Chapter 3
Wetland Design and Development

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Abstract The history of efforts to design and develop wetland sites is extensive and rich, especially in the United States. This chapter provides an annotated view of the current state of wetland design and recommends an approach to future efforts using "Hydrogeomorphic Methodology." Experience over the past century indicates that the most important part of wetland design and development is upfront work to: (1) determine what type of wetland historically occurred in, and is appropriate for a site; (2) understand and attempt to emulate the key ecological processes that created and sustained specific wetland types; (3) compare historical landscapes and wetland attributes with contemporary landscape and site conditions to understand remediating needs; and (4) determine management objectives and capabilities. The foundation for hydrogeomorphic assessments is analysis of historical and current information about geology and geomorphology, soils, topography and elevation, hydrological regimes, plant and animal communities, and

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physical anthropogenic features. The availability of this information is discussed and the sequence of actions used to prepare hydrogeomorphic matrices of potential historical vegetation communities and maps is provided as in application of information. Specific considerations for designing wetland infrastructure and restoring wetland vegetation are reviewed. An example of a wetland restoration project for the Duck Creek Conservation Area, Missouri is provided to demonstrate use of the hydrogeomorphic approach. We believe that future wetland design and development strategies should include the following actions: (1) wetland conservation must seek to achieve incremental gains at landscape-level scales; (2) the foundation of wetland design is determining the appropriate wetland type for the site being considered; (3) wetland designs should seek to restore and emulate historical form and process as completely as possible and to make systems as self-sustainable as possible; and (4) future design and development of wetlands must anticipate change related to climate, land uses, encroachments, and water availability and rights.

3.1 Introduction

To date, the conservation of wetlands worldwide typically has been based on four primary actions: (1) protection of existing wetlands and watershed landscapes; (2) enhancement of existing wetlands that have been degraded by changes to historical form, function, and processes; (3) restoration of wetland basins and sites that have been at least partly destroyed; and (4) management of wetlands of varying degrees of functionality using techniques and approaches that range in intensity from passive to active (Mitsch and Gosselink 1986; Weller 1994; Heitmeyer et al. 1996; Fredrickson and Laubhan 2000). The appropriateness of these strategies varies depending on geographic location, wetland type, degree of physical alteration, and extent that ecological processes have been disrupted (Fig. 3.1). In at least the latter three approaches, active design and physical development of wetlands usually is required to achieve goals of creating functional wetland sites and complexes. Even protection programs must consider the need for future wetland developments within the landscape context of the protected site.

The history of efforts to design and develop wetland sites is extensive and rich, especially in the United States (U.S.). The recognition of the widespread loss and degradation of wetlands and the commensurate loss of ecological and economic functions, values, and services has been a motivating influence for wetland conservation and development since the late 1800s (Vileisis 1997). Specific reasons for wetland development projects have ranged from active or pre-emptive conservation initiatives to legislative and regulatory mandates. The decline in waterfowl populations across North America beginning in the early 1900s was an especially powerful factor that increased public awareness of wetland loss and degradation and stimulated efforts to enhance, restore, and manage wetlands throughout the range of waterfowl and other wetland-dependent species. Early efforts to initiate resource conservation programs in the U.S. often were initiated by sportsmen, especially waterfowl hunters. These sportsmen recognized and called not only for

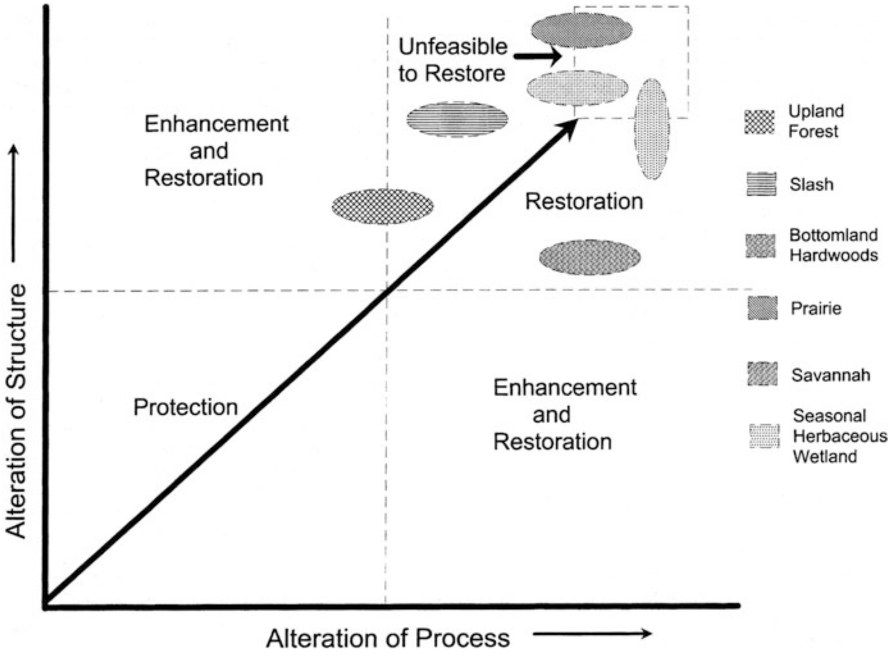

Fig. 3.1 Conceptual model of wetland conservation actions most appropriate, and the intensity of future management required, on sites of varying alteration of the presettlement physical structure and ecological processes. Habitat sites are those in the Grand Prairie Region of Arkansas (Heitmeyer et al. 2000)

protection of existing wetlands, but also restoration and rehabilitation of wetlands to increase waterfowl populations locally and across the North American continent (e.g., Reiger 1975; Connolly and Heitmeyer 1992). The extensive drought in North America during the 1930s deepened the concern over declines in waterfowl populations caused by wetland loss and degradation (More Game Birds in America Foundation 1931). Many wetland conservation programs were initiated at this time such as the Duck Stamp Program in 1936, which made monies available to purchase and develop lands specifically for waterfowl habitat. Consequently, most early wetland restoration and enhancement projects in the United States were located in areas of traditional waterfowl use and sought to emphasize wetland attributes such water area and depth, food resources, nest sites, and structural cover that were presumed to be most favored and used by ducks, geese, and swans (Sanderson 1980). Much of the early infrastructure to develop and manage these newly acquired areas was developed by the Civilian Conservation Corps using engineering techniques and philosophies of the time. Unfortunately, early wetland development projects occurred before key information concerning waterbirds and wetlands was available and some dogma became established that compromised the primary goal of maintaining and protecting wetlands. Foremost among this dogma was the desire to store water and maintain stable water levels on sizable

Table 3.1 Common causes of wetland design and development failures and corresponding consequences of these failures

Cause	Consequence
Disregarding geomorphology	Inappropriate vegetation communities, poor water storage ability, and disrupted ground-surface water interactions
Disregarding soil type and texture	Poor vegetation germination, growth, and survival; increased salinity, and poor soil moisture
Encouraging flat topography	Creation of vegetation monocultures, lack of impoundment independence, and inefficient drainage of units
Blocking natural waterways	Disrupted type and pattern of surface water flow, disconnection of nutrient flow patterns and animal movement corridors, and increased damage with flooding
Structures and management that stabilizes water regimes	Reduced biodiversity, loss of long-term productivity, and costly developments and water management activities

areas (to counter the effects of droughts such as occurred in the early 1930s), which led to widespread problems with wetland productivity because wetland hydrological and vegetation cycles that assured long-term productivity were compromised (see Weller 1994).

In the mid 1900s, governmental agencies and private conservation groups interested in waterfowl and wetland conservation developed a plethora of techniques manuals and handbooks to guide the enhancement, restoration, and management of wetlands specifically to benefit waterfowl (e.g., Mississippi Flyway Council 1958; Pacific Flyway Council 1959; Atlantic Waterfowl Council 1959, 1972; Linde 1969, and others). Subsequently, techniques were refined for specific objectives and wetland types (e.g., Fredrickson and Taylor 1982; Brown and Dinsmore 1986; Fredrickson 1991; Kelley et al. 1993) as well as for state (e.g., Miller and Arend 1960; Brakhage 1964; Linde 1969; Piehl 1986; Ringleman 1991), federal (e.g., U.S. Fish and Wildlife Service (USFWS) 1979; Bureau of Land Management 1989; Strader and Stinson 2005), and private (e.g., Nassar et al. 1993; Ducks Unlimited Canada 2000; Massey 2000) interests. Unfortunately, wetland managers and conservationists often attempted to export a technique or method that was successful in one system or wetland type to other different systems or types. For example, wetland designs for northern prairie pothole wetlands that included more permanent water regimes, island construction, level-ditching, and the planting of dense nesting upland cover adjacent to wetland basins (e.g., Hammond and Lacy 1959; Mathiak 1965) were implemented in very different ecoregions such as intermountain riparian valleys, Great Basin desert, coastal, California Central Valley, and southern bottomland hardwood forests where the technique/approach was mismatched to the ecological conditions causing long-term degradation and sometimes complete transition of communities, functions, values, and services (e.g., Heitmeyer and Fredrickson 2005; Heitmeyer et al. 2011; Heitmeyer et al. 2010a, 2012a). Other causes of failure in wetland design and construction were related to the failure to recognize or consider soil type, land form and geomorphology, elevation and topography, hydrological system, and ecological processes of many wetland types (Table 3.1).

In the late 1900s, the design and development of wetlands began to evolve from working in select locations, for specific attributes, and primarily for select species groups to more complex "system-based" approaches. Collectively, new conservation strategies and techniques for wetland design and construction began encouraging a more holistic approach that integrated wetland management with larger landscape needs, for multiple species and biodiversity, emulation of natural communities and dynamics, and functional ecological drivers or processes (see reviews in Chabreck 1988; Smith et al. 1989; Laubhan and Fredrickson 1993; Galatowitsch and van der Valk 1994; Weller 1994; Heitmeyer et al. 1996; Middleton 1999; Murkin et al. 2000). However, only recently have wetland designs attempted to be more process-oriented, integrated within entire landscapes and watersheds, and developed for maximum opportunity to restore ecosystem integrity (see discussions in Lubinski 1993; Sparks 1995; Heitmeyer et al. 1996; Galat et al. 1998; Laubhan et al. 2005).

This chapter does not attempt to provide a comprehensive review of the interesting and relatively extensive history of designing and developing wetlands, but instead offers an annotated view of the current state of wetland design and recommends an approach to future efforts using "Hydrogeomorphic Methodology" (Heitmeyer 2007a). Consequently, this chapter is not a listing of techniques, nor is it intended to be an engineering or construction manual; these are available elsewhere (e.g., Fredrickson and Taylor 1982; Weller 1989; Cahoon and Groat 1990; Kusler and Kentula 1990; U.S. Soil Conservation Service 1992; Fredrickson and Batema 1992; Payne 1992; Galatowitsch and van der Valk 1994; Fredrickson and Laubhan 2000; Laubhan et al. 2005; Massey 2000). Our experience over the past century clearly indicates that the most important part of wetland design and development is the upfront work to: (1) determine what type of wetland historically occurred in, and is appropriate for, a site/region; (2) understand, and attempt to emulate, the key ecological "drivers" and "processes" that created and sustained specific wetland types; (3) compare historical landscapes and attributes to contemporary landscape/site conditions to understand remediating needs; and (4) determine management objectives and capabilities. If these upfront considerations are addressed then an engineering design can be developed to meet ecosystem restoration and management goals. This chapter also does not attempt to delineate techniques for specific locations or wetland types (which would require an entire book for each area/type such as was done for northern prairie wetlands by Galatowitsch and van der Valk 1994), but rather advocates an approach that is applicable to all wetland types and systems.

3.2 The First Step: What Type of Wetland Belongs Where?

In general, we believe that wetland conservation projects should be designed to include features that will promote landscape-level natural resource conservation and efficient system-based management strategies. Incorporation of natural resource conservation features and objectives in wetland development projects requires an understanding of historic and current landscape conditions including the basic physical and biotic structure, ecological processes, and landscape-scale interactions that control ecosystem characteristics, functions and values. Hydrogeomorphic methodology now is commonly used to understand historic ecosystems and specific lands within an area, and to evaluate restoration and management options for landscapes (e.g., Heitmeyer and Fredrickson 2005; Heitmeyer and Westphall 2007; Heitmeyer et al. 2010a, b, 2012a, b). The foundation of this method is the analysis of historical and current information about: (1) geology and geomorphology, (2) soils, (3) topography and elevation, (4) hydrological regimes, (5) plant and animal communities, and (6) physical anthropogenic features of landscapes ranging in scale from site-specific tracts to large watersheds. These data essentially provide a context to understand the physical and biological formation, features, and ecological processes of lands within a region of interest. Incorporation of this historical information provides the foundation, or baseline condition, to determine what changes have occurred in the abiotic and biotic attributes of the ecosystem and how these changes have affected ecosystem structure and function. Ultimately, hydrogeomorphic assessments define the capability of the area to provide key ecosystem functions and values and identify options that can help to restore and sustain fundamental ecological processes and resources.

Hydrogeomorphic evaluations typically address the following three basic objectives for the area of interest:

1. Determine the historic condition and ecological processes of the site/region in question using a variety of historical (usually immediately before European settlement and subsequent major landscape alteration) and current information including geomorphology, soils, topography, hydrology, faunal and floral accounts, maps, and other information sets.
2. Identify changes to physical, biotic, and ecological process components of the site/region from the historic condition with specific reference to alterations in hydrology, vegetation community structure and distribution, and resource availability to key fish and wildlife species.
3. Identify restoration and management options and ecological attributes needed to successfully restore/enhance specific habitats and conditions within the site/region.

The first objective identifies landscape context and potential community type and distribution for an area by developing a “matrix” of understanding of which plant communities historically occurred in different geomorphic, soil, topographic, and hydrological settings (see Heitmeyer 2010a; Klimas et al. 2009; Theiling et al. 2012) and the primary ecological “drivers” or “processes” that both created and maintained the system. The “baseline” for the “historic” condition usually is the time immediately prior to major European settlement in the area (typically the late 1700s to mid 1800s). While some settlers occupied some areas prior to the late 1700s, human activities by these settlers typically did not substantially alter native vegetation communities, regional hydrology, or topography (e.g., Houck 1908; Douglass 1912; Ogilvie 1967).

Table 3.2 An example of the hydrogeomorphic matrix of historical distribution of major vegetation communities/habitat types in the vicinity of the Ted Shanks Conservation Area in northeast Missouri

Habitat type	Geomorphic surface	Soil type	Flood frequency	Elevation (feet above mean see level)
Bottomland Lake	Abandoned	Clay	Permanent river channels	<450.0
Sloughs	Late Holocene	Clay	Permanent-channel belt, semi-permanent	<450.5
Shrub/scrub	Edges of sloughs and lakes	Silt/clay	Semi-permanent	450.5–451.0
Riverfront forest	Narrow edges of rivers, sloughs, lakes	Sand	1 year	450.5–451.0
Floodplain forest	Late Holocene channel belt and low depressions in the Salt River tributary fan	Silt/clay	1–2 year	451.0–453.0
Bottomland	Salt River tributary fan, terraces on old Holocene channel belt	Silt/clay	2–5 year	>453.0
Slope Forest	Alluvial fan	Erosional mix	>5 years	>456.0
Bottomland Prairie	Old Holocene	Silt/clay	2–5 year channel belt	>455.0

Relationships were determined from land cover maps prepared by the General Land Survey in 1816, historic maps prepared by the Mississippi River Commission (1881), U.S. Department of Agriculture soil maps, geomorphology maps (Bettis et al. 1996), flood frequency data provided by the U.S. Army Corps of Engineers St. Louis District, and various naturalist/botanical accounts and publication from the 1800s and early 1900s (Reprinted from Heitmeyer 2008a. Published with kind permission of © Blue Heron Conservation Design and Printing, LLC 2008. All Rights Reserved)

The hydrogeomorphic matrix is developed from comprehensive scientific data discovery and field validation using published literature, vegetation community reference sites, and state-of-the-art understanding of plant species relationships (i.e., botanical correlation) to geomorphology, soil, topography and elevation, hydrological regimes, and ecosystem disturbances (Nelson 2005). These plant-abiotic correlations are in effect the basis of plant biogeography and physiography whereby information is used to describe the distribution of plant species and community assemblages throughout the world relative to geology and geomorphic setting, soils, topographic and aspect position, and hydrology (e.g., Barbour and Billings 1991). The matrix allows maps of potential historic vegetation communities in an area to be produced in an objective manner based on the botanical correlations that identify community type and distribution, juxtaposition, and "driving" ecological processes that created and sustained them. An example of a completed matrix is provided in Table 3.2. Obviously, the predictions of the historical community types and their distribution are only as good as the understanding and documentation of plant-abiotic relationships and the geospatial data for the abiotic variables for a location and historical period of interest.

In most U.S. ecoregions, the major vegetation communities that were present during the Presettlement period are known (e.g., Nigh and Schroeder 2002; Nelson 2005) and the botanical relationships of these communities with abiotic factors usually are extensively documented and robust. For example, the relationships of bottomland hardwood wetland species to seasonal and annual flooding regimes and local topography in the Upper Mississippi Alluvial Valley (MAV) have been widely studied (e.g., Bedinger et al. 1979; Keeley 1979; Wharton et al. 1982; Black 1984; Heitmeyer et al. 1991; Conner and Sharitz 2005, and many others). As a specific example, the distribution of pin oak (*Quercus palustris*) and willow oak (*Quercus phellos*) in the Upper MAV typically occurs on sites with silt-clay-loam soils, dormant season flooding for up to 3 months, and within the 2–5 year flood frequency zone (Heitmeyer et al. 1989, 2006a; Fredrickson and Batema 1992; Klimas et al. 2009). The interrelationships among abiotic factors for this region also are well understood and documented. For example, the type and spatial position of soils generally are closely related to geomorphic surface and formation. As a specific example, Crevasse sandy soils are found on the inside slopes of natural levee crests (Autin et al. 1991).

The sequence of actions used to prepare the hydrogeomorphic matrix and a map of potential historic communities for a site/region is as follows:

1. The general distribution of major vegetation community/habitat types such as forest, prairie, bottomland lake, and river channels and chutes (Nigh and Schroeder 2002; Nelson 2005; Heitmeyer 2008b) can be determined from General Land Office (GLO) surveys, historic cartography (e.g., Hutchins 1784; Collot 1826; Colton 1857; Couzens 1861; Warren 1869; Mississippi River Commission 1881; Brauer et al. 2005), and early settlement/naturalist accounts (e.g., Brackenridge 1814; Nuttall 1813; Schoolcraft 1825; Hus 1908). A generalized map of the historic distribution of communities using the above collective information is then overlain on contemporary geomorphology, soils, flood frequency, and topography data layers.
2. The presettlement vegetation communities from the above map sources are overlain on contemporary abiotic geomorphology, soils, and topography map layers to determine general correspondence where possible. Confidence in this “map” correspondence is best when geo-referenced digital maps are available, such as the GLO surveys, and is weakest when older maps and cartography are used. Despite the imprecision of some older maps and accounts, analyzing habitat information from these sources provides useful information to determine the general distribution of communities. Using this first-step overlay of map information, relationships between communities and abiotic factors sometimes are clearly defined by one or two factors. For example, chute-and-bar surfaces (Woerner et al. 2003) with recently deposited and scoured sandy soils along the current Mississippi River channel historically supported riverfront forest communities (Heitmeyer 2008b, 2010a, b). Often, however, it is necessary to use multiple abiotic variables to understand botanical relationships.

3. Remnant native vegetation communities in an area are identified from aerial photographs and other sources (e.g., Missouri Natural Areas Committee 1996). Select sites are then visited to document vegetation characteristics (such as species composition), and to determine if the sites matched the community types predicted from step #2. If the historic maps and contemporary field data are consistent, then the field sites are considered a reference site of former community types (Nelson 2005; Nestler et al. 2010).
4. Major community types are subdivided into ecologically distinct sub-communities using botanical information for the respective communities where possible. For example, bottomland hardwood forest communities in southeast Missouri and northeast Arkansas typically are distributed along topographic/hydrologic gradients and can be separated using the combination of soils, geomorphology, and topography (e.g., Nelson 2005; Heitmeyer et al. 2006; Klimas et al. 2009).
5. A matrix of predicted community types in relationship to the geomorphology, soils, topography, and flood frequency variables discovered in steps 1–4 is prepared.
6. The location of predicted communities from the hydrogeomorphic matrix on the composite digital geo-referenced maps of geomorphology, soils, topography, and flood frequency is mapped,
7. Contemporary aerial photographs are used to identify remnant habitats of the map predicted types (i.e. prairie, forest, shrub/scrub, and bottomland lake) and reference sites and remnant habitats are revisited to determine the vegetation that is present. This field data collection is similar to step #3 in finding reference sites that represent and verify various communities.
8. Based on field and map data developed in steps 6 and 7, the hydrogeomorphic matrix is refined.
9. A map of potential historic vegetation communities is prepared by sorting the landscape relative to the matrix parameters. Each community then has a unique signature of attributes.

The final product of the above methodology is a potential presettlement vegetation community map depicting the types and distribution of historical community types, which can be developed at any scale ranging from site-specific (Fig. 3.2) to watershed levels (Fig. 3.3) as well as larger regional levels (Fig. 3.4). This map then becomes the basis for subsequent decisions about what type of wetland (s) to restore in the project area and the corresponding processes/drivers that must be incorporated into design and management strategies to ensure the wetland is sustainable and emulates natural dynamics.

The second objective of hydrogeomorphic evaluations approach uses contemporary geospatial map information to describe alterations to the historic ecosystem attributes in relation to land form and soils, hydrology, vegetation community structure and distribution, and resource availability to key fish and wildlife species. A major part of this objective is determining the extent to which the presettlement vegetation communities predicted by the hydrogeomorphic method (step #9 above)

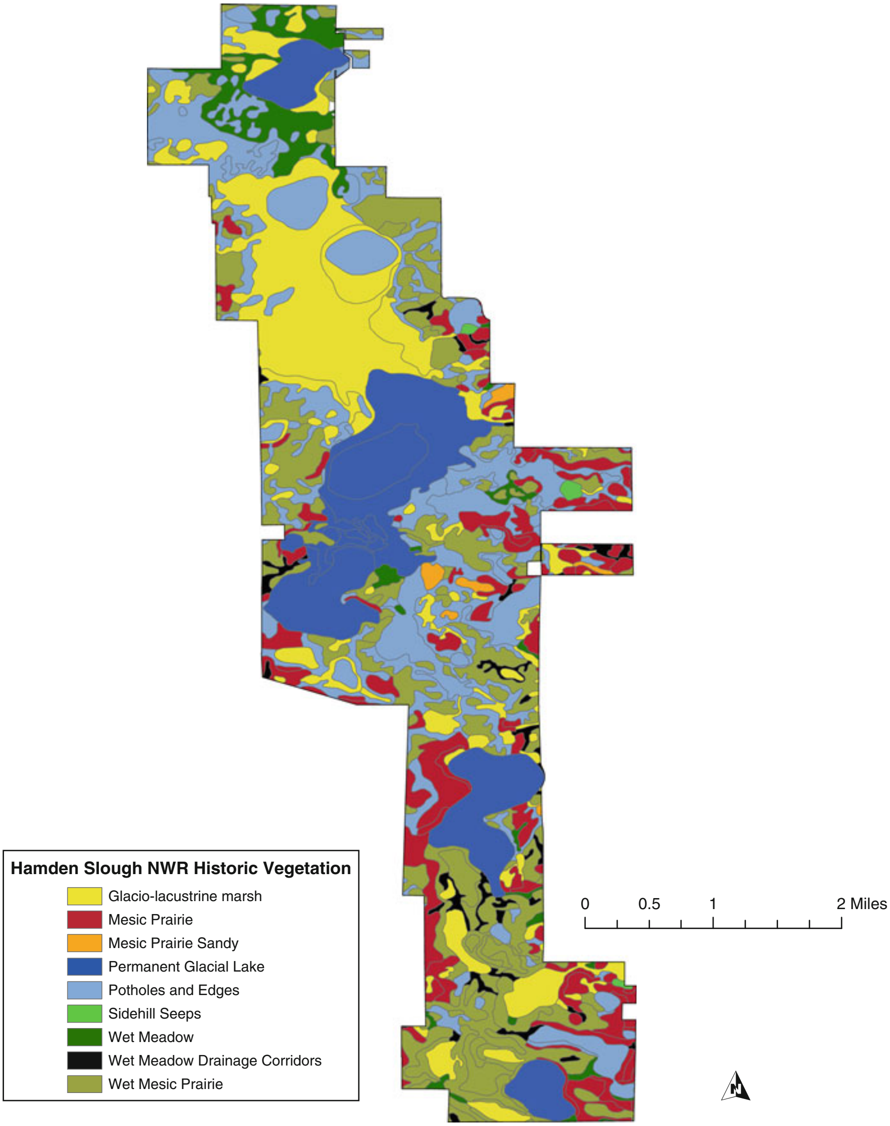

Fig. 3.2 An example map of potential distribution and types of vegetation communities modeled for an individual site, Hamden Slough National Wildlife Refuge, Minnesota (Published from Heitmeyer et al. 2012a with kind permission of © Blue Heron Conservation Design and Printing, LLC 2012. All Rights Reserved)

have been lost and converted to other land types. Overlaying the potential historic community map on contemporary U.S. Department of Agriculture (USDA) National Agricultural Inventory Program (NAIP) photographs provides an objective and quantitative way to assess current conditions including types and magnitude of changes. This comparison of historic vs. current conditions not only

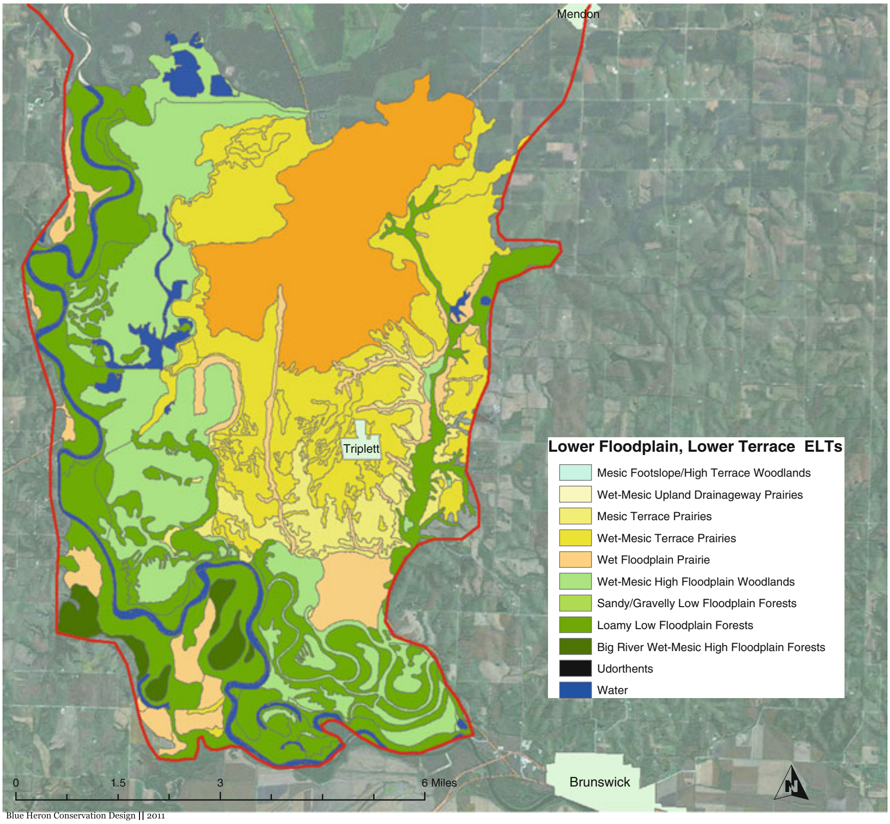

Fig. 3.3 An example map of potential distribution and types of vegetation communities (*ELT* ecological land types) modeled for a regional site, Lower Grand River floodplain, Missouri (Published from Heitmeyer et al. 2011 with kind permission of © Blue Heron Conservation Design and Printing, LLC 2011. All Rights Reserved)

identifies which communities have been destroyed or degraded, but also helps us understand the resiliency of specific communities to environmental changes, the potential impacts of development projects, and potential opportunities to reverse or mitigate/minimize degradations and restore communities if that is desired (Heitmeyer et al. 2006; Heitmeyer 2008b).

The third objective of evaluations is the development of options for wetland restoration, enhancement, and management under the current or future hydrogeomorphic conditions. In many cases this typically involves taking corrective actions to restore key physical attributes (e.g., topography) and/or ecological processes such as the proper timing, frequency, duration, and magnitude of disturbance regimes (e.g., hydrology, fire, grazing). However, in some cases, major landscape changes (e.g., river locks-and-dams, urban development, and sea-level rise) may preclude restoring major ecological structure or processes. In these cases, hydrogeomorphic models of community distribution can be made using existing

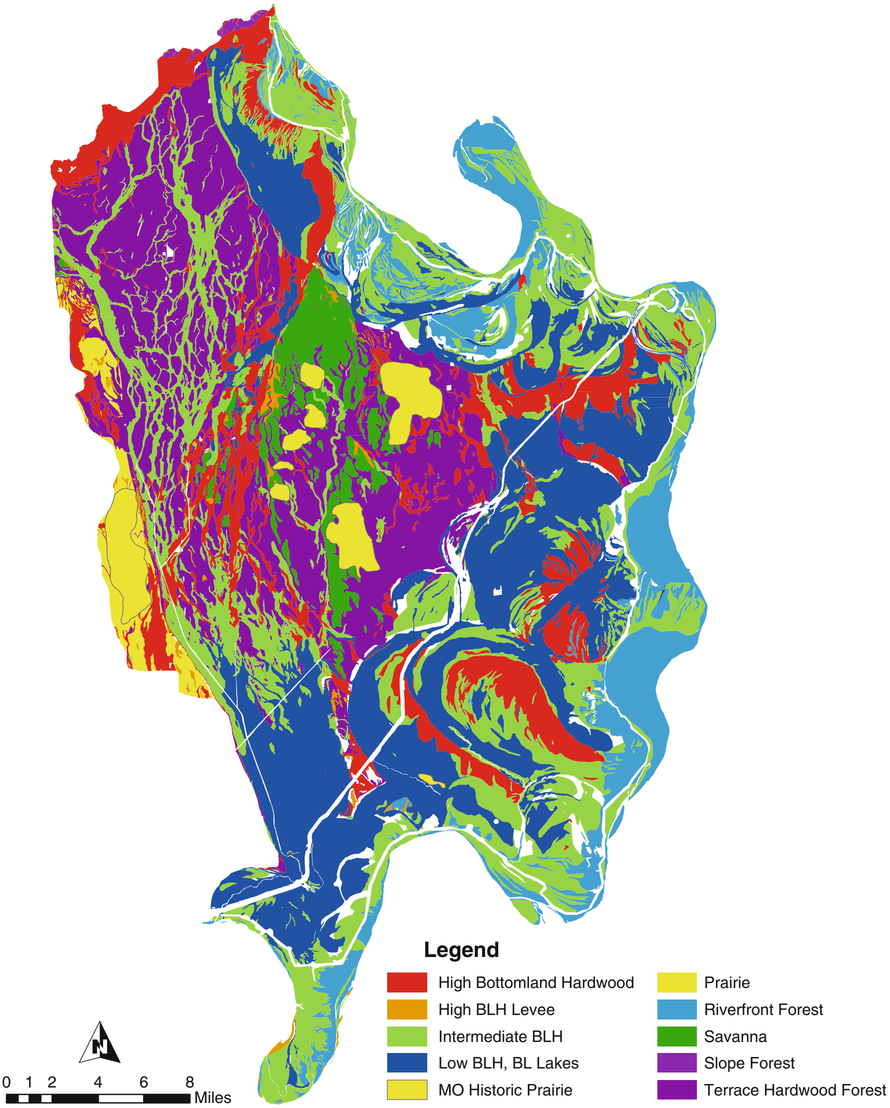

Fig. 3.4 An example map of potential distribution and types of vegetation communities modeled for landscape-scale site, St. John's Bayou Basin-New Madrid Floodway, Missouri (Published from Heitmeyer 2010a with kind permission of © Blue Heron Conservation Design and Printing, LLC 2010. All Rights Reserved)

landform, soil, and hydrological conditions (Klimas et al. 2009). Decisions regarding the ability and benefits of complete or partial restoration are based on evaluating the information generated in meeting the first two objectives above. This information essentially defines the template for the new "desired state" and determines the appropriate wetland design and development strategies embodied in this chapter.

3.3 Availability of Hydrogeomorphic Data

The hydrogeomorphic process of evaluating wetland development and management options for a site relies heavily on eight types of data/information, most of which requires geospatial information usable in an ArcGIS/ArcMAP format (see e.g., Heitmeyer 2007b). A brief description of the availability of these data sets in the U.S. is provided below:

3.3.1 Soils

Digital soils data and maps are readily available for almost all areas of the U.S. Most importantly, the USDA Natural Resources Conservation Service (NRCS) now has developed a U.S. General Soil Map (STATSGO) and Soil Survey Geographic data base (SSURGO) for the entire U.S., with a few exceptions (e.g., western Wyoming). STATSGO is a contemporary soil map of general soil association units developed by the National Cooperative Soil Survey and supersedes the State Soil Geographic Dataset that was published in 1994. It is a broad based inventory of soils and non-soil areas that occur in a repeatable pattern on the landscape and can be displayed at various scales. This data set is assembled from data on geology, topography, vegetation, and climate along with LANDSAT images. The data set is geo-referenced vector digital data and tabular digital data. SSURGO is the soil mapping database with map scales ranging from 1:12,000 to 1:63,000. SSURGO is the most detailed level of soil mapping ever conducted by NRCS and is based on digitizing duplicates of original soil maps and refining older maps with recent ground surveys. Information that can be queried from the database include attributes such as available water capacity, soil reaction, electrical conductivity, flooding frequency, building and site developments, engineering uses, and potential for vegetation establishment. A convenient website to obtain soil survey information is www.websoilsurvey.nrcs.usda.gov. In addition to contemporary soil maps, hard copies of older soil survey maps and reports are available for most U.S. counties. Dates of older soil surveys vary depending on when each county was first surveyed and how many times revised surveys and new reports were completed. As independent reports, they are useful because they often have ecological descriptions of areas that existed at the time of original surveys (some dating back to the early 1900s, e.g., Edwards et al. 1927) that help the user understand topographic and vegetation community distribution and subsequent changes that have occurred in the last century.

3.3.2 Geomorphology

Several sources of geology and geomorphic information usually are available for a site/region. This information ranges from U.S. Geological Survey (USGS) and

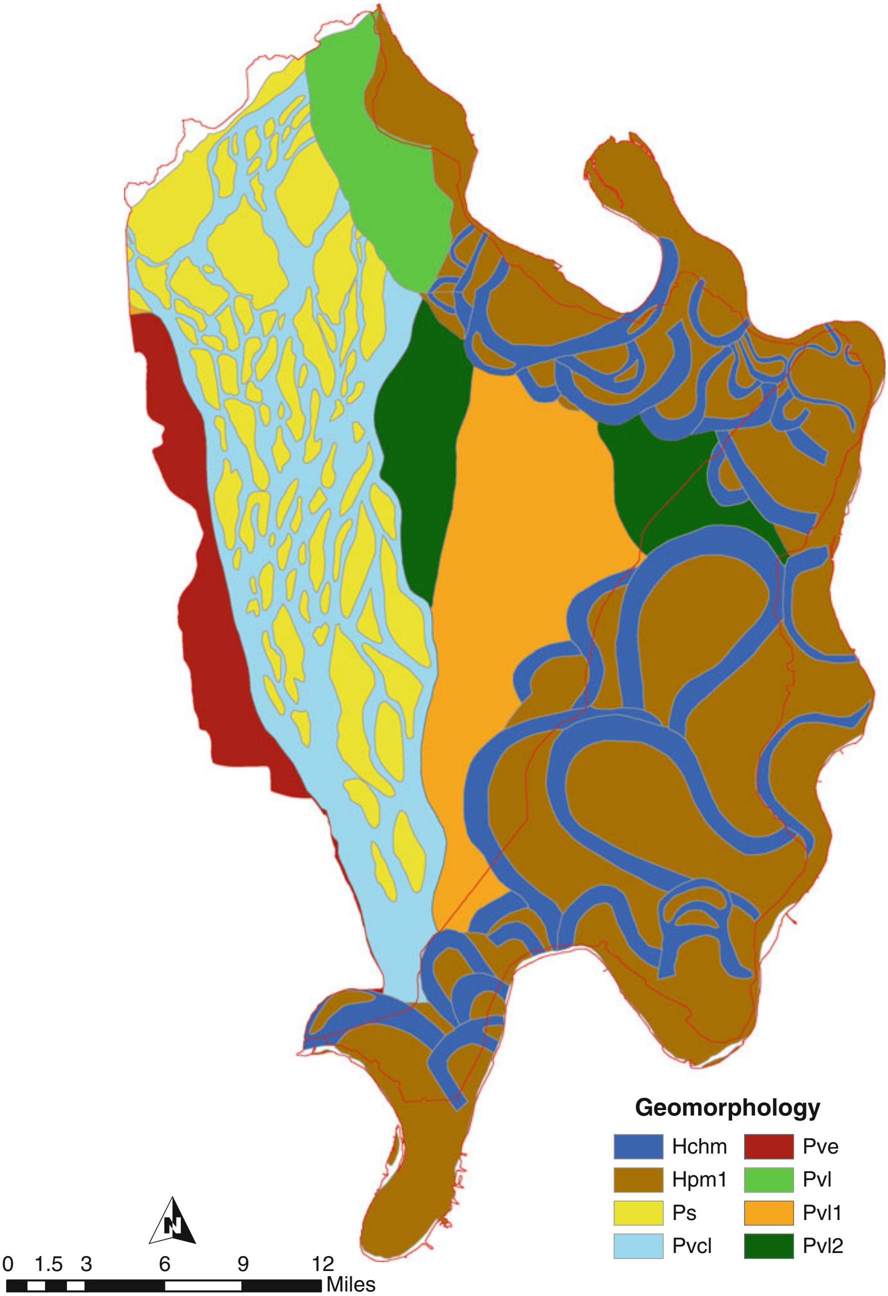

Fig. 3.5 An example map of geomorphology surfaces from an area – St. John's Bayou Basin-New Madrid Floodway, Missouri (Published from Heitmeyer 2010a with kind permission of © Blue Heron Conservation Design and Printing, LLC 2010. All Rights Reserved). *Hchm* – abandoned channels of the Mississippi River, *Hpm1* – point bar (meander scroll) deposits of Mississippi River

state geological survey maps and reports of regional geology and surficial geomorphology to detailed studies of land form assemblages (LSA). Where LSA maps are available they provide great geospatial detail on surface and subsurface formation and attributes and typically are digitized using ArcInfo GIS platforms. Examples of these geomorphology maps include those available in the Mississippi and Illinois River Valleys (Hajic 2000; Bettis et al. 1996; Madigan and Schirmer 1998; Saucier 1994, Fig. 3.5). Understanding geomorphic stratigraphy (see Saucier 1994) from the surface down through subsurface layers to bedrock is important to determine soil restrictive layers, surface and groundwater flow, root-zone penetration areas and depths, and availability of nutrients and/or contaminants. These features affect which plant communities can survive on a site and are important considerations for development plans if projects intend to remove or alter surface soils for levees and ditches (Willman 1973).

In some areas, especially large river systems, geomorphology studies have documented river channel changes (Brauer et al. 2005). These studies qualitatively and quantitatively record the types and times of historic planform changes of the river and adjacent floodplain areas. These channel change maps are based on many historical maps, surveys, and journals dating to the eighteenth century and include 1800s GLO surveys, Mississippi River Commission (1881) surveys and maps, old aerial photographs, and other old maps that originate from river charts (Collot 1826).

Many geological articles, reports, and maps exist for most U.S. areas including detailed stratigraphy maps, published accounts of geology, digital surface geology maps (e.g., www.geo.umn.edu/mgs, www.igsb.uiowa.edu, www.uwex.edu/wgnhs, www.usgs.gov). Also, many site specific geological and archaeological studies have been conducted (Munson 1974; Smith and Smith 1984). As with other data categories, literature searches will be needed to determine the availability of local published information.

3.3.3 Topography and Elevation

Data on topography and elevations of U.S. sites are variable in extent and scale. Digital and hard copy 7.5 min USGS quadrangle maps usually at 5-ft contour scale are available for most areas and are stored in UTM coordinates. These maps

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Fig. 3.5 (continued) meander belt 1 (most recent age), *Ps* – sand dune fields and eolian deposits on valley trains, *Pvcl* – relict channels of Late Wisconsin state valley trains, *Pve* – Early Wisconsin-age valley train, *Pvl* – Late Wisconsin-age valley trains where levels (ages of surface) are separately delineated, *Pvl1* – Late Wisconsin-age valley train level 1 (most recent age) that includes interfluves and relict channels unless channels are separately delineated, *Pvl2* – Late Wisconsin-age valley train level 2 (next newest age) that includes interfluves and relict channels unless channels are separately delineated are 1:24,000 digital raster graphic maps mostly from the late 1990s that are available through ArcSDE and as TIFF and SID files. Older hard copy USGS quadrangle maps also are available for many areas but dates of maps vary widely. Other topographic maps for areas may also be available from site- or region-specific investigations. For example, one of the oldest efforts to map topography at a large scale was conducted by the Mississippi River Commission (1881) for the Mississippi River floodplain from New Orleans to Minneapolis. Other maps often have been generated by special project needs conducted using on-ground point – and contour-mapping techniques.

More recently, topography in many areas has been mapped using high accuracy digital elevation models (DEM) developed from aerial photography and available elevation data. Light Detection and Ranging (LIDAR) elevation maps also now have been produced for some areas of the U.S. and can map elevation at various degrees of specificity usually to less than one foot contour scales. Ground elevation GPS data also are available from many sources such as USDA Wetland Reserve Program (WRP) lands, state and federal resource agency acquisitions and ownerships, private hunting properties, and non-governmental conservation organization projects.

3.3.4 Hydrology

Obviously, understanding historical and contemporary wetland systems requires information on surface and groundwater hydrology of an area. Specifically, data on source, timing, depth, duration, and frequency of water inputs and drainage is needed. Many diverse data sets can provide this hydrological information, with the type and availability of data depending on the location and type of system. For example, in areas where wetlands are influenced by periodic inputs of surface water from rivers and streams, data usually are present from stream gauges along the drainages. These river and stream gauge data have variable periods of record, but larger rivers have relatively uninterrupted data dating back to the late 1800s or early 1900s. Gauge data is readily available in graphic and tabular form from USGS and U.S. Army Corps of Engineers (USACE) websites (e.g., www.mvr02.usace.army, http://water.weather.gov/shps/). Some areas also maintain a metadata inventory of hydrographic survey, cross-section, and hydrological information (Soileau 2002).

Usually, major wetland concentration regions of the U.S. also have various hydrogeological reports which document both surface and subsurface water resources and regimes (Heitmeyer et al. 1989; Demissie et al. 1998; Nimick 1997; Luckey and Becker 1999; Franklin et al. 2003) and some even model past and present dynamics (e.g., Sophocleous 1992). In other cases data from local/regional water dynamics coupled with good topographic data can enable predictive models of flood frequency, including use of Hec-Ras models (Heitmeyer et al. 2012b). And, in some systems, sophisticated modeling of flood frequency and inundation probability are modeled from topographic and hydrological information such as the Scientific Assessment and Strategy Team (SAST) models for 11-digit watersheds of all ecological drainage units along the Mississippi River (Heitmeyer 2007b).

In addition to data on water source and mass-balance water data, considerable information often is available on water quality for most U.S. surface waters, and some groundwater, at least at a watershed scale. These studies include limnological information from long-term monitoring stations and local waters (USGS 1999; Wiener and Sandheinrich 2010), sediment analyses (Davinroy 2006), and bathymetric change (Bellrose et al. 1979, 1983). Information on groundwater levels and subsurface water interactions between wetlands and water recharge/discharge sources and locations is less available than information for surface waters, but often groundwater wells and peziometer stations are present in an area and may be available in CAD files, hard copy files, Excel spreadsheets, and engineering design data sheets.

3.3.5 Aerial Photographs and Older Cartography Maps

In most U.S. areas, at least some older aerial photographs are available that show historical landscapes prior to many contemporary land/water alterations. In some cases, excellent time-series of these photographs exist (Heitmeyer et al. 2009, 2010a) that can show periods of extreme flood or drought, water flow pathways and patterns, vegetation communities, proximity of various wetland types and complexes, and timing of past alterations (Fig. 3.6). Increasingly, older photographs have become available in digital files scanned at 300 dpi resolution and also are geo-referenced. Various state and federal agencies index and store archival photographs and maps including analog aerial, paired-stereographic, ortho-, and individual ground photographs.

Historical cartography maps of many regions also are available and they identify information on elevation/topography, transect bathymetry, land cover, and other ecological features including wetland distribution (Fig. 3.7). While most of these maps (with the exception of GLO survey maps) may be imprecise and non-georeferenced, they provide valuable information to confirm or distinguish major landscape and hydrological features. Examples of these maps include the Lewis and Clark maps from the 1700s (http://lewisclark.geog.missouri.edu/website/lewisclark1.htm), French and British regime maps from the late 1700s, (Eckberg and Foley 1980; Thurman 1982; Collot 1826), GLO maps from the early to mid 1800s (Sickley and Mladenoff 2007), the “Warren” maps from 1866 (Warren 1869), and county plat maps from the late 1800s and early 1900s (e.g., Birdsell and Dean 1882).

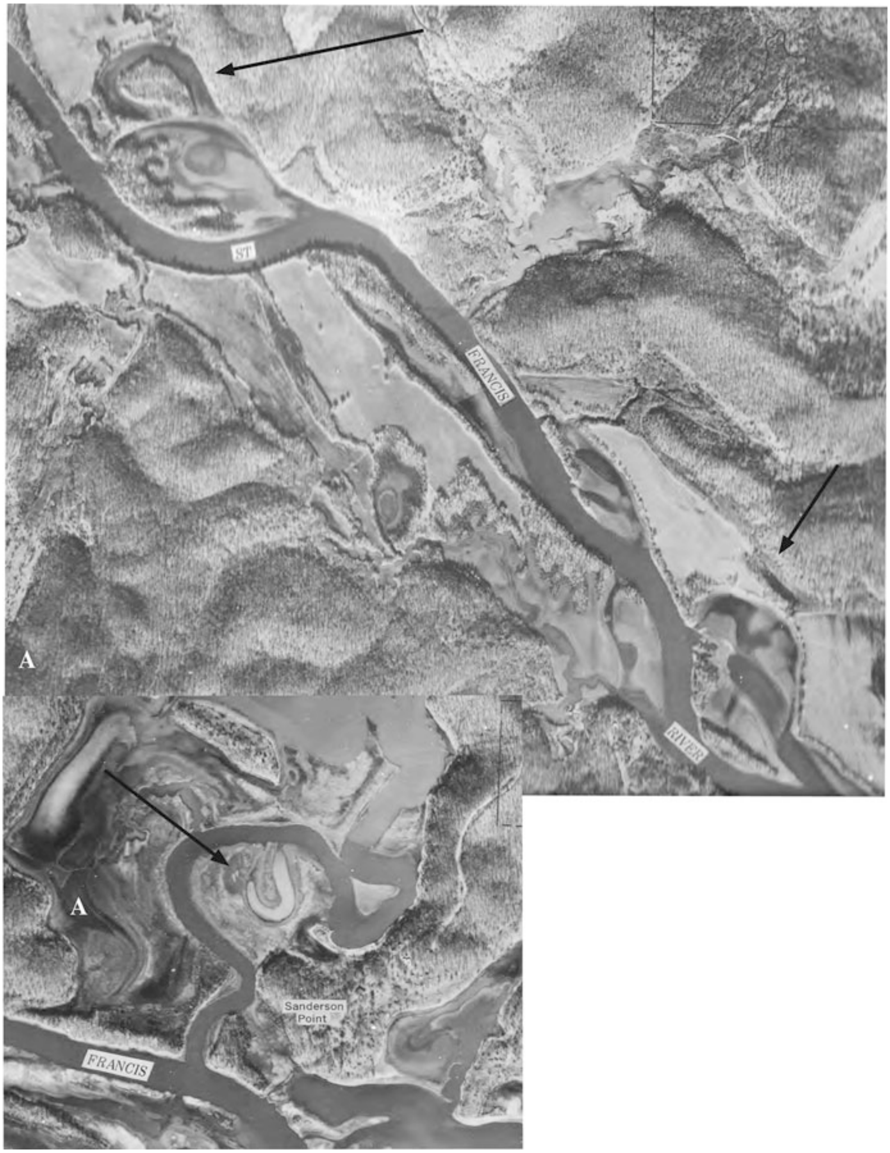

Fig. 3.6 Aerial photographs of the St. Francis River floodplain during low water periods in March 1968 prior to inundation by Wappapello Lake showing: (**a**) abandoned river channels, (**b**) relict drainage routes and floodplain sloughs, and (**c**) meander scrolls with ridge-and-swale topography (Published from Heitmeyer 2010b with kind permission of © Blue Heron Conservation Design and Printing, LLC 2010. All Rights Reserved)

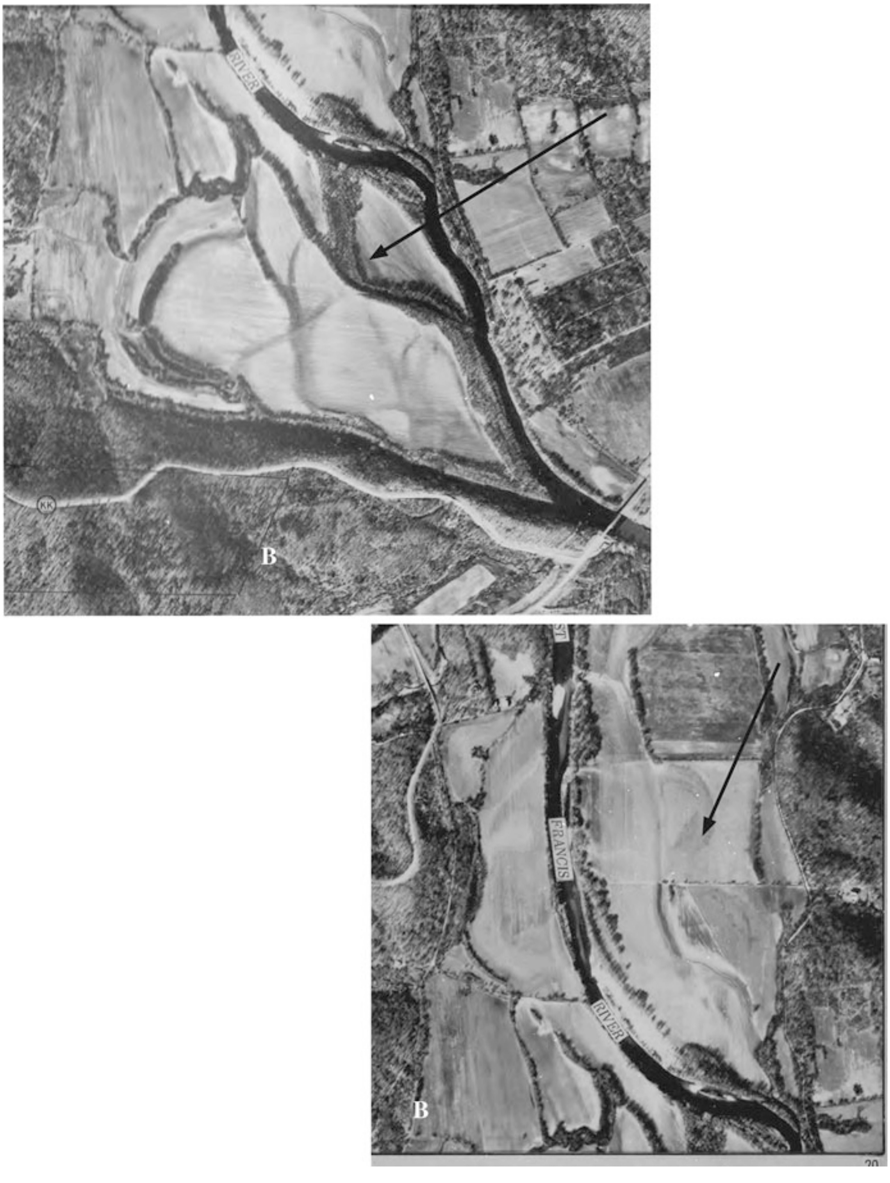

Fig. 3.6 (continued)

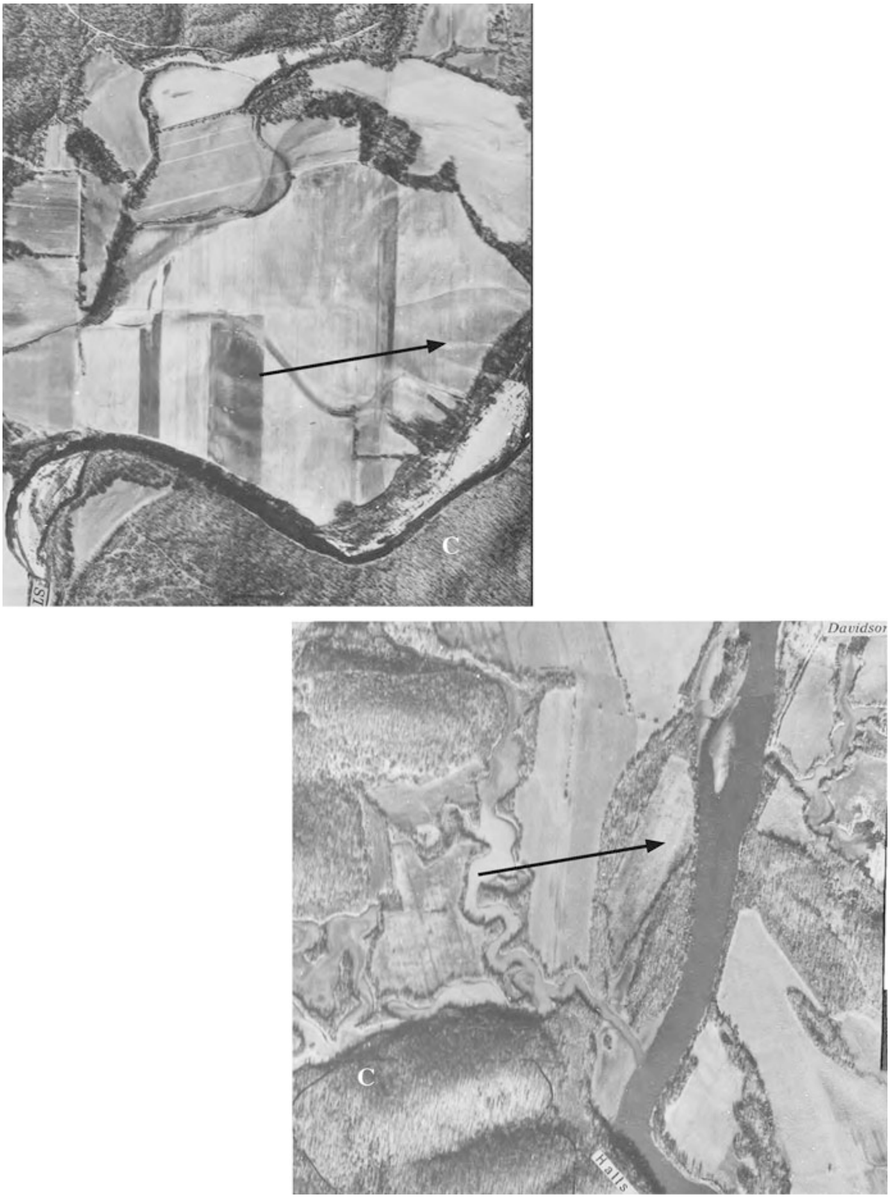

Fig. 3.6 (continued)

Fig. 3.7 Example of an historic map of low "swamplands" in Southeast Missouri (*SEMO*) in 1903 (Obtained from the Little River Drainage District files, Kent Library, Southeast Missouri State University, Cape Girardeau, Missouri and presented in Heitmeyer et al. 1996)

3.3.6 Vegetation and Ecological Communities

Perhaps the most geographically extensive and quantifiable maps that provide accounts of historical vegetation communities, and distribution of at least larger wetlands, are from the GLO maps and survey notes. By nature of these surveys, the information is geospatially correct. These data record tree species and other vegetation at specific location on land survey transect lines. The notable "witness tree" information comes from trees at section corners GLO databases now have been compiled by many conservation groups, especially The Nature Conservancy and the U.S. Bureau of Reclamation. These databases include information and summaries along transect lines with maps of generalized major vegetation groups (i.e., prairie, woodland, forest, wetland) and their distribution. Caveats exist with the GLO information (Bourdo 1956; Hutchinson 1988; Schulte and Mladenoff 2001) but many studies have used interpreted GLO data to analyze trends and changes in vegetation communities in specific locations (Brugam and Patterson 1996; Yin and Nelson 1996; Nelson et al. 1998; Theiling et al. 2012).

Many other older cartography maps and aerial photographs also have information on general vegetation communities and include some reference to specific species at certain locations. For example, the Mississippi River Commission (1881) maps usually identify forest vs. open or prairie lands and include information of specific tree distribution. Some older maps (such as ownership plat maps) have relatively precise definition of wetland areas with the descriptors "oxbow", "pothole", "lake", "marais", "marsh", "swamp", and "etang." Other maps include drawings of smaller wetland depressions and swales, drainage systems, and overflow flood basins. Collectively, these maps help inform understanding of not only vegetation communities but also historical water movement and flow patterns, which can be a basis for contemporary development and emulation of water regimes and movements.

In addition to historical maps and survey notes, many older studies and published accounts offer description of vegetation and ecological communities in various regions. These published articles are too numerous to list, and require managers and wetland designers to "mine" available literature of all types. Examples of such botanical accounts include Forman (1789), Nuttall (1813), Schoolcraft (1825) and Hus (1908). In some cases the historical literature on landform and communities has been summarized (White 2000; Havera et al. 2003) and provides a basis for understanding and evaluating changes within an area.

Information on contemporary vegetation composition and community distribution now exists in digital georeferenced form for most areas, and often has chronological sequence maps (e.g., www.umesc.usgs.gov/data_library.html). Many areas also have specific vegetation inventory data (Korschgen and Toney 1978) and the USGS has created a National Land Cover Database for many areas.

An important part of reconstructing historical vegetation community type and distribution, and in preparing the HGM matrix mentioned earlier, is identifying "reference" sites that contain various combinations of geomorphology, soils, elevation, and hydrologic features in addition to at least some remnant native vegetation communities (Nestler et al. 2010). At least in some states and areas, Natural Heritage Databases and listing of reference sites is available (e.g., Missouri Natural Areas Committee 1996).

3.3.7 Species/Habitats of Concern

Most states in the U.S. have natural history/heritage inventory lists and distribution maps of plant and animal species including many that are considered species of management concern or are listed as either state or federally threatened and endangered. Much of these data are available from USFWS or state agency websites; however, some information on specific locations may not be available to the general public. In addition to inventories of plant and animal species of concern, most states have identified habitats of concern that now are in limited distribution or area (Nelson 2005). Most states are in a second round of planning for State Wildlife Action Plans as part of the national Comprehensive Wildlife Strategy funding project. And, the USFWS has adopted a Landscape Conservation Cooperative Strategy, which seeks to identify ecological areas and community types (including specific wetland types) that are high priority, identify best management practices, connect conservation efforts, identify gaps in landscape scale science information, and avoid duplication through improved conservation planning and design. Other specific wetland areas of interest are identified in state wetland plans; the North American Waterfowl Management Plan, North American Bird Conservation Initiative, Partners in Flight, and some areas have extensive wetland data bases of areas and species. All of these data are important considerations for planning wetland designs so that the cumulative impacts of site-specific design and construction ultimately contribute to larger scale ecosystem and landscape level benefits and integrity.

3.3.8 General Geographic Cadastral Data

Wetland design and construction planning using hydrogeomorphic information relies on many basic GIS cadastral data layers of physical features, many of which are man-made. These data include contemporary information on roads, levees, ditches, towns, political and governmental units such as levee and drainage district boundaries, ownership, easements, Federal Emergency Management Agency (FEMA) and flood prone areas, planning and zoning maps, and many others. These cadastral data sets usually are readily available from state and local governmental entities and provide information on specific physical features that may impact the design and construction of a wetland such as location and size of drainage features including water-control structures, pipes and ditches, revetments and dikes, and dredge placement areas. These data can be old (Minton 1912), but recent (WEST Consultants, Inc. 2000) publications include details of construction and operation chronology, design features, and management capabilities. Other physical and hydrological data often are compiled by USACE, Bureau of Reclamation, USDA, and state Water Resources agencies and include information on project developments such as levees, water-control and delivery structures, dredge-and-fill sites, ownership and management, and special project areas such WRP sites.

3.4 Application of Information

Obtaining the above information and preparing hydrogeomorphic matrices and maps of potential ecosystem restoration and management options helps address four basic sets of questions that guide decisions about what communities can/should be restored at sites ranging from broad ecoregions and regional floodplain corridors and watersheds to specific tracts of land. The four question sets are:

1. What was the historic presettlement vegetation community? What landscape features were associated with this community? What abiotic and biotic mechanisms sustained it?
2. What changes have occurred from the historic conditions, both in physical structure and ecological processes?
3. What potential communities can be restored and sustained on the site or region now? In other words, what is the "new desired state?"
4. What physical and biological changes are needed to create and sustain the new desired community?

The hydrogeomorphic information provides most, but not all, of the answers to these questions to help conservation planners and land managers make restoration decisions. At a broad landscape scale, these above data sets identifies the historic types and distribution of communities in an area (e.g., Figs. 3.2, 3.3 and 3.4), the current land cover, and the current suitability of areas for restoring community types (Fig. 3.8). This information can be used by conservation partners to understand which communities have suffered the greatest loss in an area and where they may wish to work to restore basic parts of the local/regional ecosystem. At the site-specific scale, these data provide information needed to determine what specific communities historically occurred on, and potentially could be restored at, a site. This understanding helps planners identify what physical features and ecological processes sustained the endemic communities and determine which of these that must be present or restored/developed if the community is to be restored.

The following sequence of questions may be helpful for determining the best restoration potential for specific sites:

1. Ask what the historic community types were on the site. This is provided in an HGM historical vegetation map (e.g., Figs. 3.2, 3.3 and 3.4).
2. Ask what the physical and biological features of the communities were and what biological mechanisms controlled their expression. This is provided in the review and description of communities at an area and the hydrogeomorphic matrix (Table 3.2).
3. Ask what changes have occurred to the site. Obtaining information about detailed changes in landform, hydrology, and community composition usually will require site-specific investigations.
4. Ask what communities are appropriate and ultimately can be sustained for the site given current alterations (i.e., the desired community). Specific information will be required about elevation and flood frequency to determine the new desired state and detailed distribution of species within the site.

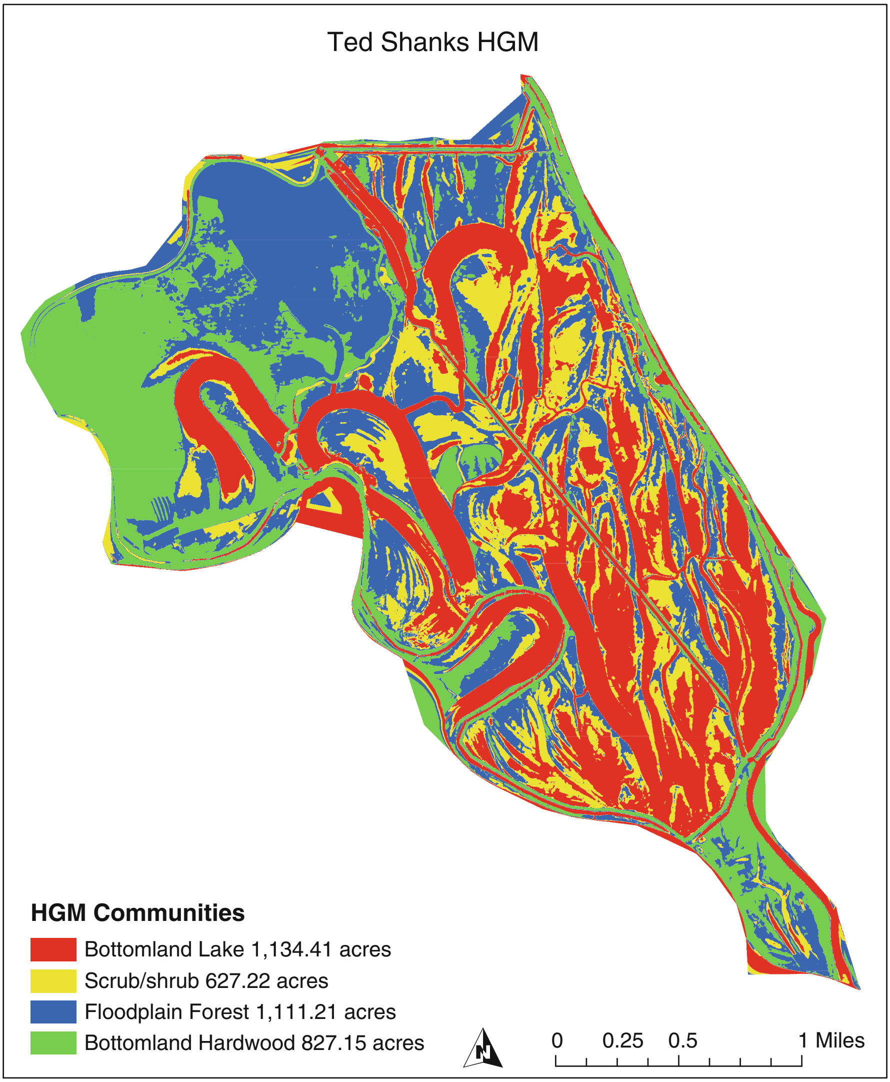

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Fig. 3.8 Potential distribution of wetland types that could be restored on the southern portion of the Ted Shanks Conservation Area, Northeast Missouri, based on current topographic, flood frequency, geomorphology, and soils data. BLH in legend = bottomland hardwood forest (Published from Heitmeyer 2008a with kind permission of © Blue Heron Conservation Design and Printing, LLC 2008. All Rights Reserved)

5. Ask what physical and biological changes will be needed to restore the desired community – this is effectively the design plan for future site-specific wetland developments.

The degree that more detailed site-specific information will be needed depends on what information exists for that site. The most common data deficiency often is the lack of historical site-specific flood frequency information and detailed topographic information (i.e., at least a 1-ft, and preferably <0.5-ft contours). Additionally, the cumulative effects of multiple alterations of former hydrology, community structure and dynamics, nutrient and energy flow, etc. caused by site changes (e.g., levees, ditches, roads) and systemic alterations (e.g. lock and dam effects upstream) often is uncertain. Despite some gaps and uncertainties, the hydrogeomorphic methodology provides the basic information and tools to plan regional conservation and restoration actions and to conduct the majority of site-specific evaluations. Undoubtedly, some refinement of predicted communities, both past and future, will occur as new information is acquired and existing data are refined.

3.5 Specific Considerations for Designing Wetland Infrastructure

Restoration and development wetlands in contemporary modified landscapes often require construction of at least some infrastructure to manipulate water, soil, and vegetation. Unfortunately, most man-made and man-manipulated wetlands are typically less productive when compared to natural systems (Weller 1994; Middleton 1999; Fredrickson and Laubhan 2000). The conservation conundrum is that few naturally functioning wetland systems remain, so wetland design and development must seek to restore physical and biotic attributes to the extent possible and then conduct subsequent management accordingly (Laubhan et al. 2005). In the past, the goal of most developed and managed wetlands was to stabilize or create annually consistent water regimes and vegetation conditions. Specifically, intensively managed systems with water-control structures typically have less plant diversity and productivity because of somewhat artificial seasonal and annual water regimes. Natural wetlands have variable shapes and elevations that allow water inputs, retention, and outflows to change as water levels rise and fall. The movement of water through a water-control structure is different from natural water flows because water tends to move through a structure with a box or tube of a set size, at a usually constant rate, until the outlet opening is no longer filled. Water-control structures with multiple bays are superior to a single bay opening but they still do not duplicate the variability found in natural outlets. Another problem common to structures is that the constricted outlet typically increases flow velocity, compared to natural flows, which can increase suspended sediment loads in discharges that are subsequently deposited near the control structure where velocity decreases rapidly. These patterns of sediment deposition regularly obstruct distribution channels and require costly continued maintenance to the site.

Another common problem in infrastructure design is that drainage outlets (water control structure or overflow) are often designed for average conditions rather than extremes. Thus heavy inputs from on-site precipitation can easily overwhelm the control structures potential to discharge enough water to prevent rapid increases in levels that compromise management objectives. In wetlands used by breeding waterbirds that nest over water this can be especially problematic when water rises faster than birds can add nest material to the nest structure to keep it above water. On migration and wintering areas, outlet structures of insufficient size often preclude drainage dynamics required to sustain existing vegetation (e.g., bottomland hardwood forests) or create diverse saturated substrates for desired plant germination.

Despite the limitations of many infrastructure designs, the following general considerations can increase the effectiveness and efficiency of wetland developments.

3.5.1 Land Survey Techniques

Topographic surveys should be obtained before wetland developments are designed. The availability of existing topography information ranges from standard USGS topographic maps to more sophisticated maps derived from satellite technology. USGS topographic maps often contain information that may be outdated, or the scale of elevation detail may not be sufficient to make informed decisions. In these cases, if the area to be surveyed is small (<500 acres) on-ground surveys using a level and grade rod can be utilized. The standard ocular level and grade rod requires two people to operate, while modern laser levels and grade rods can be operated by only one person. The ocular level has inherent problems that include poor weather and limited visibility that can cause inaccuracies at long distances (>1,000 ft).

Currently more sophisticated methods of surveying elevations are available to produce extremely high detail topography maps and that can cover large expanses of lands. These include LIDAR and Real-Time Kinematic (RTK). LIDAR (mentioned in the preceding section of available Hydrogeology data) is a remote-sensing technology that is used to collect high-resolution, high-accuracy elevation data. An aircraft equipped with LIDAR flies over the area to be surveyed and records distances to surfaces that can be used to create detailed topographic maps typically accurate to within one foot or less. While LIDAR data is a valuable tool, managers should use care when interpreting LIDAR maps, especially those in coastal and forested wetlands where radar signals of distance are distorted by above-ground vegetation structure. LIDAR data tend to have more uncertainty in wetlands than in uplands, where the technology has been tested more extensively. It is common for less than 5 % of the "ground points" to have actually hit the ground surface in wetlands with dense stands of persistent emergent or woody vegetation. Standing surface water can also alter signals so that ground topography underneath the water is distorted or absent (Fuller et al. 2011). LIDAR also can be rather expensive, and is best used for landscape level planning.

RTK is a position location process whereby signals received from a reference device (such as a GPS receiver) can be compared using carrier phase corrections from a reference station to the user's roving receiver. RTK improves GPS accuracy with real-time signal comparison and corrections, while compensating for atmospheric delay to increase accuracy and productivity. These systems are well suited to disciplines such as wetland engineering where precision is a vital component of a successful product application (Large et al. 2001).

3.5.2 Topographic Restoration and Infrastructure Placement

In many altered wetland areas, the natural topography has been highly modified by roads, levees, rail beds, ditches and canals, channelization and consolidation of drainages, and varying degrees of land leveling. An excellent review of objectives and methods to restore micro- and macro-topography in wetlands is provided in Stratman and Barickman (2000).

If the decision is made to develop new, or reconfigure, old wetland impoundments, the number of units required or desired will be determined by the landscape. Topography, existing fields, rivers and streams, and water sources may all influence the number of impoundment units. Unit size is largely determined by the landscape, and can be very different within and among areas. For example, some wetland impoundments in the Cheyenne Bottoms Wildlife Management Area in Kansas total thousands of acres (Zimmerman 1990) whereas some impoundments at the nearby Quivira National Wildlife Refuge are less than 5 acres (Sophocleous 1992).

Determining the location to construct levees or other earthen structures is one of the most important decisions made when developing or reconstructing impoundments. Often field or drainage borders influence the placement of the infrastructure. Generally, building levees along existing topographic contour lines is preferable to straight levees. By placing levees on contours, managers can maximize the number of acres that can be managed at preferred water depths. The cost of constructing levees is influenced by elevation gradients in an area and the desired contour spacing. Contour levees built at 1-ft intervals have the advantage of ensuring that water depths will be shallow to maximize foraging resources for most dabbling ducks, shorebirds, and wading birds (Fredrickson and Laubhan 2000). At 2-ft contours, part of a wetland unit will have deeper water and provide habitat for species that prefer and use resources in deeper water; these deeper areas also will be used for loafing and roost sites and typically remain open longer during freezing conditions.

The height, slope, and top width of levees influence cost, access, and sustainability of levees and other impoundment structures. Obviously, larger levees require more material to build and increases costs. If a levee will be used as a road, then the top width must be at least 10–12 ft wide. The amount of freeboard (height of the levee above full-pool water level) also influences whether a levee can withstand substantial vehicle traffic and levee integrity during high water flood events. Early levee slope engineering designs called for a slope of 3:1 (3 ft of horizontal run to every 1 ft of vertical rise), which was cost efficient and structurally sound (U.S. Soil Conservation Service 1992). Steeper slopes can make levee maintenance dangerous, as the potential for tractors to overturn while traversing the slope is high. A levee designed with a 5:1 slope makes for a safer structure, while adding little to the initial cost of construction. Levees built with more gradual slopes are inherently stronger, as additional dirt on the front and back sides of the levee increase the holding capacity of the structure. However, there are conditions that may require levee slopes to exceed the 5:1 ratio. If the hydrology of the site is prone to flooding from adjacent rivers, streams, or is subject to high run-off rates from the adjacent watershed, a gentler slope of 10:1 or even 15:1 is appropriate. Levees designed with these features are less prone to erosion damage when overtopped by flood waters, and are also less susceptible to damage from decaying tree roots or mammalian burrowing. Levees constructed with low wide slopes also mimic natural levees along river and streams, and can support woody vegetation without fear of levee failure, which has the added benefit of reducing maintenance costs.

3.5.3 Construction Equipment

Heavy equipment usually will be necessary to efficiently and correctly develop wetland levees, restore topography, reconnect waterflow pathways and patterns, and remove or modify existing land form alterations. Many types of equipment exist for construction projects and each has advantages and disadvantages. For example, if a small levee with a life span of less than years desired a rice levee plow can be used. Invented to construct small levees on contours of one to two tenths of a foot to facilitate flooding in rice production, these plows have been used to create shallow water habitats in low topography agricultural fields for years. Major advantages of rice-dike levees include construction can be accomplished quickly with a farm tractor and they can be built quickly and cheaply. The disadvantages are that levee heights are low, subject to erosion and breaching, and the inability to support any type of vehicular traffic.

In the past, many wetland developments were constructed using crawler tractors (i.e., bulldozers). Levees constructed in this manner were the backbone of the early wetland developers as bulldozers were fairly inexpensive and military surplus equipment was readily available. The advantage of building levees and other earth-works with a bulldozer or boom-bucket machine (such as a trackhoe) is that work can be accomplished fairly quickly and in less than ideal conditions. The disadvantages are that soil compaction is greater and the material used for construction must be obtained near the levee because it is pushed into place by the blade or dropped on the site by the bucket. This method typically results in “borrow areas” located along the toe of the levee, which normally results in a deep water

Fig. 3.9 Photograph of modern earth moving machinery using tractors and dirt pans

zone that increases the amount of water needed to flood an area and delays complete drainage of a site. These borrow areas also attract burrowing mammals such as beaver (*Castor canadensis*) and muskrat (*Ondatra zibethicus*), which cause damage to levees.

The availability of modern earth moving equipment such as tractor-drawn dirt pans and scrapers has greatly improved capabilities of developing wetlands, at least in non-coastal areas. These machines are hydraulically operated with a vertical moving hopper (the "bowl") behind a sharp horizontal front edge (Fig. 3.9). When the hopper is lowered, the edge cuts into soil and fills the bowl. When full, the hopper is raised and closed with a vertical blade (the "apron"). The machine is then moved to the fill area; the rear of the hopper is rotated upward and the load is dumped.

Global position systems (GPS) began to assist earth moving machinery in the 1990s (Trimble 2008). GPS improves the capability of building precise level slope and height grades. GPS systems mounted on machines usually use two receivers on the machine blade and a base station located in the field to transmit elevation information. The tractor and dirt pan may be outfitted with a laser transmitter and receiver that operate the tractor controls automatically to adjust the dirt pan to cut or fill to the pre-determined grade. Using this technology, levee grade can be constructed to within one-tenth foot accuracy.

The importance of where to excavate or "borrow" the material for construction using laser-assisted dirt pans and scrapers often is overlooked and the consequences not well understood. Using the wrong material (e.g., sand) or excavating from the wrong site can create problems. If it is desirable to not have a defined borrow area, then the scraping method can be used. Shallowly scraping the fill material from multiple areas avoids having a “hole” in the unit, but removes valuable topsoil and places it in the levee. In contrast, efforts to restore natural topography (e.g., natural levees, hummocks, mounds, swale banks, and depressions of various depths) will require creative borrowing (Stratman and Barickman 2000). Constructing creative borrowing requires the use of a tractor and dirt pan, as excavation sites will be some distance from the location of the levee.

3.5.4 Water Source and Movement

A primary requirement of many wetland projects is restoring and/or providing water management capabilities to a site. In these cases, potential water sources must be determined. On-site rainfall, local surface water runoff, or groundwater discharge may be the only options for a water source in some locations. If more predictable and consistently available water is desired, managers sometimes can take advantage of water in nearby rivers and streams, tides, impoundments, and wells. At some sites, building infrastructure to allow gravity flow of water into a wetland (preferably in a natural flow manner) can be done to make water sources cost effective and reliable. In other cases, pumps will be required to obtain and move local water sources to the wetland. These pumps range from larger stationary units located at strategic locations on the water source and delivery infrastructure to mobile units placed in areas where seasonal water may be available.

Groundwater wells have traditionally been a major source of water for wetland restoration and management. The usual high availability of well water has been a primary reason that managers have invested in this type of water source. Installing a deep well is not easy or cheap, and requires a professional well driller to complete the installation. Wells typically are operated with stationary or movable pumps usually powered by electric or fossil-fuel turbines or engines. Electric power is clean and requires little effort to start power units once electrical connections are installed. Installing electric power to a well can be cost prohibitive. For example, single-phase electricity (which will power pumps up to 25 horsepower) will cost less, and in most areas an electric line can be installed (for a limited distance) for free by the local electrical utility company. In contrast, three-phase electricity, which will power electric motors up to 100 horsepower, will require an installation fee that can cost from 2 to 4 dollars per linear foot. Thus, if the location of the well is far from an existing three-phase power source, the cost of installation can run into hundreds of thousands of dollars. Fossil fuel power, whether diesel, gasoline, or propane creates exhaust emissions, can cause spill contamination, and usually requires extensive time to set up. The advantage to fossil fuel power is that the power unit is mobile and can be used at multiple sites.

The location of a well is usually dependent on the location of groundwater aquifer sources that are sufficient to provide the desired amount of water to an area. If multiple well locations are possible, then wells can potentially be located at the high elevation “top” or low elevation “bottom” end of a wetland. Placing the well inlet on the bottom side of a wetland impoundment sometimes can save water because water is directly flooding the area from low to high elevations. A disadvantage is that higher elevations do not receive water until the lower elevations are full. In contrast, placing the well inlet on the top side allows more flexibility as the well water can be used for irrigation purposes during the growing season and water can be moved across and through a wetland in a more natural manner if natural topography is still present or restored.

Water can be moved into, through, and out of wetlands in many ways. Generally, attempting to create independent flood and drain capability among wetland units is important to allow for management flexibility. However, in some cases, water movement between managed units is desired to restore natural water movement patterns that are critical to emulate natural patterns of nutrient, energy, and animal movement. A disadvantage when wetland units or impoundments are interconnected is that water must be moved by pumping or gravity flow from one unit to another to fill (or drain) a higher or lower elevation site (see Fredrickson and Laubhan 2000). In these situations, it is desirable to have independent inlets and outlets to each unit to maximize management capability. Distribution canals have been used for many years, and can deliver water to individual units independently. However, these delivery systems waste a lot of water, require frequent maintenance, provide sites for establishment of undesirable plants due to frequent wetting and drying of soils, and take up space in the impoundment system that could be utilized as habitat. Underground piping systems can work well and save pumping costs but the initial cost for material and installation can be high and may prohibit overland sheetflow of water if that is desired.

3.5.5 Water-Control Structures

Much has been written about water-control structures in wetland engineering and management handbooks and publications. We refer managers to the many publications that specifically address structures appropriate in different wetland systems ranging from coastal to inland ecosystems (Fredrickson and Taylor 1982; Weller 1989; Fredrickson and Batema 1992; Hammer 1992; Payne 1992; U.S. Soil Conservation Service 1992; Kelley et al. 1993; Nassar et al. 1993; Fredrickson and Laubhan 2000; Massey 2000). Many different types of water-control structures are available and can work well depending on the location and type of wetland; these include common stop-log, screw-gate, radial-arm, coastal tidal trunk, and spillway structures. Each has advantages and disadvantages that are discussed in detail in other publications. A few commonly occurring issues that affect management capabilities include structures that:

- have opening diameters that are too small to effectively flood or drain a unit
- have materials that are subject to rapid corrosion and damage
- do not accommodate large flood events

- require intensive monitoring and maintenance
- require large equipment or many personnel to operate
- are subject to being obstructed by beavers, debris, and vegetation.

3.6 Specific Considerations for Restoring Vegetation

Following wetland development or restoration, the soil surface of a site usually is at least partly exposed. Attaining the composition and distribution of the plant community that is ultimately desired for the site (based on the hydrogeomorphic design) depends on how vegetation recolonization occurs, which is controlled by many biotic and abiotic factors (Fig. 3.10). Initially, the type and density of available plant propagules (i.e., seeds, tubers, and root stocks) determines the potential vegetation community that can be established. Propagules may be resident in the soil bank of the wetland site or are imported to the site from the surrounding areas. Although seemingly straightforward, both sources tend to be comprised of diverse assemblages that can include annuals and perennials, herbaceous and woody, and native and non-native plants that reflect the long-term land-use history of the site and surrounding area. Although some propagules in the soil bank are removed (e.g., consumption by animals) or suffer mortality, many remain viable for several decades; thus the soil bank can be comprised of hundreds of plant species, many of which have not been observed at the site by current managers (Thompson 1992).

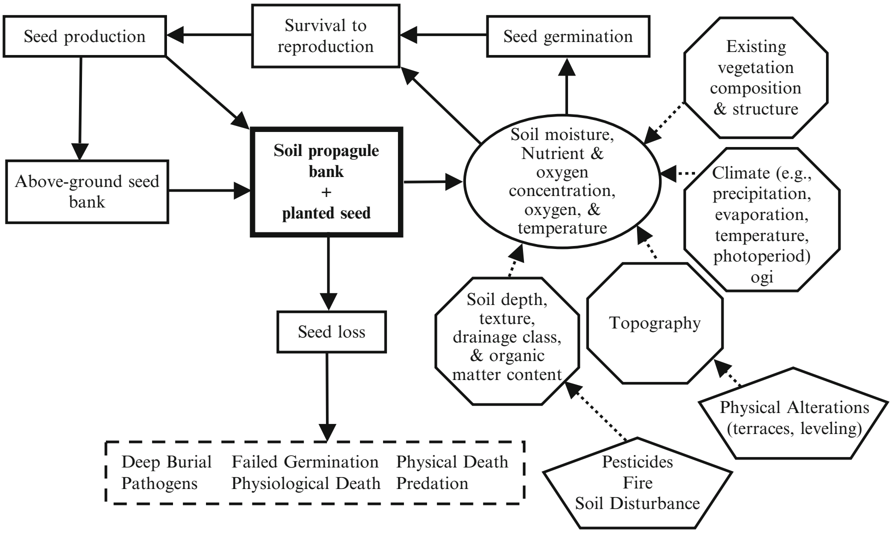

Fig. 3.10 Conceptual model of soil propagule bank and planted seed relationships in wetland systems (Published from Baker 1989 with kind permission of © Elsevier 1989. All Rights Reserved)

Similarly, the types and densities of propagules that have dispersed into a basin tend to be diverse because there are many different dispersal agents that operate at various spatial scales ranging from local to international. Some of the most common dispersal agents include wind (e.g., cottonwood and willow), water (e.g., acorns), and animals (e.g., seeds with protuberances that adhere to the coats of mammals and feathers of birds) (Cronk and Fennessy 2001; Mueller and van der Valk 2002). Humans also cause intentional (e.g., direct seeding of preferred species) and unintentional (e.g., transport of propagules via boats, machinery, and constructed ditches) dispersal (Johnson and Padilla 1996). Given the large number of potential dispersal agents, coupled with the extensive distances that plant propagules can be dispersed by various agents, it is no surprise that undesirable plant invasions are one of the most significant issues plaguing wetland productivity and management today.

3.6.1 Factors Affecting Germination and Survival

Of those propagules that are in wetland sites, the plant species that germinate and survive is determined by environmental conditions in relation to individual life history requirements of species (van der Valk 1981). Seeds of some species are dormant and cannot germinate until specific environmental conditions occur (i.e., physiological dormancy) or the seed coat is scarified (e.g., physical dormancy). In contrast, seeds of other species and most tubers and root stocks have no dormancy period and can germinate any time environmental conditions are favorable. Typically, only propagules in the upper few inches of the soil and on the soil surface are capable of germinating because this is the only region where all appropriate environmental conditions are met. This region often is referred to as the active component of the soil bank, whereas propagules occurring at lower depths in the soil profile are part of the inactive soil bank. Although incapable of germinating in most conditions, many propagules in the inactive portion of the soil bank are still viable and can move into the active component of the soil bank through various natural (e.g., water and rodents) and anthropomorphic (e.g., disking) mechanisms.

Within the active seed bank, only those propagules that receive appropriate environmental cues can break physiological dormancy (if a requirement) and germinate. Primary factors operating as cues include photoperiod, soil temperature, and soil moisture and oxygen concentrations, and salinity (Baker 1989; Baskin and Baskin 1989; Cronk and Fennessy 2001). Other factors also can be important, including nutrient availability, presence of fungal populations, and adaptations to disturbance (Miller 1997; Reynolds et al. 2003; Kulmatiski et al. 2006). Most of these factors continue to influence survival and reproductive potential following germination (Baker 1989).

Although conceptually simple, the pathways controlling plant germination and survival are complex because many of the factors influencing germination are interrelated. For example, soil temperature tends to increase with increasing photoperiod, soil moisture varies intra- and inter-annually based on precipitation, and soil oxygen content decreases as soil moisture increases. In addition, and equally important, the primary factors controlling germination are influenced by numerous interacting abiotic and biotic factors (Fig. 3.10). For example, the capacity of soils to retain moisture and nutrients vary depending on the texture and organic matter content of soil which, in turn, are influenced by parent material, climate, and topography. Finally, human activities have substantially altered many of these interrelationships, both unintentionally and intentionally (Laubhan et al. 2005). Examples of unintentional activities include the construction of roads that have altered surface and groundwater flow paths and changes in land-use practices that have increased sedimentation rates and concentrations of fertilizers and pesticides entering wetlands. Intentional activities include those often used in the construction or restoration of wetlands, including development of levees and ditches to enhance water management capability at the expense of interrupting natural flow paths, installation of river diversions and ground-water pumps to augment water supplies that alter natural stream flows and can impact groundwater tables, and the use of machinery and pesticides to control invasive species and other undesirable vegetation while simultaneously altering topography and soil properties that determine hydraulic conductivity and nutrient retention capacity (Bouma 1991; Messing and Jarvis 1993; Fuentes et al. 2004). Collectively, these changes can have significant impacts because they may favor establishment of plant species suited to high resource availability (Davis et al. 2000; Vinton and Goergen 2006) or disrupt plant-soil feedback mechanisms that affect plant community dynamics, including the invasion potential of exotic species (Calderon et al. 2000; Symstad 2000).

3.6.2 Development Considerations

Consideration of the complex interactions among abiotic factors and how they affect germination potential and resulting plant community composition in relation to providing resource benefits (e.g., food production, vegetation structure) is important when planning wetland developments. Of particular importance is the ability to control hydrology, including the ability to remove surface water and reliably dry the upper soil profile in a timely manner. Achieving this capability will allow management for the complete range of soil moisture and oxygen conditions necessary to promote germination of propagules in the soil bank. In addition, it will facilitate the use of other techniques (e.g., prescribed fire, herbivory, mowing, disking) to alter plant community composition and structure following establishment.

Proper soil tilth (i.e., structure and nutrients) also is important for initial establishment of a diverse and productive plant community. Extensive quantities of soil often are moved and mixed during construction projects. Following development, soil structure (e.g., bulk density) often is altered, which will affect propagule types and densities in the active soil bank, soil moisture, and nutrient retention capacity. For example, if large soil prisms remain following restoration, small seeds (e.g., sedges and rushes) will tend to migrate downward and may enter the inactive soil bank. Further, seeds in the active soil bank that germinate may not survive because emerging radicles are not in sufficient contact with the soil to obtain necessary nutrients and soil water for growth. Therefore, the soil should be evaluated and treated, if necessary, to create a proper seed bed that will facilitate establishment of desirable vegetation.

Knowledge regarding the general composition of the propagule bank and the germination requirements of the various species in the bank (or that will be purchased for seeding), coupled with information on the abiotic factors that influence germination and survival of plants, is the key to successfully restoring and managing wetland plant communities. Composition of the propagule bank is difficult to determine, but presettlement vegetation communities identified during a hydrogeomorphic assessment and observation of plant communities in the local area of interest can be valuable in developing a general list. Alternatively, samples of soil from the basin can be manipulated experimentally to develop a list of dominant propagules in the active propagule bank. In contrast, general (e.g., short photoperiods, cool/warm temperatures and dry/moist/wet soil conditions) and technical (e.g., 35–40 C soil temperature and moisture $<60\ \%$ field capacity) information regarding the germination requirements of various plant species are becoming increasingly available in books and the scientific literature.

Information on germination conditions can be evaluated in the context of site-specific abiotic information to develop initial management strategies that create desired environmental conditions. Key factors that often can be controlled by management are the time and rate of soil drying, which not only influences soil moisture but also soil temperature and oxygen concentrations as well as photoperiod exposure (e.g., ability of sunlight to penetrate to the soil surface). Thus, hydrogeomorphic maps depicting the location of different soil characteristics (e.g., type and drainage class) and elevations (e.g., microtopography) are examples of information that are valuable for determining appropriate water management strategies. For example, soils dominated by sands tend to dry more rapidly than soils dominated by clay. Further, given the same soil type, areas at high elevations will dry sooner than areas at low elevations. This information often is available as part of the original design and evaluation phases of projects and, if not, can be developed relatively quickly and at low cost with today's technology.

The extent to which hydrology can be controlled is dependent on the type of development. In most man-constructed sites, hydrologic control is seldom complete and the types and densities of propagules that germinate and survive to establish the dominant plant community likely will include species that are both desirable and undesirable in relation to management objectives. Therefore, additional management capability often is required to modify species composition and structure following initial establishment of the plant community. There are numerous techniques available to accomplish this task, including the use of natural (e.g., fire, herbivory, and hydrology) and anthropogenic (e.g., disks, cultipackers, mowers, herbicides, and biocontrol agents) disturbances. The type of disturbance possible will be partly influenced by the wetland design and infrastructure. For example, flooding is often more effective at controlling undesirable woody vegetation when applied at the seedling stage versus older growth stages.

Although the ability to effectively manage vegetation is one of the most important aspects considered when creating or restoring wetlands, it must be remembered that the abiotic and biotic factors controlling plant germination and survival also control other wetland processes (e.g., nutrient cycling). Therefore, annually implementing the same management actions at the same time in an attempt to perpetuate a given plant community may lead to disrupted wetland functions that are difficult and costly to correct. Therefore, short-term vegetation objectives must be balanced with long-term objectives of sustainable productivity.

3.7 The Duck Creek Conservation Area Example

Like many historic wetland areas in the U.S., the Mingo Basin in southeastern Missouri has been drastically altered over time (Heitmeyer et al. 2006). Fortunately, beginning in the 1930s, conservation interests recognized the importance of remnant wetlands in the region and the USFWS established the 21,592-acre Mingo NWR in 1938 and the Missouri Department of Conservation established the adjoining 6,234-acre Duck Creek Conservation Area (CA) in the late 1940s and early 1950s. Prior to becoming a NWR and CA, the streams and sloughs that spilled out and through the Mingo Basin were cut off and channelized for agricultural drainage. As the land went into public ownership, levees were erected to impound water primarily for waterfowl season in greentree reservoir units, natural basins, and former agricultural fields such as the Unit A and B areas of Duck Creek CA (Fig. 3.11). These levees were constructed at various times and often became joined in uncoordinated ways. Years of agriculture use in Units A and B altered natural topography and removed shallow sloughs and mima mounds that were historically present in this region.

Anthropogenic modification to Unit A and B wetlands before and after government ownership has challenged management at Duck Creek CA over the years. Independent water control among impoundment units was lacking and portions of the area were flooded early so that water could be pushed uphill to flood other portions of the area. In other locations, water barely “feathered out” across sites because of sharp elevation grades. Deep borrow areas existed adjacent to steep sloped levees and caused continual levee maintenance and integrity problems. Several channel fragments of the old sloughs remain, but were cut-off by levees and bypassed by straight ditches.

Duck Creek CA is one of the oldest managed wetland areas in Missouri and was identified as a “Golden Anniversary” restoration project by the Missouri Department of Conservation (Gardner 2006). Proposed rehabilitation of Duck Creek CA presented the opportunity to apply hydrogeomorphic methodology of wetland restoration at the scale of the entire Mingo Basin (Heitmeyer et al. 2006). This

Fig. 3.11 Creative restoration of topographic meander scrolls in Units A and B on the Duck Creek Conservation Area, Missouri

evaluation recommended developments to: (1) restore natural water flow patterns, (2) mimic natural water regimes, (3) restore natural vegetation communities, and (4) accommodate public uses that are consistent with resource objectives.

A combination of the DEM, aerial photos, and field observations allowed biologists to examine the landscape features and identify opportunities to restore system structure and processes throughout the Mingo Basin, especially in Units A and B. Multiple biologists from various resource disciplines were consulted to prepare the final design plans. In a couple of locations existing ditches were retained in the design to accommodate current daily hydrologic flows from private lands in the watershed's jurisdiction. However, there were opportunities to seasonally reconnect several cut-off sloughs by lowering levee tops at key positions to create spillways. These notches in the levees were high enough so that water levels within the pool could still be maintained, yet allow water from the ditch to spread out during larger flood events. By strategically placing these spillways along old depressions intermittent hydrological connection could be restored throughout the basin. This design enhanced the flood water conveyance and storage capacity by providing multiple relief valves along the current ditch system. Providing the opportunity for water to discharge through these old sloughs ultimately helped restore the historical flood patterns.

Historically, the Mingo Basin contained diverse topography that resulted in a unique mosaic of interconnected water regimes and habitat types. Over time this vegetation mosaic became more homogenized and hydrologically disconnected. The diversity of topography historically present in Units A and B was restored by MDC contractors using tractors and dirt pans. Some of the restored meander scours were tied into old slough fragments and became part of a restored stream network

(Fig. 3.11), whereas others were isolated and become flooded from direct precipitation or over-land water flow. The longer hydroperiod of the scours become colonized by aquatic plants or moist soil species associated with late drawdown. This habitat also benefits endemic bottomland fishes when flooded or amphibians if they dry out periodically. In contrast, the seasonal flooding and drying of smaller pools also provides waterbird habitat.

The dirt removed to create wetland scours was used for two purposes. Some fill was deposited adjacent to the scours to create topographic variation that results in variable water depths and islands of non-flooded ground. Other fill was used to create low-profile contour levees. By placing these broad levees along the natural contours more ground could be shallowly flooded (Kelley et al. 1993). Additionally, instead of creating an abrupt topographic change around the perimeter of the units, these low levees become a part of a gradual topographic and hydrological transition and have greater value as additional habitat to a variety of plants and animals.

During the restoration of topography, old levees and borrows that created management challenges were demolished. Steep levees were flattened and material was pushed into the adjacent borrows. In a similar fashion, remnant spoil piles along ditches were used to fill in the old field drains. In locations where it made sense, the new contour levees were merged with old sections of the levees, which were re-shaped and made lower and wider.

Working with the natural contours allowed development in Units A and B to integrate several landscape features into the final wetland design. Higher elevation surfaces along the bank of a restored slough were constructed so that levee systems graded into natural topographic features and replicated natural levees of historic streams. A mile-long section of ditch that cut across unit contours was removed (Fig. 3.12) and the drainage was moved east to the location where the original slough system historically flowed. The new restored drainage channel was built in a sinuous meandering form that provided twice as much stream habitat than was provided in the ditch system. Additionally, by placing a water control structure at the southern end of the channel, water from the surrounding watershed or wells can be used to simulate historical backwater flooding and allow it to spread out over the pools.

Prior to the new wetland development, only 535 of the total 1,165 acres in Units A and B could be flooded and provide important wetland resources. Also, the site had little independent water control and at least 90 of the 535 acres were flooded deeply. In comparison, reconfiguring levees, using two new wells, and capturing water from the surrounding watershed resulted in an additional 290 acres of shallowly flooded wetland and increased water management flexibility. The final development project included leveling 10 miles of spoil piles and steep-sided levees and replacing them with nearly the same length of low profile levees along contours. Within these larger pools, approximately 8 miles of borrows or agricultural drains were filled and nearly 16 miles of sloughs and creative scours restored depth diversity across the area (Fig. 3.13). This wetland renovation project helps reduce the chronic management challenges that have plagued Duck Creek CA for

Fig. 3.12 Ditch filling and restoration of drainage pathways in Units A and B on the Duck Creek Conservation Area, Missouri

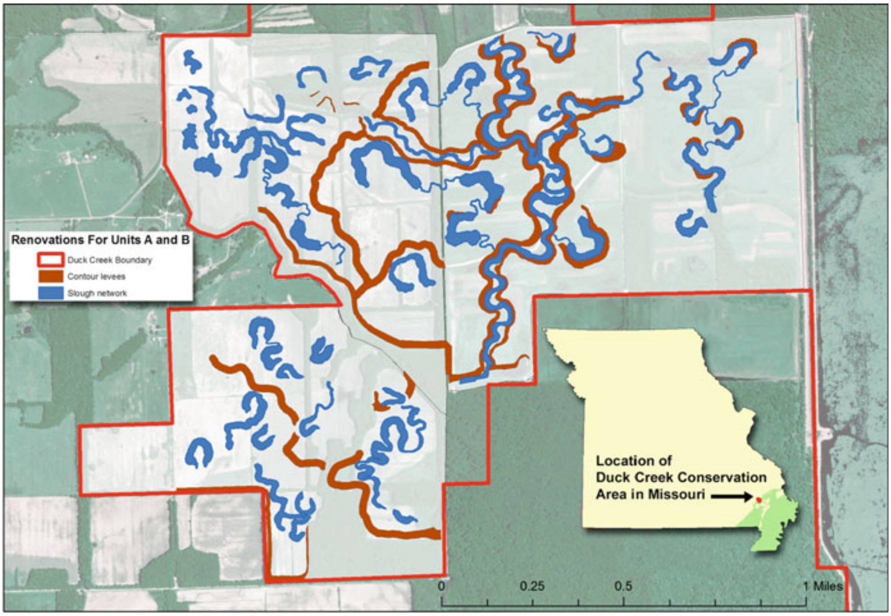

Fig. 3.13 Conceptual design for wetland developments in Units A and B on the Duck Creek Conservation Area, Missouri

years and increased the topographic diversity across the pool that helped restore critical wetland functions and values.

3.8 Integrating Wetland Developments into Landscapes

The practice of wetland conservation is an evolving (hopefully improving) mixture of “art” and “science.” The design and construction of wetlands is no exception. We are encouraged that the evolution of thought and practice for wetland design and development has proceeded to its current state and that technologies continue to advance that improve the capabilities of planners and managers. Undoubtedly, future advances in geospatial technology, basic understanding of community relationships with ecosystem hydrogeomorphic attributes, taxonomy and mapping of soils and geomorphology, hydrological models, and equipment will continue to refine and improve methods and effectiveness of wetland design and development.

We also are encouraged that wetland developments are increasingly being integrated into more holistic landscape approaches that seek to restore and enhance system integrity and functions within the highly modified landscapes of the world. Challenges remain, both philosophically and technically, however. We think recent discussions about the future management of National Wildlife Refuges, for example, are instructive and helpful (Meretsky et al. 2006; Fischman and Adamcik 2011). While wetland management objectives (and thus constraints on wetland developments) will continue to be directed by legislative and policy mandates in many cases (such as for species of concern, authorizing language for establishment of NWRs, and regulatory requirements) the general trend toward conservation works (including wetland development) is to improve ecological integrity and biodiversity of landscapes where wetlands occur and fundamentally to restore and sustain the critical ecological drivers that created and sustained systems. We especially believe that the “Hydrogeomorphic Approach” discussed in this chapter is a mature, system-based, way to not only design wetland developments, but also to incorporate all wetlands into functional ecosystems and landscapes. A synthesis of thoughts discussed in this chapter highlights the following actions:

1. Wetland conservation, including protection, enhancement and restoration strategies, must seek to achieve incremental gains at landscape-level scales.

   As such, the old adage “think globally – act locally” is appropriate process for designing and developing wetlands to ultimately enlarge wetland complexes at local and regional scales, including the need to address the needs to restore lost habitat types, increase connectivity, provide critical resources, and decrease the many effects of fragmentation. In many cases. it may not be possible to completely restore a historical larger wetland basin, floodplain, or complex of wetland types because of incomplete ownership, legal issues, and large permanent structures (such as locks-and-dams). However, in these areas, partial restoration remains a viable and valuable option and can be pursued with a future vision and hope of eventually restoring most or all of an area.

2. The foundation of wetland design is determining the appropriate wetland type for the site being considered.

   The hydrogeomorphic approach we discuss in this chapter represents another step forward in understanding what historical wetlands conditions were present at a site and what wetland types and processes may be now possible to restore and sustain. Here, the adage often used in mitigation programs "like-for-like" captures the important thought of designing and then developing (if needed) wetland conservation programs that restore wetland types, forms, and processes appropriately based on geomorphology, soils, topography, and hydrology. Too many times, managers are tempted to make a site or area look and function like another wetland type or system that is familiar or is perceived to be the most desirable. Also, some managers and administrators want intensively managed sites that can be all things to all species, functions, values and services – which rarely is sustainable. In most cases, trying to import a different system type into an area that does not have similar hydrogeomorphic attributes is a recipe for failure.

3. Wetland designs should seek to restore and emulate historical form and process as completely as possible and to make systems as self-sustainable as possible.

   Based on hydrogeomorphic evaluation, not only can the appropriate physical type and structure of a wetland system be determined, but by default of the analyses, the basic ecological drivers and processes that created and sustained the system – and that now must be restored and emulated – is understood. In some cases, intensive management and development may be needed to provide the processes or some semblance of them. As mentioned earlier, however, highly developed sites seldom replicate all processes, such as varying types and timing of hydrological events; therefore some management also will be needed. Generally, the adage "less-is-more" applies to wetland developments within the constraints imposed by the extent to which the physical form and ecological processes of a site have been altered. Where limitations of budgets and personnel for future management is likely, designs should seek to make wetlands as self-sustaining as possible and address basic processes first (such as regional/local surface and subsurface water regimes and availability, disturbances, and regenerating mechanisms).

4. Future design and development of wetlands must anticipate change related to climate, land uses, encroachments, and water availability and rights.

   No one has a crystal ball that can predict future events that will affect wetland conservation, but the adage "hedge-your-bets" is wise advice when planning wetland designs and developments. The eventualities of climate change, changing economies, land/water use and law, ownerships, and politics will impact both opportunity for, and sustainability and productivity of, wetland restorations (e.g., Sparks 1993). Wetland managers must clearly understand the "process of change" in ecosystems (Samson 1996). The larger and most productive wetland systems that remain worldwide are mostly the result of fortunate insight that former wetland conservationists had to protect and restore the areas before they were destroyed, further fragmented, or irreversibly altered. While fewer opportunities currently exist to protect and restore large complexes, planning and vision for working and acting at landscape scales offer the best potential for resilience to future degradation.

References

Atlantic Waterfowl Council (1959) An illustrated small marsh construction manual based on design standards. Atlantic Waterfowl Technical Committee on Habitat Management and Development, Vermont Fish and Game Service, Montpelier

Atlantic Waterfowl Council (1972) Techniques handbook of waterfowl habitat development and management, 2nd edn. Atlantic Flyway Council, Bethany Beach

Autin WJ, Burns SF, Miller BJ, Saucier RT, Snead JI (1991) Quaternary geology in the lower Mississippi Valley. In: Morrison RB (ed) The geology of North America, vol K-2. Quaternary nonglacial geology: conterminous. The Geological Society of America, Boulder, pp 547–582

Baker HG (1989) Seed banks: general concepts and methodological issues. In: Leck MA, Parker VT, Simpson RL (eds) Ecology of soil seed banks. Academic, San Diego, pp 3–21

Barbour MG, Billings WD (1991) North American terrestrial vegetation. Cambridge University Press, New York

Baskin JM, Baskin CC (1989) Physiology of dormancy and germination in relation to seed bank ecology. In: Leck MA, Parker VT, Simpson RL (eds) Ecology of soil seed banks. Academic, San Diego, pp 53–66

Bedinger MS (1979) Relation between forest species and flooding. In: Greeson PC, Clark JR, Clark JE (eds) Wetland functions and values: the state of our understanding. American Water Resources Association Technical Publication 79–2, Minneapolis, MN, pp 427–435

Bellrose FC, Paveglio FL Jr, Steffeck DW (1979) Waterfowl populations and the changing environment of the Illinois River Valley. Illinois Nat Hist Surv Bull 32:1–54

Bellrose FC, Havera SP, Paveglio FL, Jr, Steffeck DW (1983) The fate of lakes in the Illinois River Valley. Illinois Natural History Survey Biological Notes No. 119, Champaign, IL

Bettis EA, III, Anderson JD, Oliver JS (1996) Landform sediment assemblage (LSA) units in the Upper Mississippi River Valley, United States army corps of engineers, Rock Island district. Volume I. Illinois State Museum Research and Collections Center, Quaternary Studies Program Technical Report No. 95-1004-11b, Springfield, IL

Birdsell & Dean (1882) The history of Davies County, Missouri. Publisher unknown, Kansas City

Black RA (1984) Water relations of *Quercus palustris*: field measurements on an experimentally flooded stand. Oecologia 64:14–20

Bouma J (1991) Influence of soil macroporosity on environmental quality. Agronomy 46:1–37

Bourdo EA Jr (1956) A review of the General Land Office Survey and its use in quantitative studies of former forests. Ecology 37:754–768

Brackenridge HM (1814) Views of Louisiana, together with a journal of a voyage up the Missouri River in 1811. Published by the author, Pittsburgh

Brakhage GK (1964) Waterfowl management. Missouri Department of Conservation, Columbia

Brauer EJ, Busse DR, Davinroy RD, Gordon DC, Brown JL, Myers JE, Rhoads AM, Lamm D (2005) Geomorphology study of the Middle Mississippi River. U.S. Army Corps of Engineers, Applied River Engineering Center, St. Louis

Brown M, Dinsmore JJ (1986) Implications of marsh size and isolation for marsh bird management. J Wildl Manage 50:392–397

Brugam RB, Patterson MJ (1996) Application of geographic information system to mapping presettlement vegetation in southwestern Illinois. Trans Ill State Acad Sci 89:112–125

Bureau of Land Management (1989) Waterfowl habitat management on public lands: a strategy for the future. U.S. Department of the Interior, Bureau of Land Management, Washington, DC

Cahoon DR, Groat CG (1990) A study of marsh management practice in coastal Louisiana, Volume II, technical description. Final report submitted to MMS, New Orleans, LA, OCS Study/MMS 90–0075

Calderon FJ, Jackson LE, Scow KM, Rolston DE (2000) Microbial responses to simulated tillage in cultivated and uncultivated soils. Soil Biol Biochem 32:1547–1559

Chabreck RA (1988) Coastal marshes, ecology and wildlife management. University of Minnesota Press, Minneapolis

Collot V (1826) A journey in North America. Published for Arthur Bertrand, Paris

Colton GW (1857) Maps of Missouri – Colton's general atlas. J.H. Colton and Co., New York

Conner WH, Sharitz RR (2005) Forest communities of bottomlands. In: Fredrickson LH, King SL, Kaminski RM (eds) Ecology and management of bottomland hardwood systems: the state of our understanding. University of Missouri-Columbia, Gaylord Memorial Laboratory Special Publication No. 10, Puxico, MO, pp 93–120

Connolly MB Jr, Heitmeyer ME (1992) Habitat conservation and the hunter. In: Posewitz J (ed) Proceedings of the Governor's symposium on North America's hunting heritage. Montana Department of Fish, Wildlife and Parks, Helena, pp 172–186

Couzens MK (1861) Map of the Mississippi Valley. Lang and Laing Lith

Cronk JK, Fennessy MS (2001) Wetland plants: biology and ecology. Lewis Publishers, New York

Davinroy RD (2006) Sedimentation in the Upper Mississippi river basin. U.S. Army Corps of Engineers Applied River Engineering Center, St. Louis

Davis MA, Grime JP, Thompson K (2000) Fluctuating resources in plant communities: a general theory of invasibility. J Ecol 88:528–534

Demissie M (1998) Hydrology of the Illinois river. Illinois State Water Survey, Champaign

Douglass RS (1912) History of southeast Missouri, a narrative account of its historical progress, its people and its principal interests. Lewis Publishing Company, New York

Ducks Unlimited Canada (2000) Managing small wetlands for waterfowl. Ducks Unlimited Canada, Amherst

Eckberg CJ, Foley WE (eds) (1980) An account of Upper Louisiana by Nicolas de Finiels. University of Missouri Press, Columbia

Edwards MJ, Bailey EH, Geib WJ, Fudge JF, Butman B, Cook H (1927) Soil survey of Trempealeau County, Wisconsin. U.S. Department of Agriculture, Bureau of Chemistry and Soils, Washington, DC

Fischman RL, Adamcik RS (2011) Beyond trust species: the conservation potential of the National Wildlife Refuge System in the wake of climate change. Nat Resour J 51:1–33

Forman G (1789) Forman's journey down the Ohio and Mississippi. Draper's edition

Franklin SB, Wasklewicz T, Grubaugh JW, Greulich S (2003) Temporal periodicity of the Mississippi River before and after systemic channel modifications. J Am Water Resour Assoc 39:637–648

Fredrickson LH (1991). Strategies for water level manipulations in moist-soil systems. U.S. Fish and Wildlife Service Leaflet 13.4.6

Fredrickson LH, Batema DL (1992) Greentree reservoir management handbook. University of Missouri-Columbia, Gaylord Memorial Laboratory, Puxico

Fredrickson LH, Laubhan MK (2000) Managing wetlands for wildlife. In: Braun CE (ed) Techniques for wildlife investigations and management, 5th edn. The Wildlife Society, Bethesda, pp 623–647

Fredrickson LH, Taylor TS (1982) Management of seasonally flooded impoundments for wildlife. U.S. Fish and Wildlife Service Resource Publication 148

Fuentes JP, Flury M, Bezdicek DF (2004) Hydraulic properties in a silt loam soil under natural prairie, conventional till, and no till. Soil Sci Soc Am J 68:1679–1688

Fuller R, Cofer-Shabica N (2011) Marshes on the move – a managers guide to understanding and using model results depicting impacts of sea level rise on coastal wetlands. The Nature Conservancy Global Marine Team and National Oceanic and Atmospheric Administration, National Ocean Service Coastal Services Center, white paper

Galat DL, Fredrickson LH, Humburg DD, Bataille KJ, Bode JR, Dohrenwend J, Gelwicks GT, Havel HE, Helmers DL, Hooker JB, Jones JR, Knowlton MF, Kubisiak J, Mazourek J, McColpin AC, Renken RB, Semlitsch RD (1998) Flooding to restore connectivity of regulated, large-river wetlands. Bioscience 48:721–733

Galatowitsch SM, van der Valk AG (1994) Restoring prairie wetlands – an ecological approach. Iowa State University Press, Ames

Gardner G (2006) Golden anniversary wetland initiative. MO Conserv 67(3):8–15

Hajic ER (2000) Landform sediment assemblage (LSA) units in the Illinois River Valley and the Lower Des Plaines River Valley, vol I and II. Technical report No. 99-1255-16. Illinois State Museum, Springfield

Hammer DA (1992) Creating freshwater wetlands. Lewis Publishers, Inc., Chelsea

Hammond MC, Lacy CH (1959) Artificial potholes and ditches as waterfowl habitat. 21st Midwest wildlife conference, Minneapolis (mimeo)

Havera SP, Roat KE, Anderson LL (2003) The Thompson Lake/Emiquon story: the biology, drainage, and restoration of an Illinois River bottomland lake. Illinois Natural History Survey, Special publication No. 25, Springfield, IL

Heitmeyer ME (2007a) Conserving lacustrine and palustrine natural communities. Mo Nat Areas Newsl 5(1):3–5

Heitmeyer ME (2007b) Feasibility investigation hydrogeomorphic modeling and analyses Upper Mississippi River System floodplain. Greenbrier Wetland Services report No. 07–01. Blue Heron Conservation Design and Printing, LLC, Bloomfield

Heitmeyer ME (2008a) An evaluation of ecosystem restoration and management options for the Ted Shanks Conservation Area. Greenbrier Wetland Services report No. 08–03. Blue Heron Conservation Design and Printing, LLC, Bloomfield

Heitmeyer ME (2008b) An evaluation of ecosystem restoration options for the Middle Mississippi River Regional Corridor. Greenbrier Wetland Services report No. 08–02. Blue Heron Conservation Design and Printing, LLC, Bloomfield

Heitmeyer ME (2010a) An assessment of historic land cover for the St. John's Bayou Basin New Madrid Floodway region. Greenbrier Wetland Services report No. 10–05 Blue Heron Conservation Design and Printing, LLC, Bloomfield

Heitmeyer ME (2010b) An evaluation of terrestrial ecosystem restoration options for the Chippewa River ecoregion of the Upper Mississippi River System. Greenbrier Wetland Services report No. 10–06. Blue Heron Conservation Design and Printing, LLC, Bloomfield

Heitmeyer ME, Fredrickson LH (2005) An evaluation of ecosystem restoration and management options for the Ouray National Wildlife Refuge, Utah. University of Missouri-Columbia, Gaylord Memorial Laboratory Special Publication No. 8, Puxico, MO

Heitmeyer ME, Westphall K (2007) An evaluation of ecosystem restoration and management options for the Calhoun and Gilbert Lake Divisions of Two Rivers National Wildlife Refuge. University of Missouri-Columbia, Gaylord Memorial Laboratory Special Publication No. 13, Puxico, MO

Heitmeyer ME, Fredrickson LH, Krause GF (1989) Water and habitat dynamics of the Mingo Swamp in southeastern Missouri. U.S. Fish and Wildlife Service, Fish and Wildlife Research No. 6, Washington, DC

Heitmeyer ME, Fredrickson LH, Krause GF (1991) Water relationships among wetland habitat types in the Mingo Swamp, Missouri. Wetlands 11:55–66

Heitmeyer ME, Caldwell PJ, Batt BDJ, Nelson JW (1996) Waterfowl conservation and biodiversity in North America. In: Ratti JT (ed) 7th international waterfowl symposium, Ducks Unlimited, Inc., Memphis, pp 125–138

Heitmeyer ME, Fredrickson LH, King SL (2000) An evaluation of ecosystem restoration options for the Grand Prairie Region of Arkansas. University of Missouri-Columbia, Gaylord Memorial Laboratory Special Publication, Puxico, MO

Heitmeyer ME, Nelson FA, Fredrickson LH (2006) An evaluation of ecosystem restoration and management options for the Duck Creek/Mingo Basin area of southeast Missouri. University of Missouri-Columbia, Gaylord Memorial Laboratory Special Publication No. 12, Puxico, MO

Heitmeyer ME, Artmann MJ, Fredrickson LH (2009) An evaluation of ecosystem restoration and management options for Benton Lake National Wildlife Refuge. Greenbrier Wetland Services Report No. 09–01. Blue Heron Conservation Design and Printing, LLC, Bloomfield

Heitmeyer ME, Artmann MJ, Fredrickson LH (2010a) An evaluation of ecosystem restoration and management options for Lee Metcalf National Wildlife Refuge. Greenbrier Wetland Services Report No. 10–02. Blue Heron Conservation Design and Printing, LLC, Bloomfield

Heitmeyer ME, Lemons E, Jackson J (2010b) An evaluation of ecosystem restoration and management options for St. Francis River floodplain lands at Wappapello Lake, Missouri. Greenbrier Wetland Services Report No. 10–03. Blue Heron Conservation Design and Printing, LLC, Bloomfield

Heitmeyer ME, Nigh TA, Mengel DC, Blanchard PE, Nelson FA (2011) An evaluation of ecosystem restoration and management options for floodplains in the Lower Grand River Region Missouri. Greenbrier Wetland Services Report No. 11–01. Blue Heron Conservation Design and Printing, LLC, Bloomfield

Heitmeyer ME, Henry AR, Artmann MJ (2012a) An evaluation of ecosystem restoration and management options for Seedskadee National Wildlife Refuge. Greenbrier Wetland Services Report No. 12–03. Blue Heron Conservation Design and Printing, LLC, Bloomfield

Heitmeyer ME, Esser RL, Eash JD, Newman BJ (2012b) An evaluation of ecosystem restoration and management options for Hamden Slough National Wildlife Refuge. Greenbrier Wetland Services Report No. 12–02. Blue Heron Conservation Design and Printing, LLC, Bloomfield

Houck L (1908) A history of Missouri from the earliest explorations and settlements until the admission of the state into the union, 4 vols. R.R. Donnelley and Sons Co, Chicago

Hus H (1908) An ecological cross-section of the Mississippi River in the region of St. Louis, MO. Mo Bot Gardens 19:127–258

Hutchins T (1784) In: Tregle JG Jr (ed) A historical and topographical description of Louisiana and West Florida, Facsimile edition. University of Florida Press, Gainesville

Hutchinson M (1988) A guide to understanding, interpreting, and using public land survey field notes in Illinois. Nat Areas J 8:245–255

Johnson LE, Padilla DK (1996) Geographic spread of exotic species: ecological lessons and opportunities from the invasion of the zebra mussel *Dreissena polymorpha*. Biol Conserv 78:23–33

Keeley JE (1979) Population differentiation along a flood frequency gradient: physiological adaptations to flooding in *Nyssa sylvatica*. Ecol Monogr 49:89–108

Kelley JR, Jr, Laubhan MK, Reid FA, Wortham JS, Fredrickson LH (1993) Options for water-level control in developed wetlands. U.S. Fish and Wildlife Service Leaflet 13.4.8

Klimas C, Murray E, Foti T, Pagan J, Williamson M, Langston H (2009) An ecosystem restoration model for the Mississippi Alluvial Valley based on geomorphology, soils, and hydrology. Wetlands 29:430–450

Korschgen LJ, Toney TE (1978) An ecological inventory of indigenous plants on the Ted Shanks Wildlife Area. Job completion report, Federal Aid Project W-13-R-30. Missouri Department of Conservation, Columbia

Kulmatiski A, Beard KH, Stark JM (2006) Soil history as a primary control on plant invasion in abandoned agricultural fields. J Appl Ecol 43:8868–8876

Kusler JA, Kentula ME (eds) (1990) Wetland creation and restoration: the status of science. Island Press, Covelo

Large P, Goddard D, Landau H (2001). eRTK: a new generation of solutions for centimeter-accurate wide-area real-time positioning. Trimble Navigation Limited

Laubhan MK, Fredrickson LH (1993) Integrated wetland management: concepts and opportunities. Trans North Am Wildl Nat Resour Conf 58:323–333

Laubhan MK, King SL, Fredrickson LH (2005) Managing inland wetlands for wildlife. In: Braun CE (ed) Techniques for wildlife investigations and management, 6th edn. The Wildlife Society, Bethesda, pp 797–838

Linde AF (1969) Techniques for wetland management. Wisconsin Department of Natural Resources research report No. 45, Madison, WI

Lubinski K (1993) A conceptual model of the Upper Mississippi River System ecosystem. U.S. Fish and Wildlife Service Environmental Management technical center report EMTC 93-T0001, Onalaska, WI

Luckey RR, Becker MF (1999) Hydrogeology, water use, and simulation of flow in the high plains aquifer in northwestern Oklahoma, southeastern Colorado, southwestern Kansas, northeastern New Mexico, and northwestern Texas. U.S. Geological Survey Water Resources investigations report 99–4104

Madigan T, Schirmer RC (1998) Geomorphological mapping and archaeological sites of the Upper Mississippi River Valley, Navigation Pools 1–10, Minneapolis, Minnesota to Guttenberg, Iowa. IMA Consulting, Inc., Reports of Investigation No. 5r22. Prepared for U.S. Army Corps of Engineers, St. Paul District

Massey B (2000) Wetland engineering manual. Ducks Unlimited, Inc., Southern Regional Office, MS

Mathiak HA (1965) Pothole blasting for wildlife. Wisconsin Department of Conservation Publication 352, Madison

Meretsky VJ, Fischman RL, Karr JR, Ashe DM, Scott JM, Noss RF, Schroeder RL (2006) New directions in conservation for the National Wildlife Refuge System. BioScience 56:135–143

Messing I, Jarvis NJ (1993) Temporal variation in the hydraulic conductivity of a tilled clay soil as measured by tension infiltrometers. J Soil Sci 44:11–24

Middleton B (1999) Wetland restoration – flood pulsing and disturbance dynamics. Wiley, New York

Miller RM (1997) Prairie underground. In: Packard S, Mutel CF (eds) The tall grass restoration handbook for prairies, savannas, and woodlands. Island Press, New York, pp 23–27

Miller AW, Arend PH (1960) How to grow watergrass for ducks in California. California Department of Fish and Game, Game management leaflet No. 1, Sacramento, CA

Minton WM (1912) The Mississippi River Dam at Keokuk, Iowa. Harv Eng J 10:180–191

Mississippi Flyway Council (1958) A guide to Mississippi Flyway Waterfowl Management. Mississippi Flyway Council

Mississippi River Commission (1881) Detail map of the Upper Mississippi River from the mouth of the Ohio River to Minneapolis. Minnesota in 89 sheets

Missouri Natural Areas Committee (1996) Directory of Missouri natural areas. Missouri Department of Conservation, Missouri Department of Natural Resources, U.S. Forest Service, and National Park Service, Jefferson City

Mitsch WJ, Gosselink JG (1986) Wetlands. Van Nostrand Reinhold Company, New York

More Game Birds in America Foundation (1931) More waterfowl. More Game Birds in America Foundation, New York

Mueller MH, van der Valk AG (2002) The potential role of ducks in wetland seed dispersal. Wetlands 22:170–178

Munson PJ (1974) Terraces, meander loops, and archaeology in the American Bottoms, Illinois. Trans Ill State Acad Sci 67:384–392

Murkin HR, van der Valk AG, Clark WR (eds) (2000) Prairie wetland ecology – the contribution of the Marsh Ecology Research Program. Iowa State University Press, Ames

Nassar JR, Cohen WE, Hopkins CR (1993) Waterfowl habitat management handbook for the lower Mississippi River Valley. Extension Service of Mississippi State University, Starkville

Nelson PW (2005) Terrestrial natural communities of Missouri, revised edition. Missouri Natural Areas Committee. Published by Missouri Department of Natural Resources, Jefferson City

Nelson JC, Sparks RE, DeHaan L, Robinson L (1998) Presettlement and contemporary vegetation patterns along two navigational reaches of the Upper Mississippi River. In: Sisk TD (ed) Perspectives on the land use history of North America: a context for understanding our changing environment. U.S. Geological Survey Biological Report USGS/BRD/BSR – 1998–0003, pp 51–60

Nestler JM, Theiling CH, Lubinski KS, Smith DL (2010) Reference condition approach to restoration planning. River Research Applications (2010). Published online in Wiley Inter Science. www.interscience.wiley.com. doi:10:1002/rra.1330

Nigh TA, Schroeder WA (2002) Atlas of Missouri ecoregions. Missouri Department of Conservation, Jefferson City

Nimick DA (1997) Hydrology and water chemistry of the Benton Lake Basin with emphasis on the fate of dissolved solids at Benton Lake National Wildlife Refuge, west-central Montana. U.S. Geological Survey Water-Resources Investigation Report 97–4100

Nuttall T (1813) Fraser's catalogue – a catalogue of new and interesting plants collected in Upper Louisiana and principally on the River Missouri, North America. London. (reprinted in Pittonia 2:114–119. 1889)

Ogilvie LP (1967) The development of the southeast Missouri Lowland. Ph.D. dissertation, University of Missouri, Columbia

Pacific Flyway Council (1959) Pacific flyway waterfowl management guide. Pacific Flyway Council, Portland

Payne NF (1992) Techniques for wildlife habitat management of wetlands. McGraw-Hill, New York

Piehl JL (ed) (1986) Proceedings wetland restoration a techniques workshop. Minnesota Chapter of the Wildlife Society, Fergus Falls

Reiger JF (1975) American sportsmen and the origins of conservation. University of Oklahoma Press, Norman

Reynolds HL, Packer A, Bever JD, Clay K (2003) Grassroots ecology: plant-microbe-soil interactions of plant community structure and dynamics. Ecology 84:2281–2291

Ringleman JK (1991) Evaluating and managing waterfowl habitat – a general reference on the biological requirements and management of ducks and geese common to Colorado. Colorado Division of Wildlife Report no. 16

Samson FB (1996) Integration of landscape principles into waterfowl conservation. In: Ratti JT (ed) Seventh international waterfowl symposium. Ducks Unlimited, Inc., Memphis, pp 117–124

Sanderson GC (1980) Conservation of waterfowl. In: Bellrose FC (ed) Ducks, geese and swans of North America, 3rd edn. Stackpole Books, Harrisburg, pp 43–58

Saucier RT (1994) Geomorphology and quaternary geological history of the Lower Mississippi Valley, vol I and II. U.S. Army Corps of Engineers, Waterways Experiment Station, U.S. Department of the Army, Vicksburg

Schoolcraft HR (1825) Travels in the central portions of the Mississippi Valley. Collins and Hannay, New York

Schulte LA, Mladenoff DJ (2001) The original U.S. Public Land Survey records: their use and limitations in reconstructing presettlement vegetation. J For 99:5–10

Sickley TA, Mladenoff DJ (2007) Pre-Euroamerican settlement vegetation data-base for the Upper Mississippi River Valley. Department of Forest Ecology and Management, University of Wisconsin-Madison report to The Nature Conservancy, Madison, WI

Smith LM, Smith FL (1984) Engineering geology of selected areas, U.S. Army Corps of Engineer Division, Lower Mississippi Valley, Report 1, vol 1, the American Bottom area, MO-IL. U.S. Department of the Army, Corps of Engineers, Waterways Experiment Station, Vicksburg, MS

Smith LM, Pederson RL, Kaminski RM (1989) Habitat management for migrating and wintering waterfowl in North America. Texas Tech University Press, Lubbock

Soileau RS (2002) Inventory of hydrographic survey and cross-section data available on the Upper Mississippi River and Illinois Waterway at the U.S. Army Corps of Engineer Districts, St. Paul, Rock Island and St Louis. U.S. Army Corps of Engineers Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg

Sophocleous MA (1992) Steam-aquifer modeling of the lower Rattlesnake Creek Basin with emphasis on the Quivira National Wildlife Refuge. Kansas Geological Survey Open-file Report 92–10

Sparks RE (1993) Making predictions that change the future forecasts and alternative visions for the Illinois River. In: Kobab H (ed) Proceedings of the third biennial Governor's conference on the management of the Illinois River system, Peoria, IL

Sparks RE (1995) Need for ecosystem management of large rivers and their floodplains. BioScience 45:168–182

Strader RW, Stinson PH (2005) Moist-soil management guidelines for the U.S. Fish and Wildlife Service Southeast region. U.S. Fish and Wildlife Service Migratory Bird Field Office, Jackson

Stratman D, Barickman G (2000) Using micro and macrotopography in wetland restoration. U.S. Department of Agriculture Natural Resources Conservation Service, Illinois Biology Technical Note No. 20

Symstad AJ (2000) A test of the effects of functional group richness and composition on grassland invasibility. Ecology 81:99–109

Theiling CH, Bettis EA III, Heitmeyer ME (2012) Hydro-geomorphic classification and potential vegetation mapping for Upper Mississippi River bottomland restoration. In: Piacentini T, MIccadei E (eds) Studies on environmental and applied geomorphology. InTech, Rijeka

Thompson K (1992) The functional ecology of seed banks. In: Fenner M (ed) Seeds. The ecology of regeneration in plant communities. Cab International, Wallingford, pp 231–258

Thurman MD (1982) Cartography of the Illinois Country: an analysis of the Middle Mississippi maps drawn during the British regime. J Ill State Hist Soc 75:277–288

Trimble Navigation Limited (2008) Trimble: the construction technology authority. http://www.trimble-productivity.com/articles/95?page=3

U.S. Fish and Wildlife Service (1979) Final recommendations on the management of the national wildlife refuge system. U.S. Department of the Interior, Fish and Wildlife Service, Washington, DC

U.S. Geological Survey (1999) Ecological status and trends of the Upper Mississippi River system 1998: a report of the long term resource monitoring program. U.S. Geological Survey, Upper Midwest Environmental Sciences Center, LTRMP 99-T0001, La Crosse, WI

U.S. Soil Conservation Service (1992) Wetland restoration, enhancement, or creation. Engineer field handbook No. 13. U.S. Department of Agriculture, Soil Conservation Service, Washington, DC

Van der Valk AG (1981) Succession in wetlands: a Gleasonian approach. Ecology 62:688–696

Vileisis A (1997) Discovering the unknown landscape – a history of America's wetlands. Island Press, Covelo

Vinton MA, Goergen EM (2006) Plant-soil feedbacks contribute to the persistence of *Bromus inermis* in tallgrass prairie. Ecosystems 9:967–976

Warren GK (1869) Map of the Mississippi River from the junction of the Minnesota to the junction of the Ohio River, 22 sheets. U.S. Army Corps of Engineers, Lacrosse, WI

Weller MW (1989) Waterfowl management techniques for wetland enhancement, restoration and creation useful in mitigation procedures. In: Kusler J, Kentula M (eds) Wetland creation and restoration, vol 2. U.S. Environmental Protection Agency, Washington, DC, pp 105–116

Weller MW (1994) Freshwater marshes – ecology and wildlife management, 3rd edn. University of Minnesota Press, Minneapolis

WEST Consultants, Inc (2000) Upper Mississippi River and Illinois waterway cumulative effects study, vol I and II. Geomorphic assessment and ecological assessment. Final report prepared for Department of the Army, U.S. Army Corps of Engineers, Rock Island District

Wharton CH, Kitchens WM, Pendleton EC, Sipe TW (1982) The ecology of bottomland hardwood swamps in the southeast: a community profile. FWS/OBS – 81/37, U.S. Fish and Wildlife Service Biological Services Program, Washington, DC

White J (2000) Early accounts of the ecology of the Big Rivers area, vol 5. Illinois critical trends assessment program. Illinois Department of Natural Resources, Springfield

Wiener JG, Sandheinrich MR (2010) Contaminants in the Upper Mississippi River: historic trends, responses to regulatory controls, and emerging concerns. Hydrobiologia 640:49–70

Willman HB (1973) Geology along the Illinois Waterway – a basis for environmental planning. Illinois State Geological Survey Circular 478

Woerner EG, Dunbar JE, Villanueva E, Smith LM (2003) Geologic investigation of the Middle Mississippi River. U.S. Army Corps of Engineers, Engineer Research and Development Center ERDC/GSL TR-03-7, Vicksburg

Yin Y, Nelson J (1996) Modifications of the Upper Mississippi River and the effects on floodplain forests. In: Galat DL, Frazier AG (eds) Overviews of river-floodplain ecology in the Upper Mississippi River Basin, vol 3, Science for floodplain management into the 21st century. U.S. Government Printing Office, Washington, DC, pp 29–40

Zimmerman JL (1990) Cheyenne Bottoms – wetland in jeopardy. University of Kansas Press, Lawrence

Student Exercises

Laboratory Exercise: Developing a General Restoration Design for a Degraded Former Wetland Site

This exercise is intended to provide experience in obtaining and integrating hydrogeomorphic information to develop a restoration design, and accompanying development strategies, for sites that formerly were wetlands but now have been converted to other land uses or are degraded to varying degrees in physical form and ecological processes/functions. Examples of sites that could be chosen include wetlands converted to agricultural production such as is often the case in sites being restored under USDA WRP easements; wetland sites modified by roads, ditches, levees and water diversion structures; and fragmented larger tracts of floodplains, bottomland hardwood forests, or coastal marshes. The site chosen can be provided to the study group by an instructor or conversely be chosen by the study group from some geographical region. The exercise can be conducted in any geographical area and of any size based on the objectives of the class or individuals. The exercise also can be conducted by an individual or a small group. Ideally, several persons working as a group could obtain the various data sets and collectively work to integrate the information and evaluate various scenarios or options for a restoration and development design.

The first part of the exercise after a study site has been selected, is to obtain the following categories of information specific to the site:

- Geology and geomorphology
- Soils
- Topography/elevation data and maps
- Local and regional climate and hydrology
- Aerial photographs and maps, current and historical
- Botanical and faunal information

The sources of these data sets will vary depending on the location selected, but general guidance and potential websites to begin searching for the information is available in the chapter text. For example, soil maps and accompanying attribute information is available for most U.S. counties at www.websoilsurvey.nrcs.usda.gov. The information obtained should be usable in an ArcView or ArcMap geospatial version if possible. Obviously, some older information may not be available in electronic form or georeferenced and some hand processing and visual comparison and analyses may be needed. The group should produce several maps showing the various geospatial information clipped to the study site boundary.

The study group will need to attempt to produce a hydrogeomorphic matrix for the study site using the nine-point methodology provided in the text. This development of a matrix is the core part of the exercise and requires that the study group individuals integrate multiple information sources and use acquired ecological understanding about relationships of vegetation to abiotic attributes of the ecosystem in question. It is understood that individuals of the study group will have different degrees of education about the hydrogeomorphic attributes and botanical relationships. Hopefully, the group includes persons familiar with soils, climate, and botanical data. The integration of hydrogeomorphic information is not quantitative computer software enabled equation, but rather is a synthesis of multiple pieces of information available for the site and of varying quantity and quality. This synthesis represents real-world application experience that practicing professionals face daily in actual career employment circumstances. It is understood that some information and data sets may be unavailable or of different quality depending on the site selected. Ultimately, the success of the exercise to make a hydrogeomorphic matrix for the site will be determined by how much information is obtained and how the study group attempts to determine and confirm vegetation-abiotic attribute relationships. For example, in a bottomland hardwood restoration site, the exercise should attempt to understand and map the distribution of various forest species to soils, geomorphic surfaces, and hydrological regimes. Several recent publications offer examples of matrix development in bottomland settings (e.g., Heitmeyer et al. 2006, 2010a).

After the hydrogeomorphic matrix for the site is constructed, the study group can develop restoration options for the site using the "Application of Information" section of the chapter text. Here, four basic questions must be answered about the historic and contemporary condition of the site and the "new desired state" of the site must be recommended. Based on this recommendation of future site condition, then the actual development strategies for the site can be addressed by asking "What physical and biological changes are needed to create and sustain the new desired community?"

Finally, the exercise must identify and discuss the many considerations for designing wetland infrastructure and restoring basic ecological processes and desired vegetation communities. The types of infrastructure developments will depend on the nature of the wetland to be restored and managed with specific reference to how the natural hydrological regimes and other disturbance processes (e.g., fire, drought, herbivory) can be provided and be effectively managed. For example, if seasonal flooding regimes historically caused by overbank flooding from local streams and rivers are deemed important and desirable, then infrastructure must be designed to accommodate periodic flood flows without excessive damage to the infrastructure and also to allow flood waters to be stored and then released at natural intervals. In another example, if seasonal herbaceous wetlands are desired, then infrastructure should be designed to efficiently bring water into the site at desired times and then also be drained when needed.

Last, if time is available, the exercise should discuss how the new restored and managed site can provide important resources to different faunal groups endemic to the site and region of interest. This discussion, by default, would consider the effective "role" of the restoration site in meeting resource needs of animals of different taxa and ranges and essentially describe how the restoration site helps improve the ecological integrity of the broader ecoregion in which it sets.

Heitmeyer ME, Nelson FA, Fredrickson LH (2006) An evaluation of ecosystem restoration and management options for the Duck Creek/Mingo Basin area of southeast Missouri. University of Missouri-Columbia, Gaylord Memorial Laboratory Special Publication No. 12, Puxico, MO.

Heitmeyer ME, Artmann MJ, Fredrickson LH (2010a) An evaluation of ecosystem restoration and management options for Lee Metcalf National Wildlife Refuge. Greenbrier Wetland Services Report No. 10-02. Blue Heron Conservation Design and Printing, LLC, Bloomfield.