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17

RESTORATION OF FRESHWATER WETLANDS

Paul A. Keddy

Introduction

All life needs water. Therefore, wetlands have always influenced humans, and been influenced by humans in return. Early agricultural civilizations first arose along the edges of rivers in the fertile soils of floodplains. Wetlands also produce many services for humans – along with fertile soils for agriculture, they provide food such as fish and water birds, and, of course, fresh water. Additionally, wetlands have other vital roles that are less obvious. They produce oxygen, store carbon, and process nitrogen. Since wetlands form at the interface of terrestrial and aquatic ecosystems, they possess features of both. They are often overlooked in standard books, since terrestrial ecologists focus on drier habitats, while limnologists focus on deeper water. Shallow water, and seasonally flooded areas, fall comfortably into neither category. All wetlands share one causal factor: flooding. Hence, any discussion of wetland ecology has to place a primary focus on getting the water right (Keddy 2010; Middleton 2002; Pierce 2015). While wetlands may be highly variable in appearance and species composition, flooding produces distinctive soil processes and adaptations of the biota. Thus wetlands and water are inseparable.

Two general obstacles must be met in coming to grips with the scientific literature for wetlands in general, and for wetland restoration in particular. First, much of the work on wetlands is scattered across ecological journals and may not even appear under key word searches for wetland; instead, material may appear under a term such as bog, fen, shoreline, lake, floodplain, pothole, playa, peatland, or mire (or a dozen other terms). This problem is compounded when you add in the names used to describe wetlands in other human languages. Second, this discipline seems to have attracted a large number of conference symposia, the findings of which are recorded often in expensive books with a haphazard collection of papers, written by a haphazard collection of people, with no unifying theme whatsoever except that all deal with wet areas. One can easily be exhausted by an accumulated array of examples that seem to have few general principles. Hence, the need is pressing for a few general principles to guide restoration. In this chapter I will focus on general causal factors and their relative importance. This framework applies across wetland types and across biogeographic regions. The framework focuses upon the pool of species available, and the filters that control their relative composition, an approach which is sometimes termed assembly rules or trait-based assembly rules (Weiher and Keddy 1999).

I will first briefly introduce you to some basic information: what a wetland is, the kinds of wetlands that exist, and some key processes that occur within them. Then I will turn to causal factors. Flooding creates wetlands, so it receives a full section. Then I will consider how nutrient availability modifies wetlands. As a third key factor, I will consider the role of natural disturbances, and how they counterbalance competition and succession to produce a diversity of wetland types in a landscape. As Figure 17.1 shows, any particular wetland exists at a dynamic equilibrium set by the relative impacts of these three general processes. If one becomes predominant, the wetland will shift in area, composition, and ecological services. In the most general sense, restoration can be viewed as re-establishing the natural balance among these forces. There are two cautions. First, the relative importance of these factors differs significantly among wetland types: you cannot manage or restore a fen like you would an alluvial forest. There is no one size fits all! Second, each specific location will have additional causal factors, such as salinity, competition, herbivory, or roads. However, as Table 17.1 suggests, if you think about the problem of restoration in terms of causal factors, the first few are likely the most important. If you get these right, you can address the other factors on a case by case basis.

The kinds of wetlands

Wetlands are inherently variable. Consider that the term wetland applies equally to a coastal mangrove swamp, a beaver pond, a forested floodplain, and a wet prairie. Is there some natural

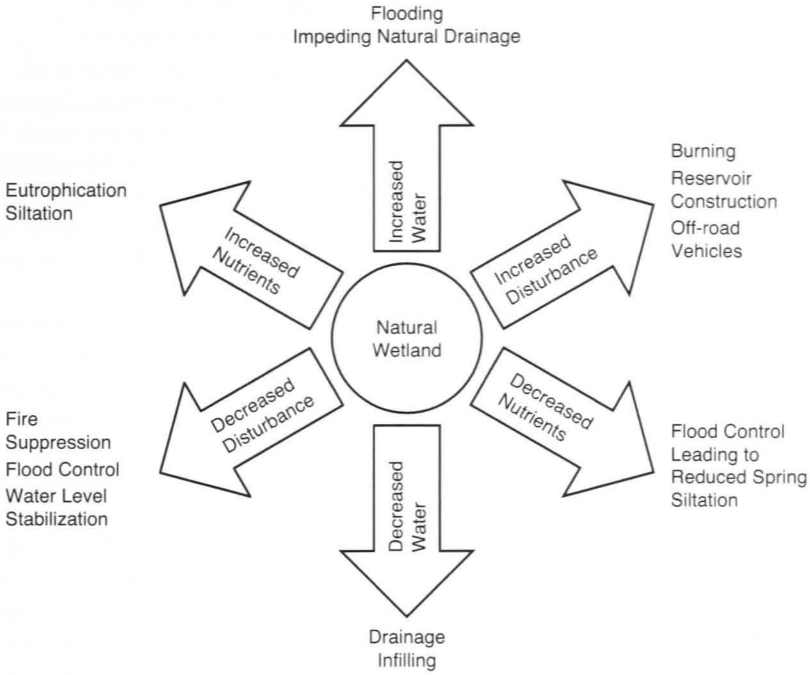

Figure 17.1 Any particular wetland exists at a dynamic equilibrium set by the relative impacts of these three general processes: flooding, fertility, and natural disturbance

Source: Keddy (1983)

Table 17.1 The estimated relative importance of environmental factors that determine the properties of wetlands. These can be considered the key filters for assembling wetlands from species pools

Environmental factor	*Relative importance (%)*
hydrology	50
fertility	15
salinity	15
disturbance	15
competition	<5
herbivory	<5
burial	<5

Source: Keddy (2010)

way to sort them into similar types? Each type can be visualized as a particular set of plant and animal associations that recur. This recurrence probably means that the same causal factors are at work. Unfortunately, the search for patterns is complicated by the terminology for describing wetlands that varies both among human societies, and among their scientific communities. Thus one finds an abundance of words used to describe wetlands – bog, bayou, carr, fen, flark, hochmoore, lagg, marsh, mire, muskeg, swamp, pocosin, pothole, quagmire, savannah, slob, slough, swale, turlough, yazoo – in the English language alone!

To keep the terminology simple, we will begin with four types of wetland:

1 *Swamp:* A wetland that is dominated by trees that are rooted in hydric soils, but not in peat. Examples include the tropical mangrove swamps (mangal) of Bangladesh and bottom-land forests in floodplains of the Amazon River in Brazil.
2 *Marsh:* A wetland that is dominated by herbaceous plants that are usually emergent through water and rooted in hydric soils, but not in peat. Examples include cattail (*Typha augustifolia*) marshes around the Great Lakes and reed (*Phragmites australis*) beds around the Baltic Sea.
3 *Bog:* A wetland dominated by *Sphagnum* moss, sedges, Ericaceous shrubs, or evergreen trees rooted in deep peat with a pH less than 5. Examples include the blanket bogs which carpet mountainous areas of the Himalayas, and the vast peatland of the West Siberian Lowland in central Russia, as well as bogs in southern South America.
4 *Fen:* A wetland that is usually dominated by sedges and grasses rooted in shallow peat, often with considerable ground water movement, and with pH greater than 6. Examples can be found within the extensive peatlands of northern Canada and Russia, as well as in smaller seepage areas throughout the temperate zone.

Two other wetland types could be added to these four.

5 *Wet meadow:* A wetland dominated by herbaceous plants rooted in occasionally flooded soils. Temporary flooding excludes terrestrial plants and swamp plants, but drier growing seasons then produce plant communities typical of moist soils. Examples would include wet prairies along river floodplains, or herbaceous meadows on the shorelines of large lakes. These habitats often have inordinately high plant diversity, and are one of the first habitats to be lost when dams and levees are constructed along rivers.

6 *Shallow water or aquatic:* A wetland community dominated by truly aquatic plants growing in and covered by at least 25 cm of water. Examples include the littoral zones of lakes, bays in rivers and the more permanently flooded areas of prairie potholes.

So, if you are going to restore a wetland, an obvious and essential first question is this: what kind of wetland are you trying to create? Of course, within each of these six categories there are thousands of subgroups depending upon which ecoregion you are in. If you are beginning a wetland restoration project, you must find the wetland classification that is applicable to your ecoregion. Once you locate an appropriate regional system, you will want to familiarize yourself with important causal factors that produce this array of wetlands. To put it into a global context, you may wish to refer to larger scale classification schemes such as those found in Vitt (1994) or Gopal *et al.* (1990).

Restoration needs

Overall, the past few centuries have seen major losses in wetland area around the globe. Hence, a first priority is to restore wetland area. This requires an understanding of why wetlands have disappeared. The most obvious cause is drainage ditches. Too often, wetlands are drained for agriculture or urbanization. In such cases, the primary tool for restoration is to plug or backfill drainage ditches. In other cases, wetlands have been lost through the deliberate construction of levees or dykes to obstruct the natural flow of water through the site and replace it with a polder. In this case outright removal of the dyke will restore wetlands.

In some landscapes wetlands will need to be reconstructed by physically creating depressions and obstacles to water flow. This allows much more precise control over topography and hydrology. However, the cost per restored acre is likely to be much higher. Here, important issues include (1) determining the availably of water to maintain the wetland (a wetland hydrograph is advised), (2) constructing the basin to create appropriate water levels and gradients (sub grading, see Pierce 2015), and (3) ensuring the availability of the right species pool, either through natural sources, added seeds, or outright planting.

An equally important target is restoring wetland composition. Often degraded wetlands become dominated by a few fast-growing dominant species of grass, or of the genus *Typha*, along with a few common species of amphibians and birds. While this may qualify as a wetland, it may not contribute to maintaining biological diversity. A large portion of the world's rare and endangered species require wetlands, and if we do not recreate the natural wetlands that once occurred in our landscapes, we will lose large numbers of wetland species. Examples you ask? The giant ibis (seasonal wet meadows in northern Cambodia); the Basra reed warbler (marshes of the Tigris-Euphrates). The eastern prairie fringed-orchid (in fens and wet prairies of North America); the Venus flytrap (coastal bogs in the Carolinas); the southern corroboree frog (*Sphagnum* bogs in subalpine woodlands in eastern Australia); the Mekong giant catfish (Mekong River in southeast Asia). For a full list of species at risk, and their habitats, consult the IUCN Red List of Threatened Species (www.iucnredlist.org). The IUCN estimates that more than 125,000 known species depend upon freshwater wetlands, including 15,000 species of fish and 5600 species of odonata.

The important point, then, is that it is not enough to restore wetland area, but one must set meaningful targets for species composition to provide habitat for the full array of wetland plants and animals. This means that restoration must consider not only regionally common wetland species, but also the ones unique to each of the world's ecological regions. According to Olson *et al.* (2001) there are a total of 867 such ecoregions, nested within 14 biomes and 8 biogeographic realms (for an online version of this map consult www.worldwildlife.org/

science/wildfinder). The first restoration challenge is to set an appropriate target for the desired species composition. This requires careful consideration of the ecoregion in which you are working, ecological states, and the tools available for restoring key environmental factors. Once the targets are set, one needs a monitoring program to measure success, and adaptive management to correct any mistakes (Keddy 2010: 373–376). These steps are summarized for your convenience in Table 17.2.

The importance of flooding and hydroperiod

Flooding makes wetlands. The conspicuous zonation of wetland plants within wetlands (Figure 17.2) shows just how important flood duration is to wetland plants. The causes of such zonation are complicated, and in part arise from reduced oxygen levels in the soil. These changes

Table 17.2 Four steps in the plan for restoring a wetland, with some guiding questions

Step	*Questions*
1. Set a target for species composition	What was the original array of wetland types in the landscape? What was the original array of gradients? What were the original key factors (filters)? What rare and significant species could serve as indicators? *What was the natural landscape really like when human populations were lower? What was the original pool of species? If you can't answer such simple questions, you need to do more homework on environmental history.*
2. Determine the key causal factors	What is the projected maximum water depth at a set of locations? What is the projected seasonal variation? What is the projected decadal variation? What is the target value for N and P? What other key factors must be considered (fire? herbivores? salinity?) *How will you ensure that these factors create a biologically significant wetland with natural gradients in species composition, as opposed to a circular wet hole with cattails and a few ducks?*
3. Decide how each key factor can be created or maintained	To what extent can you work with nature? Do you need to first recontour the site to enhance natural gradients? Are there existing obstacles to natural seasonal flows? Are there existing channels that remove too much water? Consider dykes with water control structures to be a last resort. *Artificial structures are expensive to build, expensive to run, and they will eventually fail unless given continual maintenance. For this reason, consider gently sloping berms rather than steeply angled dykes.*
4. Plan for adaptive management	What key factors will be monitored? What species will serve as indicators of desired conditions? Who will do the monitoring? How long will monitoring continue? Who will store the data and write updates? Who will make the adaptive changes, if any? *In very few cases, if any, will it be acceptable to build it, walk away, and hope for the best. This, like children without a father, is still far too common, and increases the onus to get it right.*

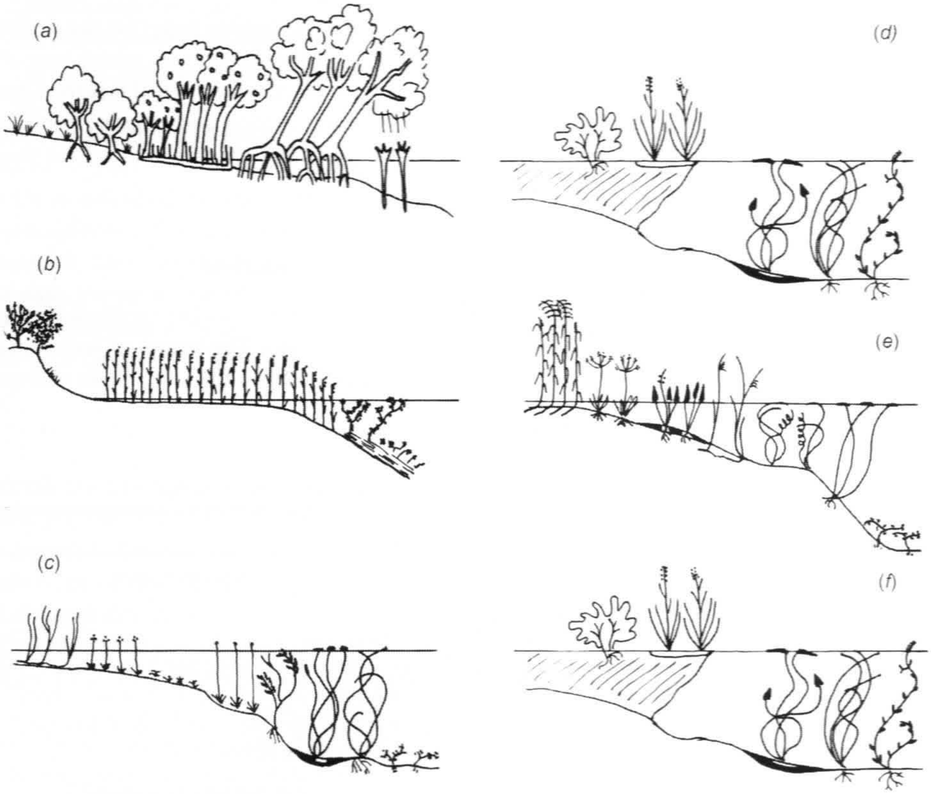

Figure 17.2 Flooding is the primary factor that produces wetlands, and the factor that controls much of the variation seen within wetlands. Examples include (a) mangroves along ocean coasts, (d) pools in northern peatlands, and (b, c, e, f) shorelines of lakes and rivers. The species names will change depending on the biogeographic region, but the wide occurrence of zonation emphasizes the overwhelming importance of getting the water right. Indeed, the wider the range of water levels, the more kinds of plants

Source: Keddy (2010)

are generally described in Keddy (2010) and Mitsch and Gosselink (2015). Hence, plants and animals have to adapt to reduced oxygen levels. The presence of distinctive plants with channels for transmitting oxygen from the atmosphere to the roots (aerenchyma) is a defining characteristic of wetlands. Aquatic plants offer the most extreme case of plants adapted to flooding (Sculthorpe 1985).

It is easy to think about zonation as resulting from some sort of mean water level, but in wetlands, the fluctuations in water level may be just as important as the mean. High spring flooding makes extensive areas of wetlands along the shores of lakes, and in many other kinds of depressions. Nearly every wetland in the world has water level fluctuations. Along the Amazon these may exceed 10 m within a year (Junk 1993). In large lakes like the Great Lakes, fluctuations may extend over 10 m over a period of decades (Keddy and Reznicek 1986; Wilcox 2012). These natural cycles must be considered in any wetland restoration project. In other books, such as Middleton (2002), this is described as 'flood pulsing'. Hughes (2003) explores how the restoration of spring floods in rivers is necessary for restoring ecological health to wetlands and watersheds. At smaller scales, where one is working with a single basin rather than a watershed, it is necessary to construct a wetland hydrograph to ensure that enough water is available to maintain desired water levels, and rather more engineering may be involved (Pierce 2015).

Trying to restore water levels is always the first step in wetland restoration. But it also brings you face to face with human intransigence. You can say it a hundred times and write books on the topic – yet people will express shock and dismay that their floodplain property is flooded in the spring, and they will equally complain about low water levels in the summer make it inconvenient to use their boat docks. They will also complain when some authority tells them they cannot build a house or factory in a flood-prone area, expecting, of course, that if anything does happen, an insurance company or government will pay for the damage. Yet, so long as snow melts in the spring and rainy seasons arrive, water levels in rivers will have high periods. A major impact humans have had on wetlands is the systematic disruption of such flood peaks in watersheds around the world (Nilsson *et al.* 2005). The importance of flood pulsing is now well documented, yet no doubt individuals will continue to think that rivers and lakes should have stable levels so they can build their houses wherever they care – alas, excellent science does not seem to provide an antidote to ignorance.

As an example of the challenges that lie ahead, consider the Tigris-Euphrates. It was one of the earliest centres of human civilization. Over the last century 32 enormous dams have been constructed, with eight more under construction and 13 more planned (Partow 2001; Lawler 2005). One of the largest dams is Turkey's Ataturk Dam. The cumulative effect of these dams allows storage of five times the volume of the entire flow of the Euphrates! The downstream effects on Mesopotamian marshes have been catastrophic. The area of marsh in the early 1970s was some 8,900 km^2 (about the original size of the Everglades), but had shrunk to 1,296 km^2 by 2000.

The importance of nutrients

Two elements, nitrogen and phosphorus, control rates of primary production in wetlands, and they also determine species composition. Alluvial floodplains and deltas usually have high production, as nutrients are carried in by spring flood waters, and these nutrients accumulate in sediment. Here one finds some of the highest rates of primary production in the world, in excess of 1000 gm^2 yr^{-1} (Keddy 2010: Fig. 11.1). This often translates directly into animals, particularly fish (Welcomme 1979). It is difficult to generalize whether it is nitrogen or phosphorous that limits growth (Verhoeven *et al.* 1996). Nutrients are not necessarily beneficial. In shallow water nutrients can generate algal blooms with negative consequences on marsh and aquatic vegetation, while at larger scales, entire lakes or estuaries may become so nutrient enriched that the resulting decay consumes oxygen, producing 'dead zones' (Turner and Rabelais 2003). The Gulf of Mexico, Chesapeake Bay, and the Baltic Sea are well-known examples of this phenomenon. Other types of wetlands, such as peatlands and shorelines, may have very low levels of available nutrients. Distinctive and rare wetland species often occupy these nutrient-deficient wetlands (Keddy 2010): the rare biota of the New Jersey Pine Barrens (Zampella *et al.* 2006) and the Everglades (Davis and Ogden 1994) are classic examples.

Hence, it may be useful to visualize wetlands arrayed along a nutrient gradient. At one end, infertile wetlands have many rare and unusual species. In these cases, the challenge is to maintain low nutrient levels to protect the unusual biota. At the other extreme, fertile wetlands, the challenge may be to maintain existing elevated nutrient levels, particularly those associated with spring flood pulses, and wisely manage the sustainable harvest of wildlife. Since eutrophication is a now a global process (with nutrients being released from burning coal, eroding uplands, agriculture, and sewage), we may expect infertile wetlands, and their associated biota, to become increasingly scarce in the future (Turner and Rabelais 2003; Keddy 2016). Dead zones, in contrast, may become more common.

In general, erosion, agriculture, and cities add nutrients to water courses, and hence to wetlands. In most cases, restoring a wetland will require minimizing the input of nutrients. This raises another problem: it is easy to add nutrients to wetlands; it is hard to remove them. Thus, one should err on the side of caution. If one is rebuilding a wetland basin to create a new wetland, the use of fertile topsoil as a substrate should likely be avoided.

There is a more general context for considering nutrients in wetlands. Most natural wetlands have fertility gradients, with some areas being fertile, productive, and dominated by nutrient-demanding species such as *Typha* spp. Other areas of the wetland, or nearby wetlands, may have lower levels of nutrients. They may contain species known as stress tolerators, with inherently slow growth and evergreen foliage (Keddy 2010). A particularly good indicator for such conditions is carnivorous plants (which compensate for low soil nutrients by capturing invertebrates) and orchids (which compensate for low soil nutrients with mycorrhizae). If you look at the natural fertility gradients in any particular landscape, you can often see evidence of centrifugal organization (Figure 17.3). There is one core habitat dominated by large fast-growing canopy-forming species that are likely competitive dominants. There are many other kinds of peripheral habitats with distinctive features such as low N, low P, recurring disturbance, and recurring drought, that have relatively uncommon species. Although each of these habitats may be uncommon, in total, they often have a large proportion of the biological diversity in a landscape. Hence, any planned restoration should consider nutrient gradients, and where possible, maintain natural gradients. Since, it is the peripheral habitats that are often most at risk in a landscape, particular attention needs to be given to maintaining existing peripheral habitats, and, if possible, constructing new ones.

Other causal factors

For each particular wetland, there is a hierarchy of causal factors. The challenge for a scientist or a manager is to identify these causal factors and to determine which ones are the most important at a specific site. Two factors of overriding importance, flooding and nutrients, have already been discussed. Superimposed upon these is a long list of other factors including: disturbance, competition, herbivory, roads, and burial. Here we will consider just four beyond flooding and fertility:

1. *Salinity* is a very important factor near coastlines, with species and communities arranged along salinity gradients created by freshwater inputs (Keddy 2010; Mitsch and Gossleink 2015).
2. *Herbivores* can have a major impact. The impacts of muskrats in marshes provides a classic case in which high population densities of herbivores can lead to almost total loss of aboveground vegetation (Keddy 2010). Such top-down effects are becoming better understood; when humans remove the top carnivores (such as crabs or alligators), the effects can be dramatic (Silliman *et al.* 2009).
3. *Fire* can occur during drought. Fire in the Everglades (White 1994) is a classic example; here, fire not only removes plant biomass, but it can even remove peat, thereby producing new areas of open water during the next wet period.
4. *Roads* can have a significant effect upon the biota of wetlands in populated regions. Not surprisingly, road density is a rather good surrogate for the overall impacts of humans in

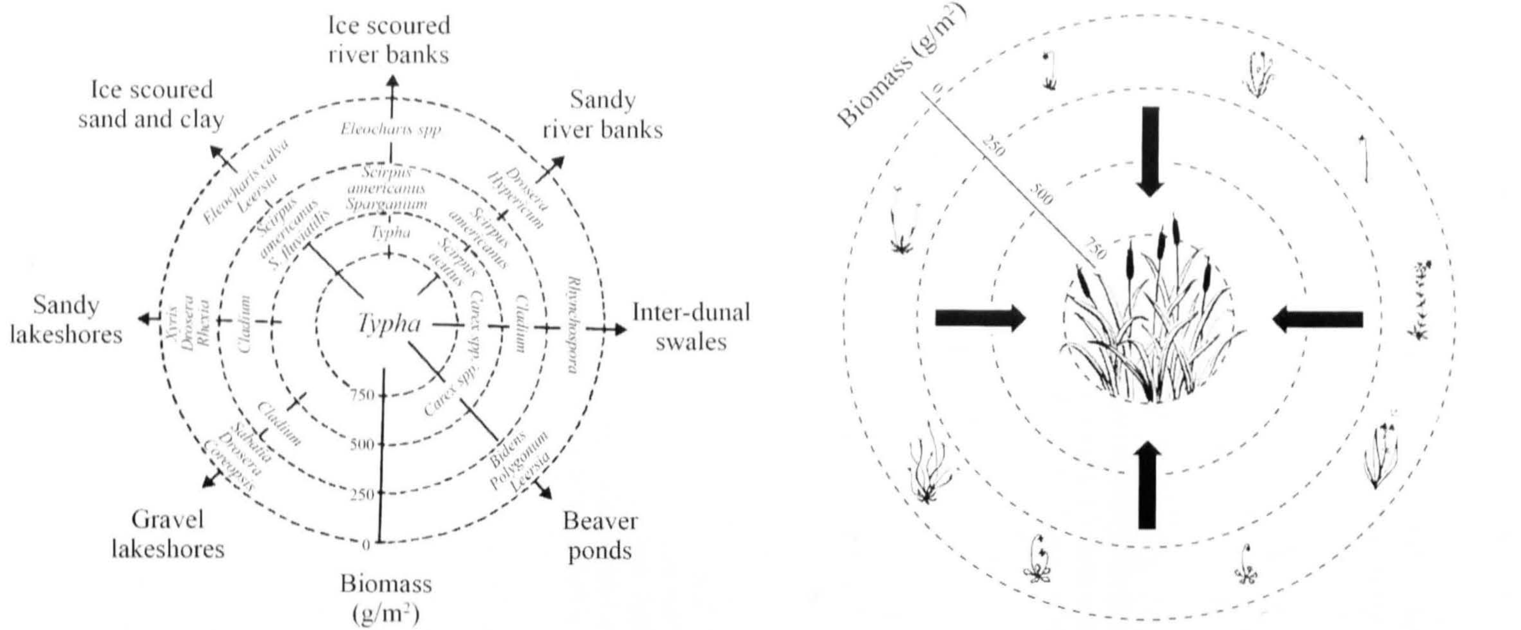

Figure 17.3 Wetlands contain multiple gradients, not just the water depth gradients shown in Figure 17.2. The centrifugal model shows how many different gradients and vegetation types generate plant diversity in wetlands. The centre (core habitat) has high biomass (>750 gm^2) and is usually dominated by a few large canopy-forming rhizomatous plants. The edges (peripheral habitats) have low biomass and distinctive species that are restricted to unusual habitats. Here is where a wide array of rosette plants, isoetids, orchids and carnivorous plants often occur. The left shows some of the presumed gradients in wetlands found along lakes and rivers in eastern North America. The right is simplified to show the general changes in growth form likely to be found in any herbaceous wetland. The black arrows show the effects of eutrophication: the loss of peripheral habits and dominance by competitive dominants such as *Typha* and *Phragmites*

Sources: left image, Moore *et al.* (1989); right image, Keddy (2010) the landscape (Houlahan *et al.* 2006). One sometimes sees road networks being built to carry out restoration; they should be avoided when possible.

The most important point when reading about these other causal factors is to keep them in perspective. In each wetland, some are very important while others are less important. Here is a case where wetland ecology is contingent: it is essential to know not only the important general factors that create a wetland, but also how these are modified by local circumstances and other causal factors. While reading the literature, one should make a concerted effort to rank other causal factors in order of relative importance.

Examples

In this section I will look at a small set of examples, arrayed along one axis: the degree of human intervention required, and, perhaps more the point, the cost of the intervention. I have a preference for simple and inexpensive methods. Partly this is a philosophical position: that I prefer to work with nature and natural forces in general, rather than trying to replace them with concrete and steel. Partly this is because my experience has led me to mistrust the ability of humans to manage large complicated engineering projects. And mostly, it is practicality: the less a restoration programme costs, the more likely it is to be implemented. However, I will indeed end with giant engineering projects that illustrate large-scale restoration with an abundance of concrete and steel.

Sometimes it is necessary to state (and restate) the obvious. With regard to wetland restoration, I need to remind you that the best option is to avoid the need for restoration in the first place. In a wisely-managed landscape, natural forces will generate biological diversity and ecological services with minimal human cost or oversight. Hence, our first rule might well be a sort of Hippocratic oath: dig no ditches or canals, erect no levees or dykes. This will obviate the need for future restoration. Alas, even if all such obscene practices were halted tomorrow, we would still have vast areas that already need restoration. In many cases, the wetlands that remain in a landscape are not only much smaller than they once were, but their composition has been greatly altered. Thus our challenge is to restore the original area and the original variety of wetland types. Some examples follow. Much remains to be done.

Low-tech examples: dealing with drainage ditches

Beaver ponds in the Canadian Shield

In the early 1800s, large numbers of settlers were brought to southern Canada from the United Kingdom. New townships were surveyed into large squares with straight roads dividing the land into rectangular lots. In order to grow their own food, these settlers had two main tasks: clear the forests and drain the wetlands. At the same time, many large species of mammals including caribou, elk, moose, and fisher were extirpated. By the time of the First World War, much of the upland area had been deforested and most wetlands had been drained either for pastures or crop production. The rocky land of the Canadian Shield however, was not well suited for mechanized agriculture, and many of the least productive farms were abandoned. This abandoned land received limited use, mostly for hunting, trapping, and logging. There was no plan for restoration, simply abandonment. But then beaver populations began to recover and by 1990 beavers had plugged many of the drainage ditches and created ponds and wetlands (Keddy 2010: 367–369). Wetland species began to recover. Other mammals such as fishers, otters, and muskrats became more common. Great blue herons and waterfowl returned to nest.

Osprey fished in the larger ponds. Snapping turtles, painted turtles and Blanding's turtles were frequently sighted. As beaver colonies collapsed from lack of food, water levels fell, and a natural cycle of flooding and seed bank regeneration was re-established.

I include this example because it is very familiar to me: my house now overlooks one of those beaver ponds. But, more importantly, the example illustrates how effective it is to simply plug drainage ditches. Beavers do it free. To complete the story, my wife and I bought several of those old farms as they became available, starting in 1975 when we borrowed money for the first hundred acres. Recently we donated a mixture of land and development rights to the Mississippi Madawaska Land Trust (www.mmlt.ca), which will protect nearly a square mile of forest and wetlands in perpetuity.

This is not to say beavers are a magical solution. They have costs, and they may generate new restoration challenges for the coming generations. Beavers need trees to construct dams, and the surrounding forests are strongly shaped by beaver cutting, which tends to shift composition away from deciduous trees toward coniferous trees. Beavers have been so effective at constructing ponds that they have all but eliminated natural seepage areas, streamside wet-meadows, and small streams. Future management may require control of beaver populations to protect these locally uncommon wetland habitats.

The Great Fen in England

The English fens are a good example to consider, because we have a long history of human activity there, and more than a century of efforts at restoration to consider. The Woodwalton Fen occurs in a flat area of eastern England. Descriptions of the fen go back to the Domesday survey of 1086; recall that, after England was conquered by Norman armies, this list was needed for the disposition of new land and other plunder. Thereafter is a period of decline from drainage and over-hunting. I have described these events in *Wetland Ecology* (Keddy 2010: 411–412), and for a longer essay you may read Sheail and Wells (1983). By the late 1890s, most of what remained was 'a dreary flat of black arable land, with hardly a jack snipe to give it a charm and characteristic attraction'. In 1910, 137 hectares were purchased as a nature reserve, but owing to the falling water table, the fen continued to deteriorate and was invaded by woody plants. Thereafter, restoration activities mostly focused upon blocking drainage ditches, and in one case, in 1935, using a portable pump to try to raise the water table during a drought. In 1972 a clay-cored bank was constructed to try to reduce the percolation of water out of the reserve. More recently, another relatively natural remnant of 256 ha has been acquired as the Holme Fen National Nature Reserve. Woodwalton and Holme will now become core areas within a 3000 ha restored wetland. The two problems of low water tables and high nutrient inputs will continue as challenges. You can read more about this under the title of The Great Fen Project (www.greatfen.org.uk). The section on restoration states:

> The Great Fen has inherited a complex and efficient network of drains, dykes and ditches whose primary purpose has been to get water away from the arable farmland as quickly as possible. Generations of farmers have deepened and straightened field ditches, and as a result, the peat fields rarely have any of the standing water that can be seen in other parts of the country after heavy rainfall. But now a major aim of the project is to retain water, rather than to drain it away.

For more on fen restoration elsewhere, you can consult Lamers *et al.* (2015). For the restoration of peat bogs, you can find useful practical instructions in Quinty and Rochefort (2003).

Larger-scale restoration

Levees, dykes, and canals in the Danube Delta

Restoration ecologists may also be challenged with larger tracts of dysfunctional landscapes. Even here, however, the principal causes may be obvious: drainage ditches and dykes. Consider the Danube River Delta in the Black Sea, which at 800,000 ha, is the largest in Europe (Gastescu 1993). The natural hydrology of this European waterway has been greatly altered – over 700 dams and weirs have been built along the river and its tributaries. The delta in the Black Sea has therefore been shrinking from lack of sediment. In addition, the delta has been criss-crossed with more than 1700 km of dredged canals. In the mid-1980s the communist dictator Nicolae Ceauşescu decreed that large areas of the delta should be transformed into agricultural land (Simons 1997). He sent 6000 men to build dikes, pump the land dry, and convert it into grain fields. Tataru Island, for example, was half drained and the local forest service had to supply 1000 m^3 of wood, 3 tonnes of meat, 700 kg of honey, 3000 muskrats, and 0.5 tonnes of medicinal plants to the state every year. The challenge of repairing their damage remains.

One relatively easy way to restore habitat along rivers is simply to remove, or breach, the levees. In autumn 2003, for example, some 6 km of levee that surrounded the aforementioned Tataru Island were removed, restoring natural flooding, and therefore in 2004 the Danube again flowed freely over the island. In 1994 and 1996, levees were also opened in two former agricultural polders, Babina (2100 ha) and Cernovca (1560 ha), in Romania (Schneider *et al.* 2008). Seventeen major floodplain restoration sites have been identified along the Danube, as part of a larger plan to re-create a green corridor along the river (World Wildlife Fund 1999).

Rebuilding landscape contours with constructed wetlands

In some watersheds, the landscape has been so transformed by dykes, levees, ditches, fill, highways, canals, and cities that it is necessary to physically create or at least re-shape the land before flooding. This physical shaping has costs. There is the cost of the equipment, and the engineering planning. There is also the cost of harm done to remnant ecosystems during the reshaping. Balanced against this are the benefits of being able to construct a desirable set of contours with complex gradients, and the ability to control the substrate type.

As an example, consider the set of constructed wetlands in the south central United States described in Pierce (2015). He describes five steps in building such as constructed wetland:

1 Defining goals and preparing plans.
2 Defining the hydrogeomorphic setting.
3 Preparing a quantitative description of the hydrologic regime.
4 Developing a substrate and subgrade management plan.
5 Preparing a planting plan.

In general, Pierce concludes that the failure to develop a predictive model for the hydrologic regime is one of the most common failings. Without the appropriate water levels, one does not end up with a desirable wetland, or a wetland at all. Hence, it is important to know the water inputs and the water outputs, and to incorporate them into a wetland hydrograph. This advice comes from decades of practical experience in constructed wetlands. It is reassuring that I have quite independently suggested (Table 17.1) that about the half the variation we see in wetlands is caused by differences in water characteristics.

Let me say more about the potential merits of constructed wetlands. One of the real advantages of a constructed wetland is the ability to make new wetlands. This is a step up from refilling existing depressions and channels. It also provides an opportunity to make kinds of wetlands that have all but vanished from local landscapes. In my experience, fens, seepage areas, and wet meadows are particularly vulnerable to being lost from landscapes. I suggest that many of these can be considered peripheral habitats (see Figure 17.3) that likely supported much of the plant diversity in the original landscape. Constructed wetlands, then, may allow the creation of not just common wetland types, but some of the rare and more locally significant types that will further enhance biodiversity. It is easy to think only in terms of the single site at hand, that is, the particular plot of land designated for a constructed wetland. But the planning process really asks us to consider the surrounding landscape as a whole. What was the original mixture of wetlands in the landscape? What were the natural gradients and causal factors? Which kinds of wetlands and kinds of species were rare, and which were common? Given the regional context, what kind of wetland would provide the greatest number of services?

This is where wetland construction grades into the entire topic of landscape conservation. Each particular wetland will have a regional context where, in many cases, there will be core protected areas, buffer zones, and ecological corridors (Noss and Cooperrider 1994). Your restored wetland may therefore become part of the regional network of conservation lands. Constructed wetlands may allow us to enhance all three components of protected area systems: restoring core areas, enhancing the quality of buffer areas, and expanding the network of corridors. This is where we can learn from the concept of biosphere reserves as developed by UNESCO. Biosphere reserves contain core areas with high ecological value, are surrounded by a buffer zone, and include management plans to maximize human benefits while minimizing human damage. As of 2015 there are 651 biosphere reserves; there is an interactive map at www.unesco.org/mabdb/bios1-2.htm. Many are familiar for their wetlands: examples include the Doñana (Spain), the Pantanal (Brazil), the Danube Delta (Romania and Ukraine), and the Sundarbans (Bangladesh and India).

Really large-scale restoration

The Everglades in Florida

It is impossible to write about wetland restoration without saying something about the Everglades. It is an extreme case which provides a context for many other projects. Comprehensive Everglades Restoration Plan (CERP) is priced at more than 8 billion US dollars. There is an ongoing flood of reports and scholarly papers; one of the main planning documents exceeds 4000 pages! Pages on the Everglades are likely being written faster than you can read them. So, what can I say in a few short paragraphs? I intend to avoid a long description of the Everglades and CERP, except for some references to guide your reading. I will try to extract a few general lessons for younger practitioners from these early years of CERP. These lessons relate primarily to nutrients, and to plant diversity in natural wetlands.

First, the Everglades themselves. They were once a vast rain-fed wetland, with extremely low nutrient levels, and steady flow from north to south, producing a distinctive sedge-dominated vegetation type adapted to wet infertile conditions (Davis and Ogden 1994). The slow but steady flow of water, combined with extremely low nutrients, and drier periods with fire, appear to have been the main environmental factors that created and maintained the system (recall Figure 17.1). Drainage began in the 1880s. Humans were principally concerned with water, extracting it for growing cities, or to create drier conditions for agriculture and urbanization.

The battles over land development, drainage, and irrigation were legendary and include many stories of political intrigue and outright corruption (Grunwald 2006). As the Everglades began to change, populations of wading birds declined. The area of natural wetland began to shrink.

A first general lesson from the Everglades is the importance of low nutrient levels to successful restoration. Phosphorus concentrations across most of the Everglades were likely as low as 4 to 10 pg/l and loading rates averaged less than 0.1 g P/m^2/year. This means that many of the species in the Everglades could be termed stress tolerators with particular life history traits associated with low nutrient levels, such as evergreen plants and carnivorous plants. So, here is one lesson to draw to your attention: nutrients really do matter. Of course you have to get the water right for restoration. A huge network of canals, berms, and water control structures is intended to recreate the natural surface flow from south to west, and into Everglades National Park. But a flow of nutrient-rich water will simply increase the degradation, converting a rich mixture of stress-tolerant plants into a cattail-dominated wetland. Hence, a second objective of CERP is to reduce nutrient concentrations in the water to below 10 $\mu g\ l^{-1}$ phosphorus. Recall that natural rainwater has minimal phosphorous, since it has come from evapotranspiration. Once such distilled water begins to flow across ground, nutrients accumulate, and if farmers are pouring phosphorus into their fields, the water will quickly become contaminated with high levels of P. In an attempt to deal with this, enormous (18,000 ha) treatment wetlands (STAs or stormwater treatment areas) have been constructed to reduce nutrient levels in runoff before this water enters the Everglades (Sklar *et al.* 2005). The general idea is that plants in the treatment ponds will extract enough phosphorus to ensure that the runoff will cause less harm to the Everglades. This, in my opinion, is one of the great untested assumptions in CERP. It is true that aquatic plants can remove phosphorus from water. But surely there are lower limits to the physiological capacity of plants to remove phosphorus – the original 4 to 10 pg/l is a very low level indeed.

A second general lesson is the importance of scale. That is, we need simple models to help us think, but they should not blind us to the wild diversity of wild nature. If you look at conceptual diagrams for the Everglades, they usually involve less than ten vegetation types (Figure 17.4). These ten types include sloughs, tree islands, and mangrove swamp. When one is managing an area the size of the Everglades, it is of course necessary to simplify the vegetation for some kinds of management. But, it is easy for engineers and zoologists to then begin to believe that there really are only ten or so vegetation types. And since many of these are dominated by just a few plant species, it is easy to begin to think that managing the Everglades means managing about 20 or so plant species. In fact, the vegetation of the Everglades was a rich mixture of species, including, as just one example, calcareous wet prairies maintained by fire (Orzell and Bridges 2006). There was high plant diversity, with more than 100 species per 1000 m^2. These habitats graded into different kinds of seasonally wetted rocklands and savannas. Thus the gradient structure in species composition was extremely complex. And these large numbers of plants rarely show up in Everglades models. Although Figure 17.4 is a classic, it risks becoming a problem if it replaces reality rather than illuminating it. That is, if the vast biological diversity of 'wet prairies' ends up being treated as one box with a couple of dominants, there is significant risk of losing much of the original diversity. Indeed, much of the plant knowledge in the Everglades relates to just a few wetland plants, particularly sawgrass and cattails. It might be helpful to have more information on vegetation gradients, indicator species, the ecology of stress tolerators, and the structure of those wet prairies, which are among some of the most speciose herbaceous vegetation types in the world. Here is where historical and palaeoecological information may help set restoration targets (Riedinger-Whitmore 2015).

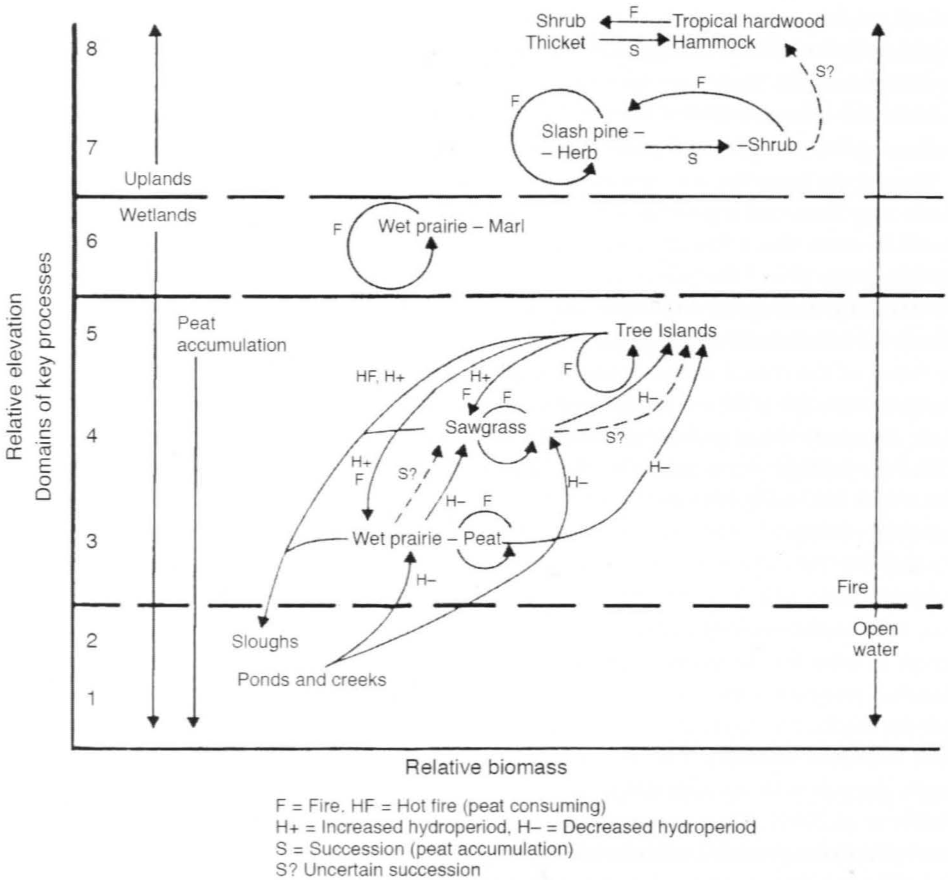

Figure 17.4 A classic illustration showing how the vegetation of the Everglades results from a few key factors. The vertical axis is elevation, which is controlled not only by the underlying topography, but by the accumulation of peat. The wettest sites have herbaceous vegetation in pools or sloughs with seasonal flooding. If enough peat accumulates, the herbaceous wetlands become tree islands (upper right). Succession then slowly moves the system from left to right. Fires move the system the other direction, from right to left. Light fires mostly change species composition, while more severe fires can create new shallow water sloughs (lower left). Superimposed upon this is a third controlling factor: nutrients. The very low phosphorous levels control both the kinds of plants found, and the rate at which sites recover from fire

Source: White (1994)

Other examples of and lessons from large-scale restoration

Much more could be written about large-scale restoration. Big scales have two potential problems. First, the stakes are bigger. Mistakes can have much bigger consequences. This is why we must get the science right. In some cases, I am far from impressed. Doyle and Drew (2008) have described five case studies of large-scale ecosystem restoration in the United States. To judge from work I have reviewed, it is easy to get the impression that teams of engineers are trying to build models of wetlands with minimal input from the science of plant ecology. We should not be reinventing the wheel. Existing knowledge about plant life history strategies, environmental gradients, succession, and pools and filters should be used, not ignored. A workshop of engineers and vertebrate ecologists, however well-intentioned, cannot reinvent a discipline they do not understand. Such oversights not only raise the costs, but they reduce the probability of success. The existence of this disconnect is readily apparent to anyone who understands plant ecology and then reads the reports and papers.

Second, the larger the scale, the more money and the greater the opportunity for abuse. Mark Twain may have said it best more than a century ago, opining that everyone disagreed what should be done about flooding along the Mississippi – but they all agreed it would take lots of federal money. Greed for federal money often over-rides scientific interests. While working in the Manchac Swamp in coastal Louisiana (Keddy *et al.* 2007) I saw distressing examples of money for restoration being squandered by administrators. Serious meetings about planning for the future of the coastal wetlands were lightly attended. But at the suggestion of federal money being available (an RFP, request for proposal), the room would packed, often with even one or more university deans present to monitor the scene. Our university received several million dollars for ecological restoration of the Manchac Swamp and for enhancing our field station. Much of it was handed out to biologists who knew or cared little about restoration. Typically, a microbial ecologist (said to be knowledgeable about plastic decomposition) announced loudly at a meeting 'This is just federal pork and I want my cut.' He got not just one, but several prime cuts, including a new boat. It became readily apparent that the vast scientific literature on restoration, community ecology, ecosystem resilience, and ecosystem health could be safely ignored, except in titles for the grant proposals. If you want an indicator for the consequences of the Manchac restoration money, you might be better to look at the participants: the size of their pick-up trucks, the upgrades to their houses, and the quality of alcohol consumed therein. All these improved markedly. The swamp did not. Without action, it may stay an anthropogenic marsh, degrade into brackish water, or even, as the climate warms, become a mangrove swamp (Keddy *et al.* 2007). More money won't help unless it is wisely spent. You can spend a lot of money on helicopters and airboats, and accomplish nothing.

I will not bore you with other stories: trainloads of rock being dumped in the swamp to hold back flood waters (one could mention King Canute but no one knows about him anymore), studies on ecosystem 'health' with minimal understanding of the environmental history of the region, new construction in the very areas flooded by hurricane Katrina, the Deepwater Horizon oil spill of 2010, or rooms of Louisiana residents chanting 'Drill baby drill!' Yes, large areas of the state are just above sea level, and yes drilling for oil will cause the land to subside, and yes burning it will cause the sea to rise, but apparently these are unwelcome facts to be ignored.

Such irritations do raise a deeper question for younger scholars to consider. What would you have done as a wetland ecologist in the Danube Delta in Romania during the 1960s? Or in the Mesopotamian wetlands in Iraq during the 1980s? Or, for that matter, in the Manchac Swamp in Louisiana in 2000? There is no easy answer. If you participate and do good work, it may simply be used as camouflage to hide the much larger body of bad work. If you walk away, there may be no one to document the waste and abuse, or to insist on at least minimal standards of scientific credibility.

These situations remind me of the dire story of the destruction of the forests of Easter Island (Wright 2004). The task of restoration is a challenging one, requiring a knowledge of wetland ecology (causal factors in wetlands), community ecology (pools and filters), and environmental history (recall Table 17.2). But the biggest challenge may be managing our own species. It appears that greed, cronyism, and corruption can at times overwhelm our better nature. How else can one explain Easter Island? Were there public meetings where the islanders chanted 'Log baby log?' I raise these unhappy topics in this handbook because there is a great risk for young restoration ecologists that they will be trampled in the rush for money by those far less qualified and even wilfully ignorant of the field of restoration and the science of ecology altogether. This is an unhappy reality, and while I once expected it to recede with time and education, I am now more inclined to think of it as an inherent part of human nature.

Conclusion

We have come a long way from Figure 17.1. It is time to remind you to follow the four steps in Table 17.2. Learn about the environmental history of your project area. Get the water right. Get the nutrients right. Do the very best science you can. Plan your restoration work with the highest aspirations for success.

Oh yes, while I am dispensing advice, let me say one more thing before I return to the forest. Instead of spending your weekends playing sports or hanging out in bars or mowing your lawn, get a canoe and get to know your wetland personally. Frogs and egrets and alligators and even dragonflies all have something useful to say, if you get to know them on their own terms, and if you take the time to listen to them, over the orchestrated din of organized sports, academic infighting, cronyism, and pork barrel politics. The better you know your wetland, and its many inhabitants, the greater your probability of success in restoration. This may not make you rich, but it should give you a life worth living.

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