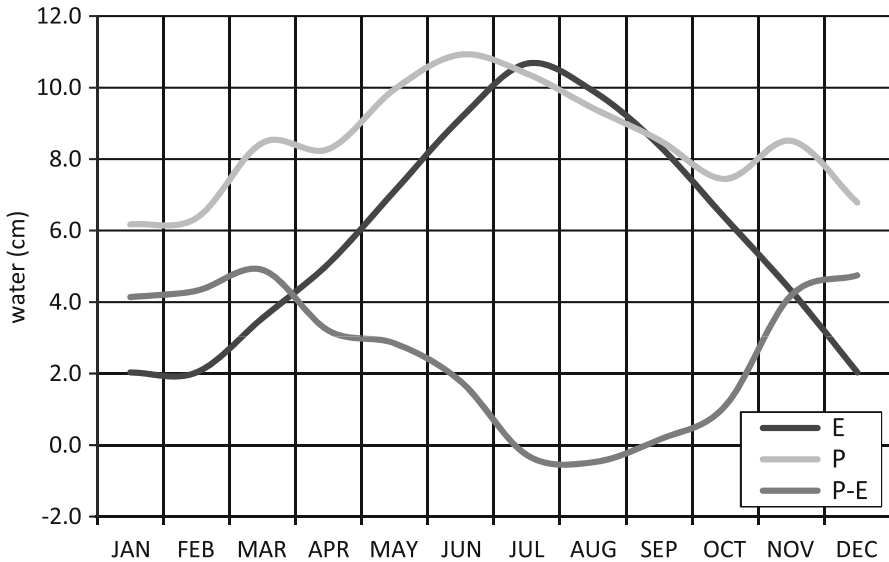


Fig. 4.2 Water balance for Centre County, Pennsylvania showing monthly evaporation (E), precipitation (P), and net water balance (P-E) all in cm. Yearly rainfall totals 101.2 cm and evaporation is 70.6 cm: <http://www.pa.nrcs.usda.gov/technical/Engineering/PaRainEvapRunoff.pdf>

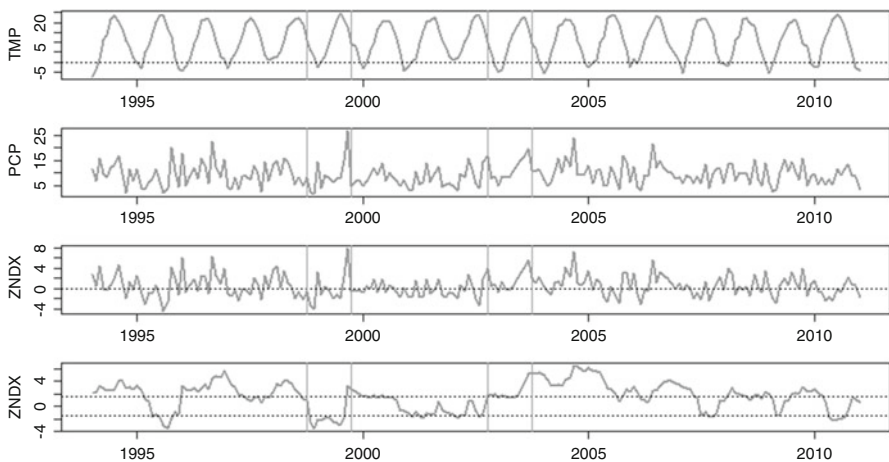


Fig. 4.3 Climatic drivers and drought indices for the Middle Susquehanna climate division. From top to bottom: mean monthly temperature ($^{\circ}\text{C}$) (TMP), precipitation (cm) (PCP), Palmer Hydrologic Drought Index (PHDI), and the Z-index or deviation from normal precipitation (ZNDX). Horizontal dotted lines indicate: 0°C on the temperature plot, the mean in the ZNDX plot, and the normal wetness range (-1.5 to 1.5) in the PHDI plot. A dry (1999) and a wet (2003) water year are demarcated with pairs of vertical lines

4.3.3 Hydrologic Patterns

General: Some of the general differences between wetland types shown in previous work can be seen in the simple time series plots of the individual well water levels (Fig. 4.4). There is the most variability in water levels at individual sites for the two riverine classes, a moderate level in slopes, and the least in the depressional wetlands. However, some of the hydrologic dynamics across sites are harder to determine from looking at the simple time series. Empirical cumulative distribution functions (ECDFs) are another way to visualize an entire dataset that allows for pattern detection without losing some of the details required when imposing metrics. The curves presented are for all observations (black) and for individual wells for reference (grey) and disturbed (white) sites across the four wetland types (Fig. 4.5) and represent the percent of time the water level was at or below a certain height. For example, the observations of all the depressional wetland wells are at or below approximately 5 cm half of the time and below -10 cm less than 10% of the time. ECDFs are also an effective way to convey the variability in hydrographs within a wetland type.

In the depressional wetlands, water levels are either standing water or in the root zone nearly all of the time, with more time in standing water and less time in the root zone in some of the disturbed sites. Reference riverine upper perennial sites also have water levels nearly always in the upper 30 cm with little standing water. This is in marked contrast to the disturbed sites which have much less time of saturation in the root zone and more standing water. Lower perennial riverine systems have water levels below the root zone about 40% of the time with standing water roughly 10% of the time. Lower perennial riverine wetlands showed less variability across disturbance, with the exception of the left most curve representing a much drier site than the others. Slope wetlands show little time in standing water and are saturated most of the time. All of the reference standard slope wetlands are saturated 75% of the time or more, while some of the disturbed sites follow similar curves to the reference sites, others are much drier as seen in the two left most curves.

Seasonal: Previous work on seasonality of wetland hydrology with the Riparia reference wetlands looked at slope, riverine upper perennial, and riverine lower perennial wetlands across a range of disturbance levels and showed that the wettest times of the year were in the spring (March–April) while the driest were in the late fall to early winter (November–December) (Cole et al. 2002).

Seasonality of wetland hydrology is seen in a dot plot of the median water level for meteorological spring (March, April, and May) vs. summer (June, July, and August) for the study wells by type and disturbance level (Fig. 4.6). If the median for the two seasons was the same, the point would fall on or close to the diagonal, points above the diagonal the median water level is higher in spring, and for points below the diagonal water levels are higher in summer. Similar to previous findings, the diagram shows that nearly all of the wells have higher water levels in the spring, with only three of the depressional wetlands slightly wetter in the summer. Depressional wetlands' median conditions are mostly slightly wetter in the spring,

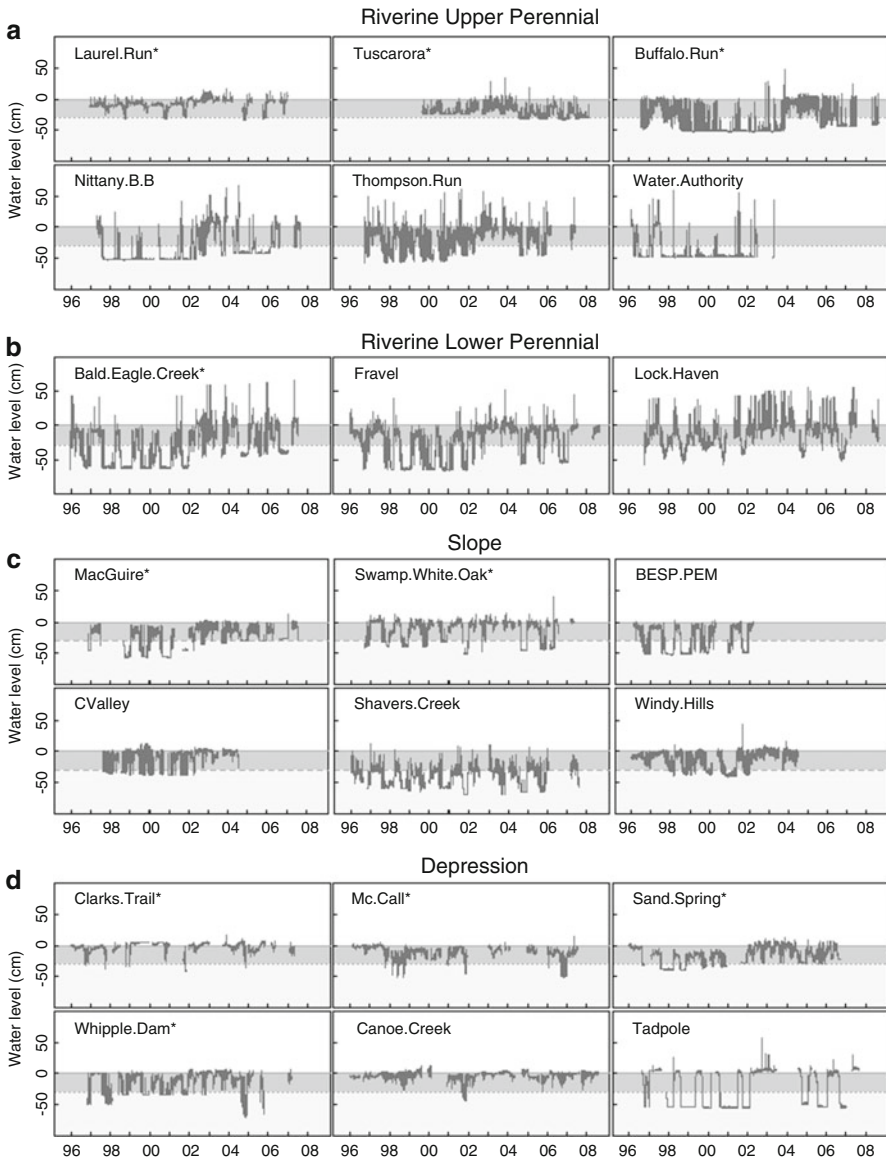


Fig. 4.4 Water levels in selected (cm) (a) upper perennial riverine, (b) lower perennial riverine, (c) slope, and (d) depression wetlands. Ground is 0 (solid line), positive values are above the surface, and negative are below the surface. Growing zone is the upper 30 cm (dashed line)

but saturated in both spring and summer, with the notable exception of two disturbed sites where median values are in standing water in both spring and summer. Riverine upper perennial systems show a number of differences across disturbance in terms of seasonality. The reference wetlands are the only systems that have satu-

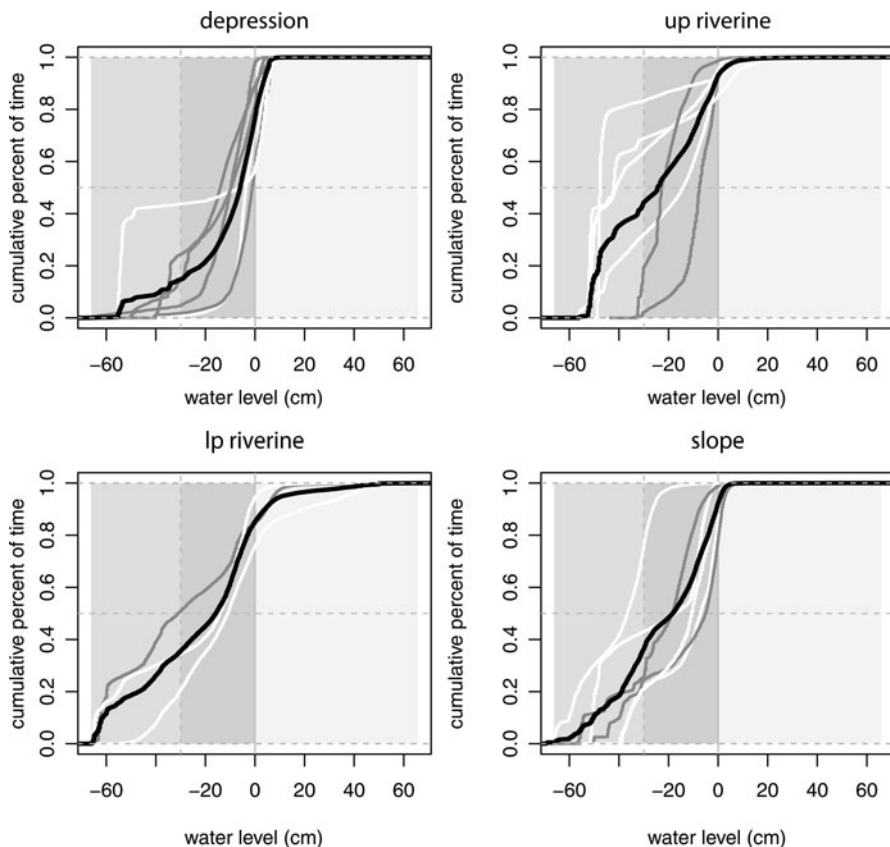


Fig. 4.5 Empirical distribution functions of water levels for individual reference condition (*grey*) and disturbed (*white*) wetlands and for all sites combined (*black*) in four classes of wetlands. The *dark shaded area* indicates the root zone (surface 0 cm to -30 cm). Where the distribution curve crosses the *horizontal dotted line* is the depth that the water level is at or below 50% of the time

rated median conditions in both spring and summer. None of the disturbed sites had saturated median conditions in the summer and all were either saturated or not saturated in the spring, with the exception of one site that had standing water in the spring and saturated conditions in the summer. All three of the reference systems showed very little difference between spring and summer medians, while there was a much bigger range in the disturbed sites with three of the sites showing greater than 20 cm difference in median conditions between spring and summer. Riverine mainstem systems, as a whole, showed a high degree of variability between spring and summer median conditions. The degree of seasonal variation in wetland hydrology varies by HGM type and disturbance level.

Inter-annual: The period of record for these wells has spanned a range of very wet to very dry conditions (Fig. 4.3), including water year 1999 (10/1/1998–9/30/1999) which had mild to moderate drought conditions with a mean PDHI of -1.7 and

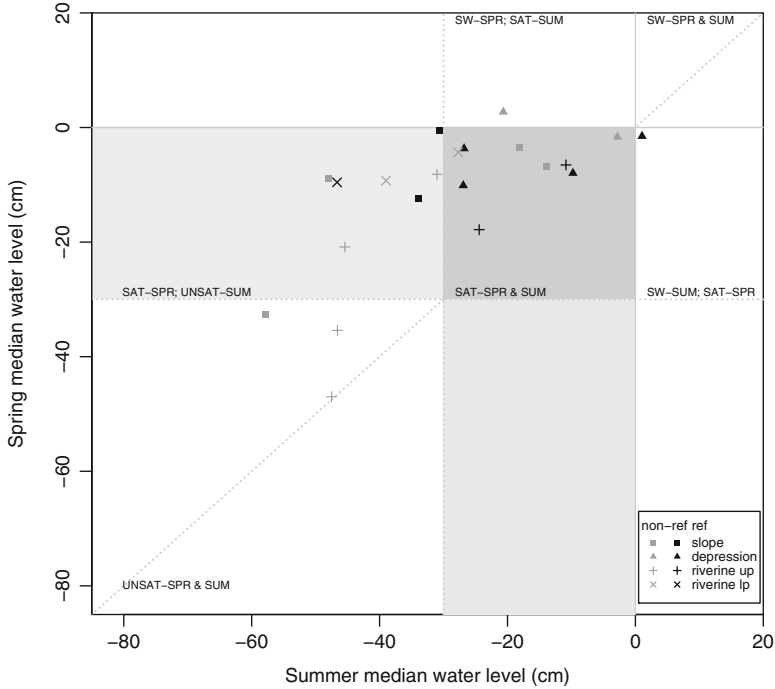


Fig. 4.6 Shows median water level (cm) in summer vs. spring for depression, upper perennial riverine, lower perennial riverine, and slope wetlands in reference standard or least disturbed (*black*) and disturbed (*grey*) condition. Wetlands with median water levels in the growing zone (upper 30 cm) for at least one season include those saturated for both spring and summer (*dark grey*, quadrant) and those saturated in spring but not summer (*light grey*, quadrant)

water year 2003 (10/1/2002–9/30/2003) which had mild to moderate wetness with a mean PDHI of 2.2. The wetlands displayed very different hydrologic behaviors during these wet and dry years. For example, depression wetlands showed a distinct pattern of saturation in the reference wetland and inundation for the disturbed site during the spring and drawdown out of the root zone in the fall of the dry year, whereas in the wet year the reference wetland stayed saturated throughout the year with periods of inundation and the disturbed site was inundated throughout the year (Fig. 4.7a). One of the wettest riverine upper perennial wetland sites in the dry year showed a small, but distinct summer drawdown in water level, whereas in a wet year the same system showed no summer drawdown and a relatively long period of standing water in the summer and early fall (Fig. 4.7b). In a much drier, disturbed site there was little time that the root zone was saturated; however, in an extremely wet year the site was saturated most of the year and similarly had standing water for extended periods. In two lower perennial riverine sites (Fig. 4.7c), both reference and disturbed sites showed distinct seasonal patterns with a period of saturation and inundation in the spring and a drawdown out of the root zone in the summer.

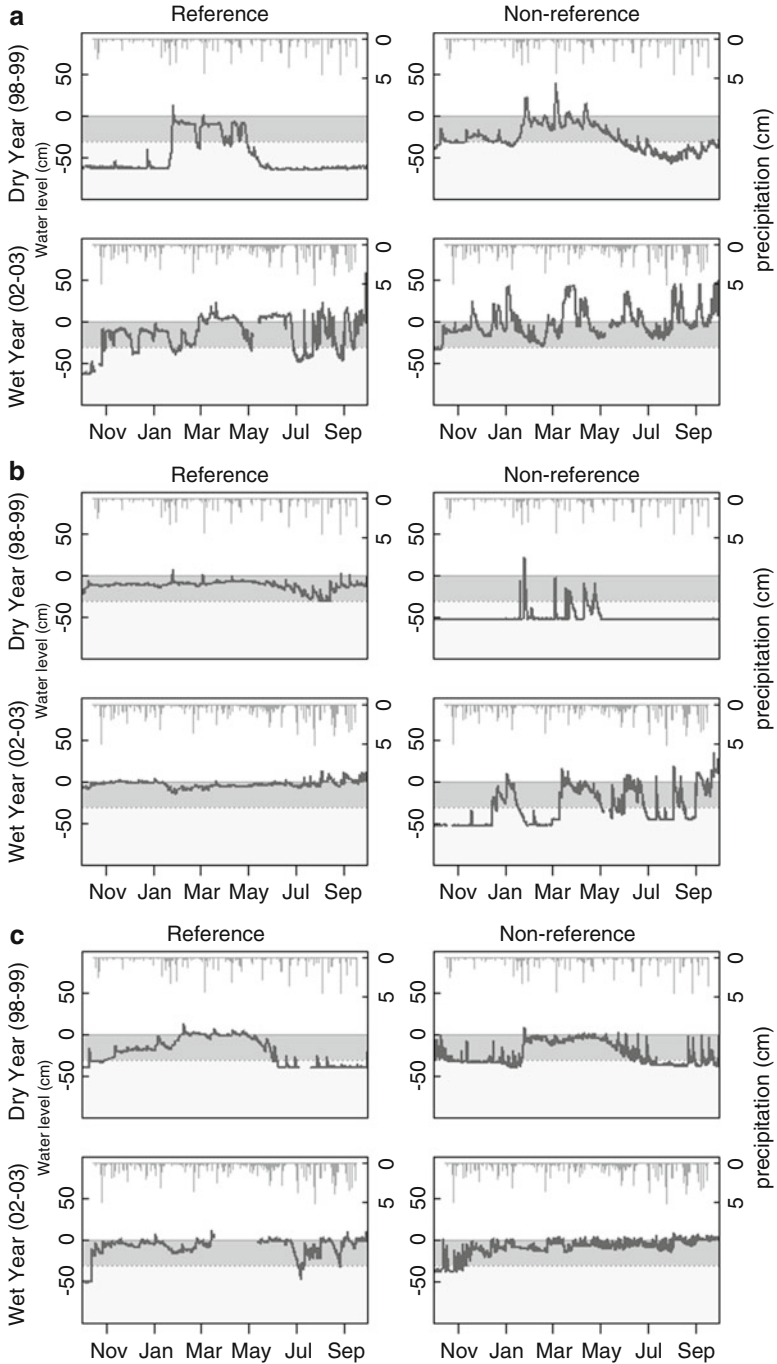


Fig. 4.7 Water level (in cm from ground level) for reference and non-reference wetlands in a dry (*top*, 1998–1999) vs. wet water year (*bottom*, 2002–2003) across four classes ((**a**) depression, (**b**) upper perennial riverine, (**c**) lower perennial riverine, and (**d**) slope). The ground level is 0 (*solid grey line*) and growing zone is the upper 30 cm (*grey dashed line*). Secondary y-axis shows the daily precipitation (cm)

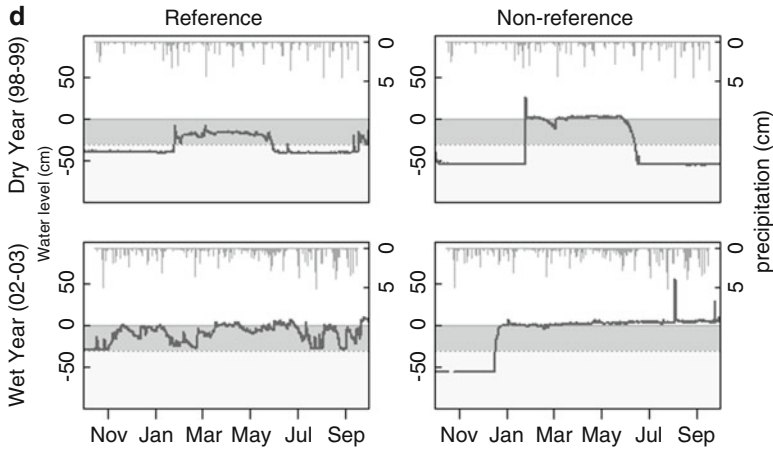


Fig. 4.7 (continued)

However, in the wet year the reference wetland was primarily inundated or saturated with a few periods where the water level fell below the root zone, and the non-reference wetland was either saturated or inundated. Slope wetlands similarly showed differences between wet and dry years, as both showed generally saturated conditions in spring with a drawdown out of the root zone in summer during dry years, and in wet years both wetlands were nearly consistently saturated with some periods of standing water (Fig. 4.7d).

In summary, the presentation of the data in this section demonstrates differences in how wetlands respond to climatic drivers such as drought and seasonal variation and has implications for the understanding of the potential vulnerability of wetlands to a changing climate.

4.4 Conclusions and Future Directions

Research by scientists at Riparia has helped to fill a critical gap in understanding about freshwater wetland hydrologic behavior. The reference wetland collection has helped to validate regional HGM classification and understand differences in wetland hydrologic behaviors across a disturbance gradient. Work comparing wetland hydrology across regions and in extending the models north and south within the Appalachians has further helped to validate the models and understand the geographic extent to which HGM classifications and models can be useful. Characterizing hydrologic characteristics of wetlands in the reference collection by HGM type and across a disturbance gradient, such as percent time the water is in the growing zone

or in standing water, has established reference criteria in the MAR for monitoring and assessment. These same hydrologic characterizations can be used to set regionally appropriate targets for restoration or mitigation sites based on the disturbance in the site's setting. Extensive work with mitigated wetlands demonstrated that created wetlands do not mimic the hydrology and functioning of analogous natural wetlands, which has played an important role in efforts to ensure that wetland mitigation accounts for losses in function and not just area (Moreno-Mateos et al. 2012, see Chap. 10 of this book). Ongoing work continues to address the multiscale and multidisciplinary problems of coupling wetland hydrology and functioning with hydrologic, land use, and climate models. Though this area of research presents some "wicked problems" (Freeman 2000), it is also situated at a critically important nexus in water resources management. Additionally, the many studies that have linked hydrology to other wetland characteristics and processes are critically important in understanding what drives wetland functioning particularly across a human disturbance gradient.

Some of the patterns in wetland hydrologic behavior presented in this chapter indicate the importance of accounting for inter-annual climatic conditions, particularly drought status, when performing wetland studies and assessments. The results during extremely wet or dry years may be quite different from the predominant site conditions. Many wetland studies, however, do not extend beyond one or two field seasons due to the nature of academic studies and funding for short-term projects. The observed inter-annual variability at the Riparia reference wetlands emphasizes the importance of maintaining long-term monitoring sites to give hydrologic context to shorter wetland studies. Climate change scenarios differ in projected changes in the timing and magnitude of precipitation in the MAR, though most forecast increases in the magnitude and duration of summer time deficits (Cowell and Urban 2010). Observing past behaviors of wetlands across a disturbance gradient to past climatic extremes can give insight into possible trajectories of change in wetlands in the face of future changes in climatic drivers.

The hydrologic data collected through efforts of Riparia's scientists are unique in the region and are critically important to wetland managers, practitioners, and researchers in performing wetland assessments, designing and evaluating created wetlands, and understanding the hydrologic role of wetlands in a watershed context. Particularly in the face of changing climate and land use, it is essential to maintain and expand upon the current network of wetland hydrology monitoring. Historic wetland hydrology records are relatively short, so it is also important to maintain the collection of hydrologic covariates that have longer records, such as temperature, precipitation, and stream flow. Finally, water resources decision-making is not solely based on scientific information, but also on a blend of economic, cultural, and political factors. As the timing and availability of water in the MAR are projected to shift under climate change, it is important to use science to inform decisions-making, but also to expand multidisciplinary research that incorporates the socio-economic context in which water resource decisions are made.

References

- Brinson MM (1993) A hydrogeomorphic classification for wetlands. U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS, p 101
- Brooks RP, Easterling M, Brinson MM, Rheinhardt RD, Havens K, O'Brien D, Bishop JA, Rubbo JM, Armstrong B, Hite J (2009) A Stream–Wetland–Riparian (SWR) index for assessing condition of aquatic ecosystems in small watersheds along the Atlantic slope of the eastern U.S. *Environ Monit Assess* 150:101–117
- Brooks R, Brinson M, Havens K, Hershner C, Rheinhardt R, Wardrop D, Whigham D, Jacobs A, Rubbo J (2011) Proposed hydrogeomorphic classification for wetlands of the Mid-Atlantic Region, USA. *Wetlands* 31:207–219
- Cole CA, Brooks RP (2000a) Patterns of wetland hydrology in the ridge and valley province, Pennsylvania, USA. *Wetlands* 20:438–447
- Cole CA, Brooks RP (2000b) A comparison of the hydrologic characteristics of natural and created mainstem floodplain wetlands in Pennsylvania. *Ecol Eng* 14:221–231
- Cole CA, Brooks RP, Wardrop DH (1997) Wetland hydrology as a function of hydrogeomorphic (HGM) subclass. *Wetlands* 17:456–467
- Cole CA, Brooks RP, Shaffer PW, Kentula ME (2002) Comparison of hydrology of wetlands in Pennsylvania and Oregon (USA) as an indicator of transferability of hydrogeomorphic (HGM) functional models between regions. *Environ Manage* 30:265–278
- Cole CA, Urban CA, Russo P, Murray J, Hoyt D, Brooks RP (2006) Comparison of the long-term water levels of created and natural reference wetlands in northern New York, USA. *Ecol Eng* 27:166–172
- Cole CA, Cirno CP, Wardrop DH, Brooks RP, Peterson-Smith J (2008) Transferability of an HGM wetland classification scheme to a longitudinal gradient of the central Appalachian Mountains: initial hydrological results. *Wetlands* 28:439–449. doi:<http://dx.doi.org/10.1672/07-57.1>
- Cowell CM, Urban MA (2010) The changing geography of the U.S. water budget: twentieth-century patterns and twenty-first-century projections. *Ann Assoc Am Geogr* 100:740–754
- Fennessy MS, Mack JJ, Rokosch A, Knapp M, Micacchion M (2004) Integrated wetland assessment program. Part 5: biogeochemical and hydrological investigations of natural and mitigation wetlands. Wetland Ecology Group, Division of Surface Water, Ohio Environmental Protection Agency, Columbus, OH
- Freeman DM (2000) Wicked water problems: sociology and local water organizations in addressing water resources policy. *JAWRA J Am Water Res Assoc* 36:483–491
- Godfrey B (1999) Köppen climate classification, 1st edn. State Climate Services, Department of Biological and Agricultural Engineering, University of Idaho, Moscow, ID
- Goslee SC, Brooks RP, Cole CA (1997) Plants as indicators of wetland water source. *Plant Ecol* 131:199–206
- Harris SW, Marshall WH (1963) Ecology of water-level manipulations on a northern marsh. *Ecology* 44:331–343
- Hychka K (2010) Dissertation. Characterizing hydrologic settings and hydrologic regimes of headwater Riparian Wetlands in the ridge and valley of Pennsylvania. Penn State University, University Park, PA
- Hychka KC, Wardrop DH, Hamilton A, Weaver C, Julius S, Babson A, Bierwagen B, Johnson TB, Morefield P, Warren M (in prep.) Scale issues in wetland climate change vulnerability assessment: some guidance in the face of complexity
- Julian J (2009) Evaluating amphibian occurrence models and the importance of small, isolated wetlands in the Delaware Water Gap National Recreational area. Pennsylvania State University, University Park, PA
- Karr JR (1991) Biological integrity: a long-neglected aspect of water resource management. *Ecol Appl* 1:66–84
- Karr JR, Chu EW (1999) *Restoring Life in Running Waters: Better Biological Monitoring*. Island Press, Washington, DC

- Lammert M, Allan JD (1999) Assessing biotic integrity of streams: effects of scale in measuring the influence of land use/cover and habitat structure on fish and macroinvertebrates. *Environ Manage* 23:257–270
- Laubscher SE, Conklin AM, Brooks RP (2004) Wetland macroinvertebrates in Pennsylvania: Level 3 condition assessment using indices of community integrity (ICIs) Part II.3.c.2.a. Final Report for Cooperative Agreement No. X-827157-01, between Penn State Cooperative Wetlands Center, Pennsylvania State University, University Park, PA and U.S. Environmental Protection Agency, Office of Wetlands, Oceans, and Watersheds, Washington, DC
- Magee TK, Kentula ME (2005) Response of wetland plant species to hydrologic conditions. *Wetlands Ecol Manage* 13:163–181
- Miller RC, Zedler JB (2003) Responses of native and invasive wetland plants to hydroperiod and water depth. *Plant Ecol* 167:57–69
- Moreno-Mateos D, Power ME, Comín FA, Yockteng R (2012) Structural and functional loss in restored wetland ecosystems. *PLoS Biol* 10:e1001247
- Mountford JO, Chapman JM (1993) Water regime requirements of British wetland vegetation: Using the moisture classifications of Ellenburg and Londo. *J Environ Manage* 38:275–288
- Najjar RG (1999) The water balance of the Susquehanna River Basin and its response to climate change. *J Hydrol* 219:7–19
- National Research Council (1995) *Wetlands: characteristics and boundaries*. National Academy Press, Washington, DC
- Ning L, Mann M, Crane R, Wagener T (2012) Probabilistic projections of anthropogenic climate change impacts on precipitation for the Mid-Atlantic Region of the United States. *J Climate* 25:509–526
- Palmer WC (1968) Keeping track of crop moisture conditions, nationwide: The new crop moisture index. *Weatherwise* 21:156–161
- Pennsylvania NRCS. 2000. *Rainfall/Runoff Data: climate data for use in NMP-6 Form and NRCS National Ag Waste Design Program*. Natural Resources Conservation Service, United States Department of Agriculture.
- Peterson-Smith J, Wardrop D, Cole C, Cirmo C, Brooks R (2009) Hydrogeomorphology, environment, and vegetation associations across a latitudinal gradient in highland wetlands of the northeastern USA. *Plant Ecol* 203:155–172
- Poff NL, Allen JD, Bain MB, Karr JR, Prestegard BD, Richter BD, Sparks RE, Stromberg JC (1997) The natural flow regime: a paradigm for river conservation and restoration. *Bioscience* 47:769–784
- Poiani KA, Johnson WC (1993) A spatial simulation model of hydrology and vegetation dynamics in semi-permanent prairie wetlands. *Ecol Appl* 3:279–293
- Poole GC, Stanford JA, Running SW, Frissell CA (2006) Multiscale geomorphic drivers of groundwater flow paths: subsurface hydrologic dynamics and hyporheic habitat diversity. *J N Am Benthol Soc* 25:288–303
- Rheinhardt RD, Rheinhardt MC, Brinson MM, Faser KE Jr (1999) Application of reference data for assessing and restoring headwater ecosystems. *Restor Ecol* 7:241–251
- Richards C, Host GE (1994) Examining land use influences on stream habitats and macroinvertebrates: a GIS approach. *Water Res Bull* 30:729–738
- Richardson JL, Vepraskas MJ (eds) (2001) *Wetland soils: genesis, hydrology, landscapes, and classification*. Lewis, Boca Raton, FL
- Richter BD, Mathews R, Harrison DL, Wigington R (2003) Ecologically sustainable water management: managing river flows for ecological integrity. *Ecol Appl* 13:206–224
- Ryan PW (ed) (2005) *Decomposition dynamics mediated by litter quality in headwater floodplain wetlands in Pennsylvania*. The Pennsylvania State University, University Park, PA
- Seabloom EW, van der Valk AG, Moloney KA (1998) The role of water depth and soil temperature in determining composition of prairie wetland ecotones. *Plant Ecol* 138:203–216
- Shaffer GP, Kentula ME, Gwin SE (1999) Characterization of wetland hydrology using hydrogeomorphic classification. *Wetlands* 19:490–504

- Shaffer PW, Cole CA, Kentula ME, Brooks RP (2000) Effects of measurement frequency on water-level summary statistics. *Wetlands* 20:148–161
- Shortle J, Abler D, Blumsack S, Crane R, Kaufman Z, McDill M, Najjar R, Ready R, Wagener T, Wardrop D (2009) Pennsylvania climate impact assessment: report to the Department of Environmental Protection. Pennsylvania Department of Environmental Protection; Environment and Natural Resources Institute, The Pennsylvania State University, University Park, PA
- Swistock B (2007) A quick guide to groundwater in Pennsylvania. College of Agricultural Sciences, Penn State University, University Park, PA
- Thorp JH, Thoms MC, Delong MD (2006) The riverine ecosystem synthesis: biocomplexity in river networks across space and time. *River Research and Applications* 22:123–147. <http://dx.doi.org/110.1002/rra.1901>
- Ward JV (1989) The four-dimensional nature of lotic ecosystems. *J N Am Benthol Soc* 8:2–8. <http://www.jstor.org/stable/1467397>
- Weller DE, Snyder MN, Whigham DF, Jacobs AD, Jordan TE (2007) Landscape indicators of wetland condition in the Nanticoke River watershed, Maryland and Delaware, USA. *Wetlands* 27:498–514. [10.1672/0277-5212\(2007\)27\[498:LIOWCI\]2.0.CO;2](https://doi.org/10.1672/0277-5212(2007)27[498:LIOWCI]2.0.CO;2)
- Whigham DF, Deller Jacobs A, Weller DE, Jordan TE, Kentula ME, Jensen SF, Stevens DL (2007) Combining HGM and EMAP procedures to assess wetlands at the watershed scale—status of flats and non-tidal riverine wetlands in the Nanticoke River watershed, Delaware and Maryland (USA). *Wetlands* 27:462–478. [10.1672/0277-5212\(2007\)27\[462:CHAAPT\]2.0.CO;2](https://doi.org/10.1672/0277-5212(2007)27[462:CHAAPT]2.0.CO;2)
- Willard DA, Cronin TM (2007) Paleoecology and ecosystem restoration: case studies from Chesapeake Bay and the Florida Everglades. *Front Ecol Environ* 5:491–498
- Yetter SL, Hychka KC, Wardrop DH (2011) Linking ecosystem services of biological and habitat diversity with riverine hydrological processes across a land use gradient in the Susquehanna River basin. North American Benthological Society 2011 Annual Meeting, Providence, RI
- Zedler JB (2000) Progress in wetland restoration ecology. *Trends Ecol Evol* 15:402–407