of isostatic rebound. Although nonclimatic factors may have been involved in this rapid drop, the timing corresponds to a well-documented and widespread centennial-scale drought that affected much of the North American midcontinent—activating dune systems, causing widespread fires, and leading to long-lasting changes in forest composition (Booth and others, 2005). Abrupt climate changes at that time are well documented on most continents, suggesting potential global-scale linkages.

Times of prolonged high water levels in the Great Lakes (highstands) have also been linked to climate variability. For example, bog surface-moisture reconstructions and inland lake records from throughout the Great Lakes region indicate wetter conditions during highstands (for example, Booth and Jackson, 2003; Booth and others, 2004). Pollen records indicate that populations of trees favoring moist conditions also expanded at these times (Booth and others, 2002). Although some climate changes associated with lake-level fluctuations were widespread, others were probably more spatially variable, with different areas of the Great Lakes Basin receiving more or less moisture. The water-level history of the Great Lakes integrates these spatial patterns. Comparison of localized records of climate variability from throughout the Great Lakes Basin (for example, records from small lakes, bogs, and tree rings) with the regionally integrated record of Great Lakes water-level history will allow delineation of these spatial patterns and help develop hypotheses regarding the atmospheric-circulation patterns associated with Great Lakes water-level fluctuations at scales of decades to millennia.

Clearly, the water balance of the Great Lakes region has varied considerably, and the overall variability for the past 14,000 years far surpasses that of the last 100 years in magnitude and ecological effect. Mechanisms behind climatic variability at these long timescales are poorly understood; however, many severe moisture fluctuations of the past century have been linked to dynamics of the ocean-atmosphere system, particularly variability in sea-surface temperatures and the associated changes in atmospheric circulation. For example, sea-surface temperature variability in both the Pacific and the Atlantic has been linked to changes in atmospheric circulation that influence the water balance of the midcontinent, including the Great Lakes region (McCabe and others, 2004; Schubert and others, 2004; Booth and others, 2006). Interactions between land surface and atmosphere, particularly with regard to soil moisture, often extend and amplify a large drought (for example, Delworth and Manabe, 1988; Manabe and others, 2004; Schubert and others, 2004). The extreme fluctuations in water balance evident in the Great Lakes water-level history and other paleoclimatic records may represent interactions and amplifications of this kind, as well as responses of the ocean-atmosphere system to variability in external influences such as solar radiation and volcanic activity (for example, Adams and others, 2003; Meehl and others, 2003; Rind and others, 2004).

**Figure 9.** Late Holocene lake level interpreted from beach-ridge studies in relation to surface moisture interpreted from testate amoeba studies in peatlands (modified from Booth and others, 2006).
Relation to Storage

Because of its large areal coverage and deep basin, Lake Superior stores more water (2,900 mi³ at chart datum) than all the other lakes combined (2,539 mi³ at chart datum). The maximum storage in Lake Superior in recorded history was 2,949 mi³ in October 1985 (fig. 10). Storage was only 2,925 mi³ during the low-lake-level period in April 1926. The average change in storage from wintertime low to summertime high is 6 mi³.

Storage at chart datum in Lake Michigan is 1,180 mi³ and in Lake Huron is 850 mi³. The maximum storage in recorded history for combined Lake Michigan-Huron was 2,053 mi³ in

How much water is in a cubic mile?
A cubic mile is about 1.1 trillion gallons or a football field filled to a depth of about 2.5 million feet.

How much water is in the Great Lakes?
Water from the Great Lakes could cover North America, South America, and Africa to a depth of more than 1 foot (Neff and Nicholas, 2005).
plants is due to survival of seedlings as they compete for growth in the sediments. In ensuing years, the distribution of full-grown plant species is due to the distribution of seeds in wetlands that may coexist there because of their diverse responses to natural disturbance.

In Lake Erie, storage at chart datum is 116 mi³; the maximum storage at high lake level in June 1986 was 126 mi³, and the minimum storage was 114 mi³ in February 1936. Total storage changed by about 8 mi³ between high lake levels in June 1997 and low lake levels in January 2001. On average, the change in storage between wintertime low and summertime high is 2.1 mi³.

Storage in Lake Ontario at chart datum is 393 mi³. Maximum recorded water storage was 400 mi³ in June 1952, and the minimum was 391 mi³ in November 1934, both prior to lake-level regulation. The variability in storage has been reduced by regulation, with a difference of only 6 mi³ between the recent high in May 1993 and the low in December 1998. The average change in storage of the regulated lake is 2.4 mi³ between wintertime low and summertime high.

Because of the large capacities of the lakes, alterations of storage due to diversions are relatively minor. The Chicago diversion from Lake Michigan averages 3,200 ft³/s, which results in a yearly diversion of about 0.69 mi³, only about 0.06 percent of the total Lake Michigan storage. One uniform rainstorm dropping less than 2 in. of rain directly on the lake would yield the same volume.

**Relation to Coastal Ecosystems**

Water-level fluctuations in the Great Lakes are of great ecological importance in the coastal zone because even small changes in lake level can shift large areas from being flooded to being exposed and vice versa. The vegetation of shallow-water areas in the Great Lakes is the one biotic resource most directly affected by natural or regulated changes in water level. Individual plant species and communities of species have affinities and physiological adaptations for certain water-depth ranges, and their life forms may show adaptations for different water-depth environments. Changes in water level add a dynamic aspect to the species-depth relation and result in shifting mosaics of wetland vegetation types. In general, high water levels kill trees, shrubs, and other emergent vegetation, and low water levels following these highs result in seed germination from the seed bank. Seasonal differences in the timing of water-level declines are important, especially in the Great Lakes, where the peak water levels occur in the summer and the lows occur in the winter (opposite the changes in most inland wetlands). An early summer peak and subsequent beginning of water-level decline allows more plants to grow from the seed bank than does a later peak. Water-level declines in winter can result in ice-induced sediment erosion. Consistent annual fluctuations during the growing season favor the species that are most competitive under those conditions, whereas variable summer water levels produce changing environmental conditions and result in variability in the vegetation.

Great Lakes wetlands also provide valuable habitat for fish and wildlife (Wilcox, 1995; Environment Canada, 2002). Many invertebrates are closely associated with macrophyte beds; waterfowl, aquatic mammals, and small fish are attracted to these areas because they provide food and shelter. When water levels change, habitats and organism interactions change also. Flooding of emergent plant communities allows access for spawning fish, reduces mink predation on muskrats, and increases hemi-marsh habitat (half vegetated, half open water) preferred by waterfowl. Flooded, detrital plant materials are also colonized by invertebrates that are fed on by waterfowl. Low water levels can jeopardize fish spawning and reduce waterfowl nesting area; yet, they provide the...
opportunity for regeneration of the plant communities that are the foundation of the habitat. Water-level fluctuations promote the interaction of aquatic and terrestrial systems and result in higher-quality habitat and increased productivity. When the fluctuations in water levels are removed through stabilization, shifting of vegetation types decreases, more stable plant communities develop, species diversity decreases, and habitat value decreases.

The effect of water-level changes on shorelines varies with the morphology, composition, and dominant processes of the coast. Variability in lake levels causes erosional and depositional processes to take place at different elevations over time. The most dramatic effect is the impact of an elevated storm surge during high lake levels, flooding low-lying areas and eroding mobile substrates. These storms can liberate sediment from upland areas, feeding the littoral system, and can ultimately nourish downdrift shorelines. The effects of this nourishment may not be seen until times of low water levels when exposed sand bars, widened beaches, and dune growth are evident.

Water-level fluctuations in the Great Lakes also play a major role in development and stabilization of coastal dunes (fig. 13). Studies of buried soils within dunes along the southeastern shore of Lake Superior and eastern shore of Lake Michigan show that dune building occurred during the high lake-level periods that have recurred about every 160 years.

Figure 11. Simplified diagram of the effects of water-level fluctuations on coastal wetland plant communities (from Maynard and Wilcox, 1997).
Box 3. Some species are particularly well suited to recolonizing exposed areas during low-water phases, and several emergents may coexist there because of their diverse responses to natural disturbance.