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Irreversible Investment in Wetlands Preservation: Optimal Ecosystem Restoration Under Uncertainty

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ABSTRACT / The question of how to manage a lacustrine wetland is analyzed given the uncertain potential for long-term lake level changes resulting from global warming and the uncertain biological processes involved in creating wetlands. Three management options are considered: do nothing; construct a dike that removes hydrological connections with the lake (''closed dike''); and build a dike that maintains a hydrological connection with the lake, but can be converted to a closed dike under adverse conditions (''open dike''). For all practical purposes, dike construction represents an irreversible choice.

The model, a stochastic dynamic program, is used to optimize the timing and type of protective structure under a range of management goals. A wetland can either be optimal for fish or optimal for mammals and waterfowl, but not both. Because credible estimates of the economic values of wetland services do not exist, we treat those values as parameters in a multiobjective analysis and show the decisions implied by alternative valuations. The model is applied to the case of Metzger Marsh, a Lake Erie coastal wetland near Toledo, Ohio, where the decision was made in 1993 to construct an open dike. We find that the optimal decision is robust with respect to varying assumptions about the formation of barrier beaches and the probability of climate change, but that the decision is not robust to assumptions concerning the health of an unprotected Metzger Marsh. The most important source of uncertainty is the biological health of an unprotected wetland.

Metzger Marsh is a 908-acre coastal lagoon wetland on the shores of Lake Erie in Ohio. The protective barrier beach across the mouth of the lagoon had been eroded by high lake levels, allowing wave energy to reduce the health of the wetland. In 1993, an interdisciplinary group decided to construct a dike to protect Metzger Marsh. The dike is ''open'' in that it allows both hydrological exchange and fish access from the wetland to the lake. There were other, less expensive options available, including constructing a ''closed'' dike and waiting for lake levels to fall from their historically high levels in the hope that a barrier beach would form again.

The best management decision for Metzger Marsh depends on two things. First are the goals of the wetland's management. Second are the physical processes that affect the wetland's health.

The goals of management are unobservable to us. We characterize the trade-offs facing the wetland managers and investigate what goals are implied under the assumption that constructing the open dike was the optimal decision.

The physical processes affecting wetland health are subject to several sources of uncertainty. There are three sources of uncertainty that we will focus on. The first source of uncertainty is the extent to which an unprotected wetland (such as Metzger Marsh in 1993) is still productive as a habitat. The second source of uncertainty is the likelihood that barrier beaches that shield the wetland from wave energy will form without any intervention. The third source of uncertainty is the chance that climate change will lead to a systematic

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decline in lake levels, reducing wave energy and increasing the chance that barrier beaches will form without any intervention.

The paper proceeds as follows. In the remainder of this section, we review the biological role of wetlands and the relationship between climate change, lake levels, and wetland function. In the second section, we examine the range of management decisions available for Metzger Marsh in 1993. In the third section, we construct a formal model of the marsh management decision, using a framework known as stochastic dynamic programming. In the fourth section, we simulate the effects of alternative decisions under a variety of assumptions about the uncertain physical processes that govern the wetland to highlight which uncertainties are most important for marsh managers. In the final section, we summarize our analysis and conclude.

The Role of Wetlands

Wetlands are areas where water is the dominant factor determining the nature of the soils, vegetation, and animal life. Typically, such areas are periodically or permanently saturated or covered with water. The types and locations of wetlands vary widely, but fluctuating water levels are central to all of them, whether in the form of tides, waves, precipitation, or runoff (Kusler and others 1994). Wetlands are among the most diverse and productive ecosystems in the world. Although wetlands make up only 3.5% of the land area of the United States, about half of the 209 species listed as endangered in 1986 depend on wetland habitat (Mitsch and Gosselink 1993).

As civilization has grown, many wetlands have been drained and filled for agriculture and development or were otherwise lost through degradation of their environment and hydrological processes. Currently, less than 95 million of the presettlement 221 million acres of wetlands in the lower 48 states remain. These drastic losses can be attributed to their complex dynamics, which complicate efforts to understand and manage them (Kusler and others 1994).

Great Lakes coastal wetlands are wetlands in the Great Lakes basin that have or could have direct hydrological communication with the lakes. They come in a variety of forms based on their morphology and location with respect to the lakes, but most can be classified as emergent marshes. Emergent marshes are characterized by nonwoody vegetation that is usually rooted below the water level, with the majority of the plant bodies above water. Although most marshes are primarily emergent, they may also include areas of submerged or floating-leafed vegetation. The diverse wetland vegetation provides habitat for myriad fish, waterfowl, and wildlife. Coastal wetlands provide more food and shelter for wildlife than any other habitat in the Great Lakes basin (Herdendorf 1987).

Coastal wetlands in the Great Lakes system in the United States have a combined area of 1209 km^2 (Herdendorf and Krieger 1988). Lake Erie has the least (83 km^2), yet Erie wetlands are extremely important ecologically. On the Canadian side, approximately 80% of coastal wetlands in southern Ontario have also been lost (Koshida and others 1993).

Great Lakes coastal wetlands are multifunctional because they are part of and function as a transition between both the open water and upland ecosystems. The lake interface enhances the value of a healthy coastal wetland over an inland wetland. Thus, hydrologically unconnected coastal wetlands, such as artificially diked wetlands or those coastal wetlands whose vegetation is degraded because of wave action, are less valuable than hydrologically connected healthy wetlands (Herdendorf 1987).

Herdendorf (1987) divides the values of coastal Great Lakes wetlands into three areas: biological functions, physical functions, and economic factors. Biological functions include primary productivity (vegetation), habitat for invertebrate communities, habitat for amphibian and reptile communities, habitat for nesting and migrating waterfowl, habitat for mammals, and habitat for fish. Physical functions include flood water storage, groundwater recharge, shoreline anchoring, and water quality improvement. Economic functions include recreational use, vegetation harvesting (peat, blueberries), fur harvesting (muskrat), and hunting and fishing.

Lake Level Variation and Great Lakes Coastal Wetlands

Unlike oceans, which fluctuate daily around an essentially constant mean level, the Great Lakes are subject to both long- and short-term level fluctuations, caused by changes in water supplies and storms. These fluctuations significantly influence the viability of wetlands, affecting the range and nature of vegetation and shoreline erosion. In this sense, coastal wetlands differ from inland wetlands, which are not exposed to the dangers of volatile lake levels and wave energy. However, the same water-level fluctuations that have the potential to destroy Great Lakes coastal wetlands also keep them diverse and productive. Coastal wetlands that are influenced by lake level fluctuations yet shielded from the most destructive wave activity undergo constant rejuvenation. They do not experience the senescence process of inland wetlands, where marshes age from open ponds to dense marshes to dry fields or forests (Herdendorf 1992; Herdendorf and Krieger 1988). The fluctuating water levels also prevent the development of a monoculture marsh (Klarer and Millie 1992). Water level changes affect the fish, wildlife, and abiotic functions of wetlands (Jaworski and others 1979).

Water levels in the Great Lakes follow seasonal patterns, with highs in the late spring and lows in autumn (Hartmann 1990). In Lake Erie, this fluctuation typically ranges from 0.3 m to 0.6 m. Longer-term fluctuations result from year-to-year changes in precipitation. The highest recorded monthly average level in the lake was 174.9 m above sea level (in June 1986), with the lowest recorded level at 173.0 m (in February 1936). This 2-m range corresponds to a change in lake volume of nearly 10%. The intervals between periods of high and low water can vary greatly, with no regular or predictable cycle of levels (Herdendorf and Krieger 1988).

Both long- and short-term water level fluctuations have important effects on wetland vegetation. Long-term water level shifts are the primary influence in establishing wetland zones, where intraseasonal fluctuations affect the densities and distribution of plants within those zones (Lyon and others 1986). Periodic high lake levels eliminate competitively dominant emergent plants. This allows less competitive species to repopulate from seed banks when levels recede, complete at least one life cycle, and replenish the seed bank before again being dominated by more competitive species. Water level fluctuations help maintain plant diversity and, as a result, habitat diversity (IJC 1993).

Over a multidecade time scale, wetland communities historically migrated with changing water levels up and down the lake banks as morphology allowed. However, agricultural and urban development of areas above average lake water levels prevents redistribution of many wetland zones at high water levels. Now, high water cycles result in the net loss of wetland habitat, not merely redistribution (Prince and others 1992; Kusler and others 1994). Herdendorf (1987) concludes that many lagoon marshes in western Lake Erie would have been destroyed by high water levels and erosion had they not been diked. Water levels in the 1980s and early 1990s were 1 to 2 ft above long-term averages. These high water levels contributed to the erosion of barrier beaches and subsequent wave damage. Metzger Marsh, in western Lake Erie, is one example of a formerly healthy marsh that had been adversely affected by higher wave energies after being exposed by erosion of its barrier beach. The problem facing the Metzger Marsh Restoration Project in 1993 was whether to install a dike and, if so, what type of dike.

Climate Change and Lake Levels

The decision to construct a dike at Metzger Marsh is, for all practical purposes, irreversible. Uncertainties are an important influence in the optimal decision to make irreversible investments (Dixit and Pindyck 1994). One set of uncertainties is the path of future lake levels. If lake levels dropped, then perhaps natural processes would restore Metzger Marsh to health without any dike construction costs. One significant determinant of future lake levels is climate change.

Global warming as a result of increasing concentrations of ‘‘greenhouse gases’’—carbon dioxide, methane, nitrous oxides, and chlorofluorocarbons—may have a significant impact on all aspects of life. The likelihood and potential effects of this climate change, however, are still unresolved.

The Intergovernmental Panel on Climate Change (IPCC) concluded in 1996 that anthropocentric climate change is indeed occurring (IPCC 1996). However, there are still dissenting voices that refute the certainty of this notion. Koshida and others (1993) report a warming trend of 0.7°C over the past century in parts of Canada that include areas of the Great Lakes. Although such observations are consistent with anthropogenic climate change, they are also within the range of natural climate variations. If global warming is indeed occurring, there are still questions about how severe its effects will be.

To predict climate change effects, global circulation models (GCMs) have been developed that model weather pattern responses under different climatic assumptions. Several GCMs have analyzed a scenario in which atmospheric carbon dioxide is at twice its historical levels (or the net effect of all greenhouse gases approximates that of a $2 \times CO_2$ scenario). Temperatures, wind speeds, and precipitation variables are projected for specific climate assumptions.

Most GCMs for a $2 \times CO_2$ scenario predict temperature increases over the Great Lakes basin of between 3.4°C to 9.1°C in the winter, and 2.7°C to 8.6°C in the summer (Koshida and others 1993). Using hydrological models of the Great Lakes Basin and GCM-generated predictions of air temperature, humidity, cloud cover, and wind speeds, steady-state water level predictions have been developed (Lee and Quinn 1992, Hartmann 1990).

Steady-state $2 \times CO_2$ atmospheric conditions could lead to a 1.49-m drop in mean annual Lake Erie water levels (Lee and Quinn 1992), with the results occurring slowly over time. Chao and Hobbs (1997), in a study of beach protection near Erie, Pennsylvania, model these effects as a linear decrease in mean annual levels. Noting the IPCC predictions that transient effects would lag steady-state effects, the effect of the predicted decrease between the years 1990 and 2070 (the time horizon we use in our model) would be 80% of this 1.49 m, or 1.19 m. In our modeling of Lake Erie wetland management under climate change possibilities, we shall apply this linearly decreasing water level model of Chao and Hobbs.

Although GCMs are the most sophisticated tool used to gain insights into the effects of greenhouse gases, there are several limitations to using them as predictive instruments. The models use coarse grids; for example, the entire Great Lakes region is smaller than the average grid cell for many GCMs. A decrease in lake levels is predicted as a result of increased evaporation across the entire Great Lakes basin. However, Koshida and others (1993) acknowledge that the impact of global warming on climate variables, such as precipitation over the lakes, evaporation, and runoff, are poorly understood. Though GCMs may provide plausible scenarios for global climate change, they do a relatively weak job at predicting regional climate changes (Smith 1991). Koshida and others (1993) suggest viewing GCM scenarios as possible future conditions, not for predictive conclusions. Hartmann (1990) notes that uncertainty in GCM predictions and corresponding lake level predictions from hydrological models are a major obstacle to long-term planning efforts.

Climate Change and Wetlands

The impact that a doubling of CO_2 will have on the climate of the Great Lakes is relatively uncertain, and even less is known about the effects these changes will have on the region's ecological and biological systems. It is possible that rising temperatures would enhance wetland productivity, but systematic changes in precipitation, ice, and other hydrological components of the lake system will have uncertain effects on wetland areas, with little research having investigated such relationships (Koshida and others 1993).

Perhaps the most significant variable through which global climate changes may affect Great Lakes coastal wetlands is lake levels. The dependence of wetlands on lake levels is documented above, and the drastic lake level changes implied by GCM scenarios would have substantial effects. Lower lake levels could dry up currently productive wetlands, but might establish new wetlands at lower levels, shifting the community composition. At the very least, permanent water level drops will serve to change the vegetative structure of individual wetlands significantly (Keddy and Reznicek 1985).

Smith (1991) provides an example of the uncertain effects of global warming on wetland ecosystems, noting that potential effects on fish are difficult to gauge. Although warmer waters could result in increased winter habitat and more abundant food for lake fish, such an environment could also reduce habitable shallow waters and forage food in the summer. Meisner and others (1987) suggested that rapid reductions in mean levels of over 1.0 m would adversely affect spawning and nursery grounds in wetlands by reducing access and increasing turbidity. They also noted that uncertain changes in winds and temperatures could have negative but inconclusive effects on fish populations.

For the purposes of the model we develop below, we assume that global warming affects wetlands only through its effect on lake levels. Although changes in other climate variables are likely, the nature of these changes and their corresponding effects on wetlands are unknown and are therefore not considered in our model.

The Metzger Marsh Restoration Decision

Metzger Marsh

We shall examine Metzger Marsh, a 908-acre coastal lagoon wetland on the shores of Lake Erie, to analyze the effects of various uncertainties on management decisions to make irreversible investments in the wetland. The Metzger Marsh Wildlife Area is located in Lucas County, Ohio. Metzger is part of a larger, nearly contiguous complex of wetlands along western Ohio's Lake Erie coast, including Ottawa National Wildlife Refuge, Crane Creek State Park, and Magee Marsh Wildlife Area. Once a healthy emergent wetland, years of high water levels have eroded the barrier beach that once protected Metzger Marsh from the wave energy of the open lake, to which the wetland has over 1 mile of direct exposure. What remained was a largely unproductive open water area with shores eroding at the rate of 5 to 10 ft per year (US Fish and Wildlife Service 1993). If it were to again become a productive wetland, Metzger Marsh would harbor emergent plant life similar to that of surrounding, healthier marshes, such as cattails, bulrush, water smartweed, jewelweed, marsh-mallow, bluejoint grass, swamp milkweed, and pickerel weed (Herdendorf 1992). Northern pike, yellow perch, crappie, and other game and forage fish that spawn in western Lake Erie marshes would be expected to return to Metzger Marsh, along with a host of local and migratory birds and mammals commonly found in marshes throughout the region.

Periodic destruction of barrier beaches by storms or other high water events is a natural process for coastal wetlands; however, beaches are usually replenished or restored by lakeshore currents that deposit sediments across the mouth of embayments. This process of littoral drift has been too weak in recent decades to build a new protective beach for Metzger Marsh. In the early 1900s, the barrier beach was consistently in place, but aerial maps show the beach breached in five places in 1952, and all but a 3,000-ft sand spit attached to the northwest corner of the marsh had eroded by 1964 (US Fish and Wildlife Service 1993). On several occasions since that time, barrier beaches have begun to form at extremely low water levels, only to erode and disappear before becoming substantial (Mackey personal communication). This is due to both the innately sediment-poor western Lake Erie basin and the human-made alterations to the lakeshore that prevent erosional processes that provide sediment to the nearshore system.

Historically, the southwestern shore of Lake Erie was comprised of over 300,000 acres of marshland and was known as the ‘‘Black Swamp.’’ Currently, less than 10% of the original wetlands remain, mostly as diked waterfowl marshes, and lakeshore development is proceeding at a faster pace than anywhere else in the Great Lakes (US Fish and Wildlife Service 1993). Those few wetlands that remain have a correspondingly higher ecological importance, and a healthy Metzger Marsh would join adjacent marshes in the largest wetland complex on Lake Erie. This complex is an important habitat for plants, fish, and migratory birds, although it does not provide much hydrological or sedimentology benefits due to the lack of a significant watershed. In light of the importance of the habitat and the observation that current lake dynamics would not promote the formation of a barrier beach that would rehabilitate the marsh naturally, the Ohio Division of Wildlife and U.S. Fish and Wildlife Service committed to take joint action to restore the marsh and began the Metzger Marsh Coastal Wetland Restoration Project. The primary purpose of the project is to ‘‘protect, restore, and manage 908 acres of lacustrine emergent wetland habitat along the western basin of Lake Erie’’ (US Fish and Wildlife Service 1993).

The Metzger Marsh Project was enacted as part of the National Wildlife Refuge System, the broad goals of which are to (US Fish and Wildlife Service 1993):

- Preserve, restore, and enhance endangered or threatened plants and animals.
- Preserve a natural diversity and abundance of fauna and flora.
- Perpetuate the migratory bird resource.
- Provide an understanding and appreciation of fish and wildlife ecology through quality recreational experiences compatible with the purpose of the refuge.

Funding for restoration was provided by a variety of federal, state, and private sources. Federal funding of $4.4 million came as a congressional appropriation to the U.S. Fish and Wildlife Service. Total funds raised for the restoration project amounted to $5.85 million.

Restoration Alternatives Considered

In 1993, five interdisciplinary planning meetings were held at Ottawa National Wildlife Refuge to determine how to rehabilitate Metzger Marsh. Explicit goals of the project were to meet the National Wildlife Refuge System objectives listed above. In addition to determining how well each option would meet these objectives, planners explored the effects each option would have on marsh hydrology, sedimentology, wildlife, fisheries, endangered species, and cultural and socioeconomic benefits (US Fish and Wildlife Service 1993). Five management alternatives were identified for restoring Metzger Marsh’s functionality. Table 1 summarizes the five options considered for restoration of Metzger Marsh. Four of the options involved constructing some type of rip-rap dike structure across the mouth of the wetland, with the remaining option being to do nothing at all to protect the marsh. Alternatives 3 and 4 are both widespread diking methods. Alternatives 2 and 5, the ‘‘open dikes,’’ involve a novel approach to allowing certain fish to access the marsh while keeping unwanted and destructive fish out. At several points along the dike structure, several channels cut through the dike would be constructed and fitted with special screens and detainment areas that would limit the size of fish allowed in or out of the marsh. The screen sizes could be changed depending on the seasonal needs of the marsh and the goals of management.

A key complication is that it is difficult to manage a marsh for both waterfowl / mammal and fish utilization. Marshes with standard dikes are typically maintained at low water levels in the spring and high levels in the fall to maximize available food and habitat for waterfowl. This practice counters the natural water cycle of the lake, which peaks in the spring and reaches lows in the fall (Herdendorf 1987). Marsh managers are reluctant to allow any fish access into marshes due to the harmful effects carp can have on diked emergent marshes if they gain access. Carp retard the growth of aquatic vegetation by consuming it and by roiling the water, uprooting plants and causing turbidity, reducing photosynthetic efficiency. Several studies, including Herdendorf (1987), document the lack of diverse fish communities in diked Lake Erie marshes managed expressly for waterfowl use, supporting the apparent trade-off between waterfowl and fish objectives. Protected wetlands generally have stronger submergent communities than unprotected

Table 1. Summary of Metzger Marsh restoration alternatives

Alternatives	Major features and goals
Alt 1: *Wait*	Continues status quo within the marsh; marsh would continue to erode.
Alt 2: *Open dike:* Build 7700-ft lakefront dike; water level / fish control structure, water pump system (open system with control).	Protects, enhances, and restores 908 acres of wetland habitat; provides significant fisheries / wildlife management capabilities; ability to optimize physical and biological wetland functions and economic factors; provides controlled lake / marsh exchange.
Alt 3: *Broken dike:* Build 7700-ft lakefront dike without water level control structures (open system, no control).	Protects and restores wetland habitat; allows unregulated lake / marsh exchange, limiting fisheries / wildlife management possibilities.
Alt 4: *Closed dike:* Build 7700-ft lakefront dike with interior boundary dike and water pumping system (closed system with control).	Protects, enhances, and restores wetland habitat through established procedures; provides greatest wildlife management capabilities; provides no lake / marsh hydrological exchange or fish access; limits research on alternative management methods.
Alt 5: *Partial open dike:* Build 5000-ft lakefront dike similar to alternative 2, but protecting only federal portion of marsh (open system with partial control).	Protects, enhances, and restores 300 acres of wetland habitat; provides significant fisheries / wildlife management capabilities; provides controlled lake / marsh exchange.

marshes (McLaughlin and Harris 1990). In addition to the increased vegetative diversity and correspondingly stronger food supply, the increased protection from extreme water level surges in the marsh caused by lake level changes makes the wetland more viable as nesting habitat for waterfowl and mammals.

To explicitly consider the trade-offs among the objectives at Metzger Marsh, each management option was rated on a scale of 1 to 10 for seven separate environmental factors. Ten represented the most positive effect, 5 was a neutral effect, and 1 was the most negative effect for a given environmental factor. Factors considered were: impact on the wetland community; hydrology and sedimentology processes; effects on wildlife communities utilizing the marsh; effects on fisheries; implications for endangered and threatened species, which are represented disproportionately high in Lake Erie marshes; implications for public usage, such as hiking, hunting, and fishing; and socioeconomic impacts, such as tourism and potential implications for area businesses. Each alternative's ratings are shown in Table 2.

Table 2. Summary of environmental impacts per acre by issue and alternative

	Alt 1 Wait	*Alt 2* Open dike	*Alt 3* Broken dike	*Alt 4* Closed dike	*Alt 5* Partial open dike
Wetlands	4	10	6	8	10
Hydrology / sedimentology	4	5	6	1	5
Wildlife	4	9	6	10	9
Fisheries	5	9	6	2	9
Endangered / threatened species	4	8	6	9	8
Public use	4	10	8	9	10
Socioeconomic	4	10	8	9	10

Source: U.S. Fish and Wildlife Service (1993).

Based on the information in Table 2, the Metzger Marsh management team chose Alternative 2, the "open dike" that would allow limited fish access to the lake while providing a barrier from harmful lake water energy. Although costs were not available for all options considered, the open dike was the most expensive of those considered. This decision reflected the management team's goals of restoring the marsh with minimal changes to processes that occur in a naturally protected wetland. With Metzger being one of the only remaining undiked marshes in western Lake Erie, it was deemed imperative to avoid cutting off the marsh from the lake, as has been the case in diking other marshes in Lake Erie (Wilcox personal communication).

Had the decision makers preferred to discount the value of fish access and lake connectivity and construct a closed marsh, it would have been cheaper to simply restore an area of inland wetlands (Wilcox personal communication). Therefore, the decision to implement the most expensive option showed that a relatively high value was placed on the use of new strategies to manage the marsh for both fish and waterfowl / wildlife objectives. Construction of the open dike was completed in the fall of 1995.

The decision process made the assumption that a natural barrier beach would not, in the near future, establish again across the mouth of the marsh, and that an artificial barrier would therefore be required to restore wetland functionality. This is an uncertainty that we will model below. The decision-making body then picked the alternative that would most closely replicate the benefits of a barrier beach without isolating the marsh from the lake. The possibility that lake levels might fall in the future was not considered. In particular, the possible long-term lowering of mean lake levels resulting from global climate change was not acknowledged in the decision process.

Lower mean lake levels have the potential to allow for the formation of a natural barrier beach. Although there is little sediment available for littoral transport at current high lake levels, lower levels could expose enough unprotected land to form a barrier beach at Metzger Marsh (Mackey personal communication). There is little certainty regarding what water levels would be necessary for a barrier beach to form, or if one would form at all. Given these uncertainties and the high cost of irreversible dike construction, it could be the case that it would have been optimal to wait for more information regarding the trend in lake levels and other uncertain variables. This possibility is modeled below.

Choosing Optimal Strategies: Stochastic Dynamic Programming

The management question at Metzger Marsh is essentially one of maximizing future environmental net benefits where there is incomplete information on the nature of such benefits. At a given time, decision makers can choose to take one of several essentially irreversible actions to artificially protect and restore the marsh, or they can delay such a decision to gain information on the nature of climatic change and its effects on the marsh system. Such a delay preserves options that may benefit from future information, but foregoes benefits that may accrue during the waiting period. This sequential decision problem of whether and when to invest in one of several dike structures can be described using a model of optimal investment under uncertainty (Dixit and Pindyck 1994).

Krzystofowicz (1994) suggests stochastic dynamic programming (SDP) to solve problems of this nature, which he calls stopping-control problems. He conceptually outlines the application of SDP models to natural resource management decisions dependent on nonstationary climate variables. The stopping-control problem is one of deciding whether to commit irreversible resources (‘‘stopping’’, in our case, building a dike to artificially restore Metzger Marsh), or to put off the stopping decision to gain further information about the nature of the climate variables that will affect the benefits derived from the project. We don’t specifically model the ‘‘control’’ portion of the algorithm, which deals with the optimal operation of the structure once built.

Table 3. Management option costs

Management action	Wait	Open	Closed
Wait	$0	$5,056,000	$3,570,000
Open	N/A	$ 12,500	N/A
Closed	N/A	N/A	$ 12,500

Note: Each row indicates the current option, each column a possible option in the following period. The costs of moving from open to open or closed to closed are operating and maintenance costs of a dike.

In developing the decision model, we shall only consider three alternatives for Metzger Marsh: doing nothing (waiting), constructing a standard ‘‘closed’’ dike, and constructing an ‘‘open dike’’ with fish access structures. Two other options were removed from consideration. The partial open-dike option that would have protected only the federal portion of the marsh was discarded because it was more of a political consideration than a viable alternative to restore the marsh (Mackey personal communication, Wilcox personal communication). The ‘‘broken’’ dike was removed from consideration because it was dominated by other options. The expected performance of the broken dike with respect to National Wildlife Refuge objectives was matched or exceeded by both the open dike and the closed dike without being less expensive; it was superior to both the open and closed dike in only one of the environmental issues shown in Table 2: hydrology/sedimentology, which is only a minor concern for Metzger Marsh due to its lack of a significant watershed. The broken dike would not become a preferred option at lower water levels, as it would continue to have similar effects to those of the open dike, but the open dike retains a degree of control that marsh managers prefer (US Fish and Wildlife Service, 1993).

The cost matrix in Table 3 shows the incremental price of converting from one restoration strategy to another. Costs are read across from the strategy implemented at a particular time to the column corresponding to the strategy to be implemented in the subsequent time period.

Constructing a closed dike would cost $3.57 million for the 7700-ft structure and pumping equipment; an open dike costs an additional $1.486 million for fish control structures. A decision to build an open dike or a closed dike is essentially an irreversible action. The costs of removing them, both in terms of monetary expense and ecological damage, preclude any attempt to return the marsh to its predike state. There is no incremental cost to continue doing nothing; the annual cost for operating the closed dike is an estimate of electricity costs to run water pumps. Annual costs for open dike operation (pumping and control structure maintenance) are assumed to equal closed dike annual costs.

Objective Function: General Considerations

To develop an optimal decision model for Metzger Marsh management, we must first identify the goals of management and develop objective functions to characterize and quantify the performance of the marsh with respect to these goals. A diverse and vegetatively productive marsh is crucial to the support of fish, waterfowl, and animal resources, as well as the various societal and economic benefits that derive from them. More importantly, a vegetatively healthy marsh is of prime importance in meeting the National Wildlife Refuge System objectives described earlier.

In determining what marsh composition would maximize benefits with respect to the management objectives, ODNR and U.S. Fish and Wildlife officials determined that the most beneficial breakdown of the marsh would be 50% emergent vegetation and 50% open water areas (Mackey personal communication, Wilcox personal communication). Weller and Spatcher (1965) originated this concept of the optimal ''hemi-marsh'' and showed in a study of lacustrine wetlands in Iowa that bird populations and species diversity were higher in hemi-marsh conditions than wetter or drier marsh states. They also found that muskrat populations peaked in hemi-marsh conditions. Although there are no studies that define the marsh breakdown that best suits fish, it is generally accepted that a marsh with healthy emergent and submergent plant communities is beneficial to fish production (Jude and Pappas 1992), and open water regions are necessary to give fish access to the food and cover available from marsh macrophytes.

Although a hemi-marsh may maximize some complex of environmental and direct societal benefits derived from the wetland, methods for attaining this state can have effects on other management objectives. Specifically, the construction of a protective dike structure reduces the ability for exchange between the lake and the wetland, which can reduce or eliminate fish while enhancing waterfowl use of the marsh.

For fish populations to make use of the marsh, they require access to it from the lake. A variety of important commercial, game, and forage fish make use of coastal marshes for spawning, nursery, and feeding habitat during different portions of their lives and at various times during the year (Herdendorf 1987; Mitsch and Gosselink 1993). A closed dike would all but exclude lake fish from the marsh. An open dike would allow for some fish access, as would a barrier beach, if one were to form,[1] but not as much access as without such barriers. For a given vegetative condition in the wetland, increased accessibility increases the value of the marsh for fish production. In contrast to fish, increased seclusion from lake influences appear to make a marsh more valuable for waterfowl and wildlife, given a specific vegetative / open water breakdown.

The apparent trade-off between waterfowl / wildlife and fish objectives brings the concept of marsh openness to the lake into play. A hemi-marsh will meet all management objectives, but will be more valuable for waterfowl and wildlife if the marsh is more closed, and more valuable for fisheries if the marsh is more open. Therefore, relative preferences between these two objectives will affect the optimal management decisions.

To quantify benefits at Metzger Marsh for use in decision making, we desire an objective function that captures the preferences regarding trade-offs between fish and waterfowl / wildlife (hereafter waterfowl) objectives. Simple forms are postulated for the utility functions in order to make the analysis transparent and because more complex forms are not justified based on the available information. Four factors determine the value of the marsh:

- the vegetative health of the marsh (U_{veg})
- the value of the marsh for fisheries (U_{fish})
- the value of the marsh for waterfowl and wildlife ($U_{waterfowl}$)
- the cost of the management strategy (C(protection))

Since vegetative health is a derived objective that is important primarily because it facilitates fish and waterfowl objectives, we will not include vegetation explicitly in the marsh objective function.[2] This will enable us to more easily analyze trade-offs among the waterfowl and fish objectives in the following section. Total marsh utility is defined as an additive utility function.

$$U_{total} = U_{waterfowl} + U_{fish} - U_{cost} \qquad \text{(Eq. 1)}$$

[1]Historically, when barrier beaches would form, there were always small breaches and depressions in the beach that would allow for fish movement between the lake and the marsh (Mackey personal communication).

[2]Lemly (1997) demonstrates an approach to risk assessment of wetlands that includes far more detail about the specific components of the wetland. We use a more reduced-form approach both for analytical tractability and to illustrate the main trade-offs involved in the decision.

where

$$U_{waterfowl} = \alpha_{waterfowl}(1 - q(openness))U_{veg} \quad \text{(Eq. 2)}$$

$$U_{fish} = \alpha_{fish}q(openness)U_{veg} \quad \text{(Eq. 3)}$$

$$U_{cost} = \alpha_{cost}C(protection) \quad \text{(Eq. 4)}$$

We denote the total utility derived from marsh conditions over a period of time, and the utility of the marsh derived from waterfowl/wildlife, fish, and vegetative health objectives as U_{total}, $U_{waterfowl}$, U_{fish}, and U_{veg}, respectively. Below, we shall define U_{veg} as a measure of the equivalent area of "optimal" marsh required to deliver the same benefits.

The utility derived from management expenditures on the marsh over the period in question is called U_{cost}. The cost of attaining a particular state of marsh protection (none, barrier beach, open dike, closed dike), given the current state of the marsh is called $C(protection)$. These are the costs shown in Table 3.

A measure of the openness of the marsh, or the degree of access afforded lake fish, for individual states of marsh protection is denoted $q(openness)$. Values range between 0 and 1, which represent a completely closed and a perfectly open marsh, respectively. A marsh with no dikes or beaches is considered the most open, followed in turn by a barrier beach–protected marsh, an open dike, and finally a closed dike. Equation 2 assumes that a perfectly open marsh has zero value for waterfowl.[3]

We also have scaling factors, or weights, for the utility functions, denoted $\alpha_{waterfowl}$, α_{fish}, and α_{cost}. Letting $\alpha_{cost} = 1.0$, the units of utility become dollars, U_{cost} becomes $C(protection)$, and $\alpha_{waterfowl}$ and α_{fish} become dollar values per unit of optimal marsh.[4] The two coefficients are then the monetarized benefit rates associated with the marsh for each objective. By varying these weights in the following section, we will explore trade-offs and relative preferences between the competing objectives of fisheries, waterfowl/wildlife, and cost. Ideally, the weights would reflect willingness-to-pay information from those affected by the decision. In the absence of such information, we treat the values as parameters and explore the implications for the management decision of variations in the values.

This utility function is an additive utility function, in which we assume additive independence between individual objectives and total utility (Keeney and Raiffa 1976).[5] We also assume that decision makers are risk neutral and that the aggregate of total utility through time is the discounted sum of annual utility values. Under this assumption, there are no interannual utility relationships. That is, the benefits derived from a wetland in a given time period are independent of the condition of the wetland in previous times. Many wetland scientists have noted that in actuality there are complex temporal relationships between the state of a wetland and the different benefits that derive from it (for example, see Mitsch and Gosselink 1993), but the exact nature of these relationships remains unknown. Our assumption captures a significant portion of the true benefit behavior and has the advantage of being straightforward to model.

Measuring Open Water and Vegetation

Although we have identified that a 50/50 split between emergent vegetation and open water areas within the marsh is ideal, there are differing approaches in the literature for defining and delineating vegetative ranges in wetlands, making it important to be explicit about what we mean by open water and emergent vegetation. Open water regions have no rooted vegetation, due to their depth or other factors, yet are still within the wetland. Submergent vegetation, or aquatic vegetation, includes rooted macrophytes either entirely below or rising just to the water surface. We group open water, submergent, and floating-leafed areas as one wetland zone, the open zone. This grouping is commonly used when comparing water-dominant portions of marshes with vegetation-dominated areas, and it is the approach taken by Metzger Marsh planners.

Emergent vegetation is generically defined as macrophytes rooted beneath the surface of the water with major growth above the surface. The lower boundary of the emergent zone begins at the upper boundary of the open water zone. Identifying the landward boundary of the emergent zone is more difficult, as different studies segment emergent and upland communities in different ways (see Bloczynski 1996 for details). Fortunately, the need to identify which plant types should be

[3]The figures in Table 2 suggest that an open dike will be fairly supportive of a variety of wildlife. Thus, the objective function we develop here is biased against finding the open dike option optimal, all else being equal.

[4]It is important to note that these are values for *optimal* marsh areas (defined using the 50/50 ratio of emergent vegetation to open water) and should therefore be higher than those describing *average* marsh areas.

[5]Ideally, we would elicit preferences from the people included in making the decision and others affected by the decision. This was not possible, so we infer preferences from the decision made and illustrate how altering preferences would affect the optimal decision. Equations 1–4 can also be viewed as a measurable value function (Dyer and Sarin 1979), which unlike utility functions does not reflect risk attitudes. Under an assumption that decision makers are relatively risk neutral, measurable value functions and von Neumann–Morgenstern multiattribute utility functions are identical.

considered emergent proves somewhat unnecessary. Regardless of the specific type of plant community, the greatest plant diversity and production is found in the shallow water emergent zone (Keddy and Reznicek 1982).

This simple definition of the emergent zone by water depth should not be much different from defining specific emergent plant communities and modeling their distribution through time within the marsh. This is because plant communities are assumed to respond quickly to annual water level changes. Although a time lag is typically noted between a change in long-term water levels and complete response to the change by wetland vegetation, this lag is relatively short for the emergent vegetation found in Metzger Marsh (IJC 1993).

The transition between the lakeward edge of the emergent zone and the landward edge of the open water zone depends on the nature of the specific emergent vegetation in the marsh. For our model, we will use 0.0–1.0 m average annual water depth as the range of emergent vegetation, which is consistent with the type of vegetation expected to appear. Depths greater than 1.0 m are considered open water regions. However, this range is only applicable to the marsh in a protected (barrier beach or artificial dike) state. At Metzger Marsh, we observe that in an unprotected state there has been effectively no emergent vegetation, and we assign an emergent depth range of 0.0 m to an unprotected marsh. Thus, in this model, the undiked marsh needs a barrier beach to reestablish before it displays beneficial properties associated with wetland vegetation.[6]

Metzger Marsh is bounded landward on three sides, with a boat canal, parking lots, and paved roads abutting the marsh edges and preventing marsh migration inland at higher lake levels. It also has extremely steep banks, resulting in negligible transitional, nonemergent vegetation at current high lake levels. At lower water levels, significant portions of the 908-acre marsh may lie above the mean annual water line and thus above the emergent zone as we have defined it. (Though these ‘‘upland’’ regions may be flooded for part of the year and perhaps as a result populated by wetland plants, they are not included in the emergent and open water zones we identify.) Therefore, although the boundaries of the marsh area, including open water, emergent, and upland vegetation zones, are well defined at 908 acres, the area of the marsh for our purposes is considered to be the open water plus emergent zones, which will change with lake levels and fall somewhere between 0 and 908 acres.

Based on the discussion above, the marsh vegetative health utility function, U_{veg}, should have the following general properties:

1. For a constant total of open water and emergent area in the marsh, the function is maximized when there is an equal amount of both, and should decrease to 0 when the marsh is entirely open water or entirely emergent vegetation.
2. For a particular ratio of open water to emergent vegetation areas, a larger total area should have a higher value than a smaller one.

A simple utility function that satisfies both criteria:

$$U_{veg} = \frac{4OE}{(O + E)} \qquad \text{(Eq. 5)}$$

where O is the area of open water in the marsh, and E is the area in the marsh in the emergent range. This equation ranges from 0 to the area of the marsh, peaking when O and E are equal. This function assumes a linear relationship between marsh area and utility derived from the marsh. That is, doubling marsh area (holding constant the fraction of open water and emergent vegetation) doubles its value. Mitsch and Gosselink (1993) note that the actual relationship between wetland area and marginal value is more complex, due to the complicated nature of the scales of various wetland processes. However, this simplifying assumption is a reasonable first approximation in the absence of more information on those processes.

To calculate the extent of open water and emergent vegetation zones at different water levels, a function relating water levels to areal coverage of the marsh was developed based on the marsh’s bathymetry (Figure 1). Given this relationship and Equation 5, we can derive $U_{veg} = U_{veg}(L)$, where L is the mean annual water level (Figure 2).

We observe that U_{veg}, is only nonzero for water levels between 173.36 m and 175.35 m above sea level. The optimal water level is at 174.35 m, with a value of 908. Under the assumptions described above concerning the nature of the vegetative and open water ranges, 174.35 m is the mean level at which the marsh should be maintained if a standard closed dike were built and the marsh water levels regulated. This optimal annual water level is *above* the historic mean Lake Erie water levels (174.125 m, as reported in Chao and Hobbs 1997), although not as high as the extreme levels reached in

[6]We shall examine scenarios with a nonzero emergent depth range for the unprotected marsh to examine whether our results are robust to this assumption. We also note that complete revegetation will take more than 1 year. It would be difficult in the current framework to add long and variable lags to the model of vegetation, and this extension is left for future work.

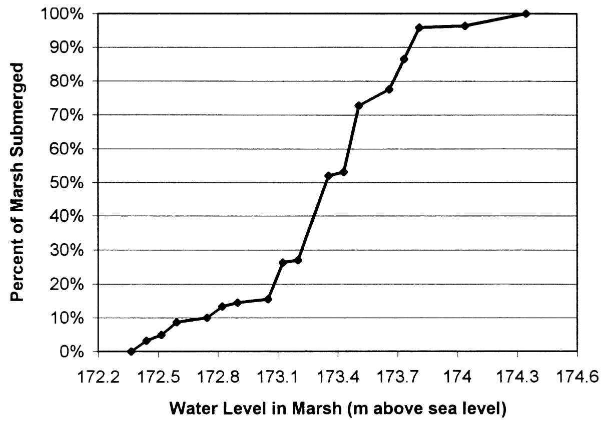

Figure 1. Water depth versus areal coverage in Metzger Marsh.

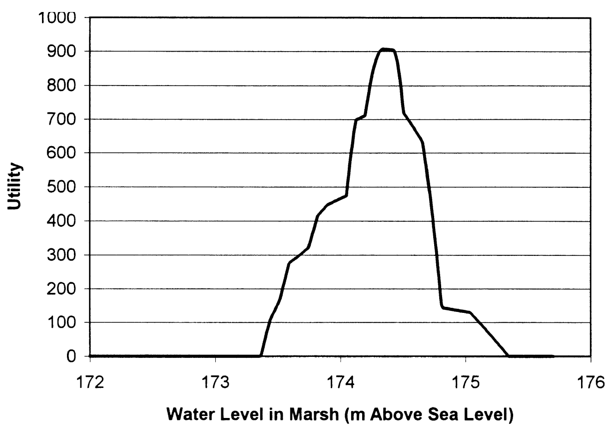

Figure 2. U_{veg} for Metzger Marsh for different lake levels.

the 1980s. Therefore, we suspect that the marsh's present unproductive state is due more to the lack of protection from wave attack than to recent high lake levels.

Since we assume no emergent depth range for an unprotected marsh, U_{veg} and the corresponding $U_{waterfowl}$ and U_{fish} have values of zero for marsh conditions with no barrier beach or dike. Thus, Figure 2 applies only to the dike options and those scenarios in which a barrier beach forms. (For a closed dike, we can maintain the water level at any desired level by pumping.)

The Decision Process

The decision setting modeled by the SDP can be described as follows: At a given time (stage), the wetland is in a known state, which consists of:

- the mean annual level of Lake Erie
- the probability of a climate change scenario that will drastically reduce lake levels
- the current state of marsh management (no dike, open dike, closed dike)
- the likelihood of barrier beaches forming at certain levels.

Potential future states of the wetland and their associated probabilities and expected utilities are also known. Uncertainty stems from random events that include natural fluctuations in lake levels and whether a barrier beach forms. This information is used to update the subjective probabilities via Bayes' Law. Two of the state variables are probabilities, representing the decision maker's subjective state of knowledge.[7]

A decision is made at each stage that maximizes expected future utility. The process then proceeds to one of the future states based on the decision. The decision at the next state is similarly made to maximize expected utility.

If the current state of the wetland is "no dike," then marsh managers can choose from among three management options:

- Wait, continuing in the "no dike" state
- Build an open dike
- Build a closed dike

Once a dike is in place, no more management decisions can be made, and a Markov chain is entered that calculates the expected future stream of benefits. The calculation of transition probabilities and arc utilities is described in Bloczynski (1996).

The optimal decisions are made according to Bellman's Principle:

$$U_t^*(i) = \max_d \left\{ \sum_{j=0}^{n} P_{ij}(t,d) * \left(\underbrace{u_t(i,j,d)}_{\text{arc utilities}} + \underbrace{U_{t+1}^*(j)/1+I}_{\text{discounted utility of next state}} \right) \right\} \quad \text{(Eq. 7)}$$

where

- $U_t^*(i)$ is the optimal sum of expected utility from time t until the time horizon T, given that the system is in state i at time t
- $P_{ij}(t,d)$ is the probability of entering state j at time $t+1$ from state i at time t, given decision d is enacted

[7]The analysis uses techniques that may not be familiar to all readers. Clemen (1996) or Ang and Tang (1984) are good references on Bayes' Law and decision trees. Stochastic dynamic programs, Markov chains, and state variables are described in Ang and Tang (1984) or Hillier and Lieberman (1995).

- $u_t(i, j, d)$ is the benefit (arc utility) during period t of enacting decision d at time t from state i, given that the process enters state j
- I is the annual discount rate

The SDP is solved backward, from the last time stage under consideration to the first; this is necessary because the expected utility of a decision at time t is dependent on the expected utility at time $t + 1$ of all possible future states. To start the process, the initial values U_{t+1} at the last time stage are set to 0 for all states.[8]

Two-year time periods are used in the model. The need for a 2-year period arises from the nature of the dike alternatives, which call for a 2-year construction and dewatering period. As a major investment initiative between state and federal wildlife agencies, it is reasonable to assume that the marsh restoration issue would be reconsidered on a regular basis until an irreversible decision is made.

The state variables of the SDP must include all information necessary for the decision process; in other words, they must be sufficient to determine arc utilities and transition probabilities. Four state variables are necessary to characterize the Metzger Marsh restoration problem.

1. *L:* mean water levels over a 2-year period. Lake levels are crucial to determining marsh utility, and thus need to be included as a state variable.
2. $P(CC)$: the subjective probability of global climate change leading to a reduction in Lake Erie water levels. We consider two possible scenarios for the distribution of future lake levels. If climate change is not happening, future annual lake levels will be distributed about the historic mean level. If climate change is occurring, then lake levels will be distributed about a nonstationary trend that decreases with time (Chao and Hobbs 1997, Hobbs and others 1997).[9] The stream of future benefits depends on the trend in lake levels, but it is not possible to know with certainty which path is being followed. $P(CC)$ is the probability (belief) that the climate change path is being followed, with $(1 - P(CC))$ the probability of historic lake levels persisting. The belief in climate change will change over time, as evidence on its likelihood is collected by observing actual annual lake levels. The updating of this belief in made using Bayesian inference.
3. *PBB:* The probability of barrier beaches reforming at a certain ‘‘critical’’ annual lake level. When water levels drop below this threshold, there is a chance that enough sediment will be available for barrier beaches to form (Mackey personal communication). This chance for the marsh to ‘‘heal’’ itself at lower water levels without any expenditures on artificial rehabilitation is a key reason to revisit the decision process considering the potential for climate change. Barrier beaches, when established at high enough water levels, will increase U_{veg} without incurring the expense of constructing a dike. There are only three possible values for *PBB:* 0, 1, and our prior belief that barrier beaches would form. If annual levels drop below the threshold, either a barrier beach forms or it doesn't, and the probability of a barrier beach becomes 0 or 1 accordingly; otherwise, *PBB* remains at the prior value.
4. The current diking state, *dike.* Our problem is a stopping problem, where a decision to invest in a control structure ends the decision process. The current dike situation, *dike,* limits what management options are available in the future. The three possible values of *dike* are open, closed, and no dike.

A dynamic program requires a finite state space. Thus, the state variables lake level L and probability of climate change $P(CC)$, which are continuous variables, must be discretized in the model. If the ranges of L and $P(CC)$ are broken into l and c discrete values, respectively, there will be $n = l \cdot c \cdot 3 \cdot 3$ possible states of the system at each time stage, since there are three possible states for *PBB* and three for *dike,* and all possible realizations of the process must be accounted for. In discretizing the continuous variables, we lose information and decision accuracy, so we would like to have as large a state space as possible to minimize the effects of lost information. For our model runs, we use 15 discrete levels of L and 7 levels of $P(CC)$, together with the three states for *PBB* and three for *dike* (totaling $n = 945$). Each optimization took 7.5 min to complete on Pentium processors running at 75 MHz.

We conducted tests to determine if such a coarse grid sufficiently sampled the vegetative utility function, and whether more lake level values would increase the accuracy of the model. The resulting optimal decisions did not change.

[8]This initialization of endpoints, while necessary, can lead to ‘‘end effects’’ that distort decisions made near the time horizon of the model. We minimize the impact of end effects on current decisions by using an 80-year horizon.

[9]Although we consider only two possible climate change scenarios, the procedure could be generalized to include several possible future climate trends, with the likelihood of following each of the possibilities dealt with in a similar manner to the two-scenario model (Hobbs and others 1997).

Results: Does Accounting for Uncertainty Matter?

Optimizing the dynamic program described in the previous section leads to a large number of results that depend on the exact set of parameters. Nevertheless, some general findings can be described here before moving to a detailed consideration of the alternative scenarios. First, we find that constructing an open dike is optimal if fish are highly valued both in absolute terms and relative to waterfowl. The ratio of α_{fish} to $\alpha_{waterfowl}$ at which the optimal decision changes from constructing a closed dike to constructing an open dike is about 4 to 1, and immediate construction of an open dike is optimal only for values of α_{fish} greater than or equal to $1,000 per acre of optimal marsh. We find that uncertainties about the formation of barrier beaches and the effect of climate change on lake levels are relatively unimportant determinants of the optimal decision, except for a small set of values for $\alpha_{waterfowl}$ and α_{fish}. Uncertainty about the health of the wetland in the absence of any protective structures (including barrier beaches), though, has a large impact on the optimal decision. Specifically, a small amount of wetland health in an unprotected state makes waiting at the initial time optimal for all of the parameter values that made open dike construction optimal under the base case assumptions.

One of the strengths of the dynamic programming approach is that it yields the costs of pursuing a suboptimal strategy. If $\alpha_{waterfowl} = 100$ and $\alpha_{fish} = 1{,}000$, then the optimal action in the base case scenario is to construct an open dike in the initial period. Constructing a closed dike instead would reduce net benefits by almost $800,000, making them negative. Even choosing to wait for one period would reduce net benefits by $74,000, or about 45%. In an alternative scenario, if the marsh has some health even in the absence of protective structures, we find that constructing the open dike yields benefits that are only about 5% of the total benefits of the optimal strategy, which is to do nothing.

Base Case Parameter Assumptions

We begin with a parameterization designed to capture as closely as possible the state of Metzger Marsh in 1993 and the most probable future evolution of lake levels.

A crucial question in examining the investment decision is the lake level at which barrier beaches can be expected to form. The primary reason to wait for more information before constructing a dike is the possibility that lower lake levels will cause the wetland to naturally reform behind barrier beaches. The level at which the beaches will form is not known with certainty, but expert opinion suggests that a lake level of about 173.5 m is where barrier beach formation would occur, if at all (Mackey personal communications). We assign a probability of 30% to barrier beaches forming when lake levels are at or below 173.5 m. As a sensitivity analysis, we will vary the level at which barrier beaches form.

Another important question is the extent to which various management options preserve the hydrologic connection of the wetland to the lake, that is, the ''openness'' of the dike. The extent of openness, q(*openness*) in Equations 2 and 3, was parameterized as ranging from 0 to 1, with a wetland completely exposed to the lake (as it was initially) given a value of 1. We arbitrarily assigned an openness parameter of 0.8 to a wetland behind barrier beaches, 0.6 to a wetland protected by an open dike, and 0.1 to a wetland protected by a closed dike. We examined simulations altering the magnitudes of this parameter (Bloczynski 1996) and found that the exact value had little influence on the optimal decision.

Another assumption we made was that there would be no emergent vegetation zone in the absence of protection, whether the protection was from barrier beaches or from a dike. Because Metzger Marsh is open to the lake, wave energy prevents much vegetation from becoming established. Making this assumption biases the base case toward building protective structures, and we will consider an alternative below.

The final assumption about physical processes was the probability of climate change and its effects on lake levels. The base case assumes a 50% probability of no climate change (with no change in long-term mean lake levels) and a 50% probability of climate warming (with a steady decrease in long-term mean lake levels and reduced net basin supply).

Once the physical parameters are picked, the only remaining choices concern the relative utility of fish (α_{fish}) and waterfowl / mammals ($\alpha_{waterfowl}$). Rather than assign arbitrary utilities, we repeatedly optimize using values of α_{fish} that ranged from 300 to 2200 and values of $\alpha_{waterfowl}$ that ranged from 0 to 600. Recall that by setting α_{cost} equal to 1, we effectively state the other parameters in terms of dollars per optimum wetland acre per year. The optimizations will result in our finding critical values of $\alpha_{waterfowl}$ and α_{fish} at which the optimal decision changes, for example, from waiting to constructing an open dike. We compare the valuation of the wetland implied by these critical parameters with estimates of wetland value made by other authors in order to illustrate the relevance of our results. Given that the decision to build a dike was made by people familiar with these other estimates of wetland value, it is satisfy-

Table 4. Management decisions: base case scenario

$\alpha_{waterfowl} \rightarrow$ $\alpha_{fish} \downarrow$	0	100	200	300	400	500	600
300	Wait	Wait	Wait	Closed	Closed	Closed	Closed
400	Wait	Wait	Wait	Closed	Closed	Closed	Closed
500	Wait	Wait	Closed	Closed	Closed	Closed	Closed
600	Wait	Wait	Closed	Closed	Closed	Closed	Closed
700	Wait	Wait	Closed	Closed	Closed	Closed	Closed
800	Wait	Wait	Closed	Closed	Closed	Closed	Closed
900	Wait	Wait	Closed	Closed	Closed	Closed	Closed
1000	Wait	Open	Closed	Closed	Closed	Closed	Closed
1100	Open	Open	Closed	Closed	Closed	Closed	Closed
1200	Open	Open	Open	Closed	Closed	Closed	Closed
1300	Open	Open	Open	Closed	Closed	Closed	Closed
1400	Open	Open	Open	Closed	Closed	Closed	Closed
1500	Open	Open	Open	Open	Closed	Closed	Closed
1600	Open	Open	Open	Open	Closed	Closed	Closed
1700	Open	Open	Open	Open	Closed	Closed	Closed
1800	Open	Open	Open	Open	Open	Closed	Closed
1900	Open	Open	Open	Open	Open	Closed	Closed
2000	Open	Open	Open	Open	Open	Closed	Closed
2100	Open	Open	Open	Open	Open	Closed	Closed
2200	Open	Open	Open	Open	Open	Open	Closed

ing to find that the critical parameters found in the model imply values that are within the range estimated by other authors. In other words, our findings are a plausible model of the actual decision process.

Because the optimizations involve future costs and benefits, the choice of a discount rate is also important. In all of the simulations reported here, we use a discount rate of 5%. Bloczynski (1996) reports the results of using alternative discount rates of 0 and 10%. The levels of net benefits change, but the fundamental relations among the parameters and the optimal decisions do not.

Base Case Results

The results of the base case optimum are illustrated in Table 4. The table shows the option that is chosen in the current time period ($t = 0$) that maximizes expected utility given the alternative values of α_{fish} and $\alpha_{waterfowl}$. We now discuss these results.

Recall that the decision actually made for Metzger Marsh was to construct an open dike immediately. For that option to be optimal, a value of at least $1,000 / acre for α_{fish} is necessary. At lower levels of fish valuation, waiting is optimal for low levels of $\alpha_{waterfowl}$, while building a closed dike immediately is optimal for higher values of $\alpha_{waterfowl}$.

Consider the point α_{fish} equals 1000 and $\alpha_{waterfowl}$ equals 100. There, the total value per acre of optimal wetland per year equals $1100. This implies a capatalized value of $22,000 per acre at a discount rate of 5%. This figure can be compared to a direct measure of the economic benefits of Metzger Marsh. Teisl and Southwick (1995) estimate annual benefits from Metzger Marsh to equal about $2568 per acre. The benefits that they identify are predominately from fishing, so we can conclude that the option of constructing an open dike would be optimal given their findings. In the most extensive analysis of coastal wetlands in the Great Lakes, Jaworski and Raphael (1978) found that there were benefits of about $1100 per acre per year, with most of the benefits coming from fishing.

The other interesting result in Table 4 is the boundary in parameter space between the decision to build an open dike and a closed dike. The ratio of α_{fish} to $\alpha_{waterfowl}$ along that boundary is a little over 4, whereas the ratio of the construction costs for an open dike and a closed dike is about 1.4 (recall Table 3). The trade-off is clear. The more expensive open dike is worth building only if fish (and openness to the lake more generally) are valued highly relative to the waterfowl and mammals who would benefit from a closed dike.

Uncertainty in Natural Processes: Barrier Beaches and Climate Change

In the base case simulation, barrier beaches were assumed to form only if lake levels fell to at least 173.5 m. If you examine Figure 2, you will see that even if barrier beaches form, not much of an increase in the value of the wetland results (U_{veg} is near zero at 173.5 m and below). This means that waiting to learn more about the effects of climate change and other uncertainties is not important, because even if lake levels fall and

Table 5. Management decisions in current period: barrier beaches at higher lake levels

$\alpha_{waterfowl} \rightarrow$ $\alpha_{fish} \downarrow$	0	100	200	300	400	500	600
300	Wait	Wait	Wait	Closed	Closed	Closed	Closed
400	Wait	Wait	Wait	Closed	Closed	Closed	Closed
500	Wait	Wait	*Wait*	Closed	Closed	Closed	Closed
600	Wait	Wait	*Wait*	Closed	Closed	Closed	Closed
700	Wait	Wait	*Wait*	Closed	Closed	Closed	Closed
800	Wait	Wait	*Wait*	Closed	Closed	Closed	Closed
900	Wait	Wait	Closed	Closed	Closed	Closed	Closed
1000	Wait	*Wait*	Closed	Closed	Closed	Closed	Closed
1100	*Wait*	Open	Closed	Closed	Closed	Closed	Closed
1200	Open	Open	Open	Closed	Closed	Closed	Closed
1300	Open	Open	Open	Closed	Closed	Closed	Closed
1400	Open	Open	Open	Closed	Closed	Closed	Closed
1500	Open	Open	Open	Open	Closed	Closed	Closed
1600	Open	Open	Open	Open	Closed	Closed	Closed
1700	Open	Open	Open	Open	Closed	Closed	Closed
1800	Open	Open	Open	Open	Open	Closed	Closed
1900	Open	Open	Open	Open	Open	Closed	Closed
2000	Open	Open	Open	Open	Open	Closed	Closed
2100	Open	Open	Open	Open	Open	Closed	Closed
2200	Open	Open	Open	Open	Open	Open	Closed

Note: Decisions shown in *italics* represent changes from the base case scenario in Table 4.

barrier beaches form, little utility is gained. Because the level at which beaches will form is not known with certainty, we recalculated the base case scenario allowing for the possibility that barrier beaches formed when lake levels were as high as 174 m. This is perhaps an extreme figure, as it is just below the historic mean lake level, but it is a useful check on the robustness of the decisions.

Optimal decisions under this alternative scenario are shown in Table 5. Values of α_{fish} and $\alpha_{waterfowl}$ where the decision changed between Table 4 and Table 5 are indicated by displaying the decision in italics.

As expected, the main impact of changing the lake levels at which barrier beaches might form is to increase the range of utility parameters over which the optimal decision in the current period is to wait. The increase in the range is not large, though, particularly given that expecting beaches to form at lake levels of 174 m is an extreme assumption. The decisions in the base case scenario are fairly robust to this alternative. Because climate change is important mainly in that it leads us to expect lower lake levels, we can conclude that under the parameters considered to this point, climate change is relatively unimportant. Thus, if it had explicitly been included in the decision process at Metzger Marsh, the outcome would probably not have been affected.

All of the optimizations to this point have included the potential for future decreases in lake levels caused by climate change. Planning documents indicate that the actual decision at Metzger Marsh was made without taking the possibility of declining future lake levels into account. To directly investigate the impact of including climate change in the model, we recalculated the base case scenario under the assumption that there would be no downward trend in mean lake levels, rather than the 50/50 probability assumed in the base case. The results of this set of simulations is shown in Table 6.

There is little change between the decisions in Table 4 and Table 6. The only difference caused by assuming that historical conditions will continue in the future is an expansion of the range of values for which constructing an open dike is optimal. Thus, the decision made to construct the open dike at Metzger Marsh is robust to whether or not possible changes in lake levels induced by climate change are taken into account.

Uncertainty in Natural Processes: Emergent Vegetation in an Unprotected Wetland

In the base case scenario, we assumed that wave energy would prevent any emergent vegetation from growing in the absence of protection from beaches or dikes. However, Metzger Marsh is not a linear beach, but a lagoon with some contours that might provide limited protection. To investigate the effects of allowing (in the model) emergent vegetation in the absence of protective structures or beaches, we assumed that emergent vegetation could prosper in water less than 0.2 m in average annual depth. Recall that emergent vegetation was assumed to be found in waters up to 1 m in depth in a protected wetland. Thus, we account for the

Table 6. Management decisions: no possibility of climate change

$\alpha_{\text{waterfowl}} \rightarrow$ $\alpha_{\text{fish}} \downarrow$	0	100	200	300	400	500	600
300	Wait	Wait	Wait	Closed	Closed	Closed	Closed
400	Wait	Wait	Wait	Closed	Closed	Closed	Closed
500	Wait	Wait	Closed	Closed	Closed	Closed	Closed
600	Wait	Wait	Closed	Closed	Closed	Closed	Closed
700	Wait	Wait	Closed	Closed	Closed	Closed	Closed
800	Wait	Wait	Closed	Closed	Closed	Closed	Closed
900	Wait	Wait	Closed	Closed	Closed	Closed	Closed
1000	*Open*	Open	Closed	Closed	Closed	Closed	Closed
1100	Open	Open	*Open*	Closed	Closed	Closed	Closed
1200	Open	Open	Open	Closed	Closed	Closed	Closed
1300	Open	Open	Open	Closed	Closed	Closed	Closed
1400	Open	Open	Open	*Open*	Closed	Closed	Closed
1500	Open	Open	Open	Open	Closed	Closed	Closed
1600	Open	Open	Open	Open	Closed	Closed	Closed
1700	Open	Open	Open	Open	*Open*	Closed	Closed
1800	Open	Open	Open	Open	Open	Closed	Closed
1900	Open	Open	Open	Open	Open	Closed	Closed
2000	Open	Open	Open	Open	Open	*Open*	Closed
2100	Open	Open	Open	Open	Open	*Open*	Closed
2200	Open	Open	Open	Open	Open	Open	Closed

Note: Decisions shown in *italics* represent changes from the base case scenario in Table 4.

destructive ability of wave energy (by reducing the range over which vegetation is assumed to grow) while still allowing for some wetland vitality in the absence of any protection. The results of this scenario are found in Table 7.

Table 7. Management decisions in current period: emergent vegetation in unprotected wetland

$\alpha_{\text{waterfowl}} \rightarrow$ $\alpha_{\text{fish}} \downarrow$	0	100	200	300	400	500	600
300	Wait	Wait	Wait	Closed	Closed	Closed	Closed
400	Wait	Wait	Wait	*Wait*	Closed	Closed	Closed
500	Wait	Wait	*Wait*	*Wait*	Closed	Closed	Closed
600	Wait	Wait	*Wait*	*Wait*	Closed	Closed	Closed
700	Wait	Wait	*Wait*	*Wait*	Closed	Closed	Closed
800	Wait	Wait	*Wait*	*Wait*	Closed	Closed	Closed
900	Wait	Wait	*Wait*	*Wait*	*Wait*	Closed	Closed
1000	Wait	*Wait*	*Wait*	*Wait*	*Wait*	Closed	Closed
1100	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*	Closed	Closed
1200	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*	Closed	Closed
1300	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*	Closed	Closed
1400	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*	Closed	Closed
1500	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*	Closed
1600	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*	Closed
1700	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*	Closed
1800	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*	Closed
1900	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*	Closed
2000	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*	Closed
2100	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*
2200	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*	*Wait*

Note: Decisions shown in *italics* represent changes from the base case scenario in Table 4.

Before considering those results, it is important to emphasize that this scenario models uncertainty about wetland processes beyond just the growth of vegetation and its associated benefits as habitat and food source for fish, waterfowl, and mammals. By allowing some degree of benefits to accrue in an undiked marsh regardless of barrier beach protection, we can account for the (unknown) value the marsh retains in its unaltered state. For example, during the construction of the dike at Metzger Marsh it was discovered that the marsh had housed one of the few remaining indigenous populations of bivalves in Lake Erie (due to the inability of zebra mussels to survive the ice scour). Furthermore, it was discovered that the relatively low wave energy areas of the marsh were one of the most important habitats for walleye fry, even in the absence of vegetation. Thus, a marsh that had been considered to be unsuccessful turned out to play an important role. Our parameterization means that we can only model this type of uncertainty by altering the way in which vegetation grows, but the point is much more general.

Allowing for even a limited amount of emergent vegetation in an unprotected wetland makes waiting much more attractive. This is especially true if openness is preferred, for example, because the wetland is valued due to its fish productivity. Recall that an unprotected wetland had the highest openness parameter, implying that it was both best for fish and worst for waterfowl for a given amount of vegetation. Even though the optimal

Table 8. Benefits of alternative strategies: $\alpha_{fish} = 1000$; $\alpha_{waterfowl} = 100$

Option	Table 4 base case	Table 5 barrier beach at higher lake levels	Table 6 no climate change	Table 7 vegetation in unprotected wetland
Do nothing	0	388,898	0	3,495,293
Wait	88,621	*391,410*	366,352	*3,495,293*
Open dike	*162,887*	162,887	*515,091*	162,887
Closed dike	−616,672	−616,672	−616,672	−616,672

Note: The option with the highest utility is shown in *italics*.

decision is to wait under a wide range of parameter values, we again find that if waterfowl and mammals are highly valued enough relative to fish, then the optimal decision is to construct a closed dike immediately.

The Costs of Being Wrong

The simulations reported in Tables 4 through 7 are useful in showing how the optimal decision varies depending on both the parameters determining the evolution of the wetland and the parameters determining management objectives. What the tables do not show, however, is how bad a mistake would be made by managers choosing an option other than the optimal one. The sheer number of the comparisons to make are overwhelming, but we provide one example to illustrate both the method and the relative importance of making the correct decision.

Consider the values $\alpha_{fish} = 1000$ and $\alpha_{waterfowl} = 100$. These values indicate a cell in which constructing an open dike is optimal in Tables 4 and 6, and waiting is optimal in Tables 5 and 7. The fact that fish have the greater weight in the objective function reflects a desire to investigate as relevant a case as possible. Both the findings of Teisl and Southwick (1995) and Jaworski and Raphael (1978) discussed above and the fact that an open dike was ultimately constructed at Metzger Marsh imply that the fish productivity is crucial to the wetland managers. Table 8 presents the discounted present value of the total utility under the various options under those weights. For example, constructing a closed dike in the scenario reported in Table 4 would lead to a discounted present value of utility of −$616,672, while constructing an open dike yields a utility of $162,887. We have also included the value of another option, never constructing a structure (“do nothing”). If we choose to wait in the current period, we might choose to build in the future. The difference between the value of doing nothing and the value of waiting reflects the value of the option to construct a protective structure in the future.

The results in Table 8 show that choosing the wrong strategy can have large consequences, perhaps even resulting in a negative utility (recall that construction and operating costs enter the utility function negatively). If in Table 4 the decision had been to wait instead of constructing an open dike, then the net benefits would have been reduced by almost 50%. Building a closed dike would result in lost utility of $779,000 relative to the optimal choice. This amounts to over 20% of the construction cost of the closed dike.

Similar figures are found in other columns, with the most dramatic case being Table 7. Table 7 reported the results of a simulation in which an unprotected wetland provided some utility. In that case, we get benefits from the wetland without spending several million dollars to construct a protective structure. Even though an open dike provides a positive net benefit under those conditions, the utility from constructing an open dike would be only 5% of the benefits of never building.

The ability to wait for more information before making a decision varies in value. In Table 5, never building a dike yields a utility of 388,898, and waiting (the optimal strategy at the current time) yields utility of 391,410. The difference in the values implies that under some circumstances a structure is built in the future even if the decision at the current time is to wait. The simulation from Table 7, on the other hand, shows no difference between waiting and never building, implying that the decision to build a structure is never optimal under the conditions in that simulation.

Summary and Conclusion

This paper has developed a model to evaluate an investment decision made under uncertainty. The model considers the best available information on the role of wetlands as habitat, on the role of lake level variation in determining the extent of wetlands, and on the potential for climate change to alter the historic pattern of lake levels. A stochastic dynamic program (SDP) was used to optimize wetland protection decisions under a variety of management objectives. The SDP was applied to the question of how to best manage Metzger Marsh, a Lake Erie coastal wetland near Toledo, Ohio.

Under the base case parameters, we found that the decision actually made by the managers of Metzger Marsh (build an open dike) was optimal if the wetland’s ecological services were valued at or above $1100 per acre per year, a figure within the range found by other studies. Furthermore, the relative benefits from fish had to exceed the relative benefits from mammals and waterfowl by a factor of about four in order to make the open dike optimal. At low levels of wetland valuation, the optimal decision was to wait for more information before committing to the irreversible investment in a protective structure.

We investigated several alternatives to the base case scenario. Under one scenario, the probability that natural processes would rebuild the wetland was increased. This change led to a small increase in the range of importance weights for which the best decision was to wait. A second alternative scenario considered the possibility that the unprotected wetland conveyed some benefits. Even a small change in this direction led to a dramatic increase in the range of values for which waiting or never building is best and again completely removed immediate construction of an open dike as the preferred decision. The third scenario was to disregard the possibility of lake level changes resulting from climate change. This scenario reflects an implicit assumption of those who actually made the decision at Metzger Marsh. There was only a small change relative to the base case, involving an increase in the range of values for which immediate construction of the open dike was optimal.

We illustrated the importance of making the correct decision by evaluating the net benefits of each option and comparing them to the optimal choice. In cases where the optimal decision can change across simulations, we find that the regret from choosing the wrong option can be large. This is particularly true in cases where waiting to construct a protective structure is optimal.

We modeled several sources of uncertainty. The first source of uncertainty concerns effects of long-term climate change on lake levels. We find that ignoring this possibility changes the level of benefits, but does not alter the ranks of different options under most weights. The second source of uncertainty is the physical process governing barrier beach formation. If barrier beaches are more likely to form than we currently expect, then waiting to see if lake levels drop over time becomes more attractive. The third source of uncertainty is the operation of biological processes in an unprotected wetland. Our simulations showed that allowing even a small amount of productivity in the absence of protective structures completely altered the optimal decision. Recent experience at Metzger Marsh shows there is more productivity in unprotected wetlands than had been expected prior to the beginning of construction. We conclude that a better understanding of the biology of wetlands is the crucial step to better protecting and preserving wetlands. We also conclude that the analytical framework of investment under uncertainty is one of great value for this type of problem, especially in calculating the value of being able to delay making an irreversible decision.

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