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Geomorphic and Environmental Change Around a Large, Aging Reservoir: Lake C. W. McConaughy, Western Nebraska, USA



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Key Terms: *Reservoir, Shoreline Erosion, Waves, Groundwater*

ABSTRACT

Lake C. W. McConaughy, a 63-year-old manmade reservoir in the North Platte Valley of western Nebraska, is the largest standing body of water in the state. From the time that Kingsley Dam was completed in 1941 until the present day (2004), many geomorphic and environmental changes have occurred along the shores and within the North Platte Valley. Erosion on the southeastern shoreline of the lake had been perceived as a problem for landowners and managers for at least three decades, but the full scale of erosion was revealed only after a cumulative 18-m drawdown in lake level: bedrock platforms, extending from cliffs on headlands, as well as minor caves, alcoves, potholes, and beach erosion scarps were revealed. Actual headland retreat since 1941 has probably been on a scale of magnitude of tens of meters. Erosional platforms, however, are as much as 266 m in length, indicating that they are, collectively, the results of a combination of pre-reservoir geomorphic conditions, erosion during reservoir filling, and wave erosion after filling. Serial observations of the shoreline made in the period 1999–2002 demonstrated that shoreline erosion continues. Depositional features such as pocket beaches and beach ridges have formed *de novo* in bays between headlands. Also, a delta that prograded at least 4 km from the North Platte River into the lake between 1952 and 1993 continues to grow, and major morphometric changes have occurred on the North Platte River immediately upstream since 1941 in response to the elevation of the local base level by the lake; most of the change in channel patterns in the river upstream from the delta took place in a mere 8 years from 1952 to 1960. Since 1999, some emergent beaches and areas of exposed lake floor have developed sand dunes; eolian erosion and re-deposition is widespread elsewhere in these

areas during periods of high winds, which are frequent in western Nebraska. The water table beneath lands adjacent to the reservoir generally rose until 1953 as the lake was filling. The far-flung irrigation system of which Lake McConaughy is the key element has elevated water tables as far as 250 km from the lake. Since at least 2000, soil salinization (episodic thenardite accumulation) has developed in exposed lake sediments at the western end of the lake. On a smaller scale, groundwater has been discharging lakeward along shoreline beach scarps through springs and seeps while lake levels have been low. Slightly lowering the operating level of Lake McConaughy could slow some of the more dramatic effects of shoreline erosion when the lake returns to its pre-drought volume, but erosion will continue, particularly at the ends of headlands on the southeastern shore, which are exposed to strong waves driven by northerly to northwesterly winds. Eolian erosion and re-deposition will, on the other hand, continue as long as lake level remains particularly low as a result of drought and the removal of irrigation waters. Salinization can be considered an ephemeral phenomenon, dependent on future management of the lake, but it indirectly represents the potential for larger-scale changes in hydrogeologic systems. The longer-term effects of lake-related water-table changes, both near the lake and downstream in irrigated lands, as well as the ability of the lake to supply irrigation water if drought conditions continue, remain to be seen.

INTRODUCTION

Lake C. W. McConaughy (Figure 1, Table 1) is the largest body of standing water within the boundaries of Nebraska (35.4 km long and 6.4 km in maximum width at maximum pool level). Impoundment of the North Platte River at the site began in 1941 (Table 2) with the completion of Kingsley Dam, a massive loess-cored structure about 2,200 m long. The lake, which is managed

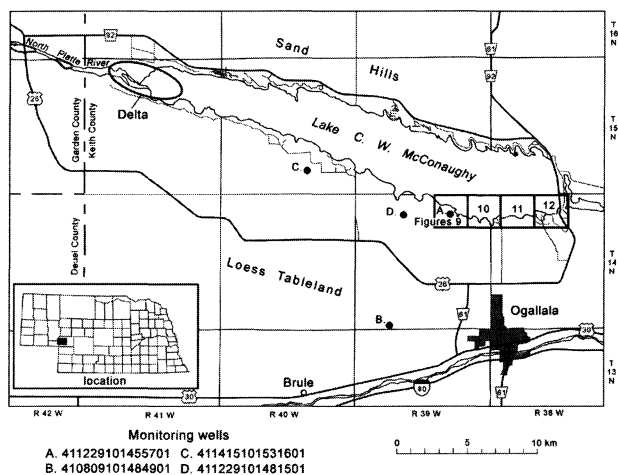


Figure 1. Lake McConaughy area, Keith and Garden counties, NE (see inset for state map). The lake fills the valley of the North Platte River between loess table lands to the south and the Sand Hills to the north. Delta has been built at western end of lake by sedimentation from river; southeastern shore of lake, detailed in forthcoming maps (Figures 9–12), is rocky and shows widespread evidence for erosion. Hydrographs from monitoring wells A–D are shown in Figure 14.

by the Central Nebraska Public Power and Irrigation District (CNPPID), was originally intended to play the key role in a far-flung surface-water irrigation system, which has served as much as 98,000 ha of agricultural lands. In 2002, 14,000 ha-m of water were delivered to customers at a total user price of about \$2.6 million. An on-site hydroelectric plant also generates over 65 million kWh per year and had been projected to produce \$6.4 million in revenue in 2003.

Although it was conceived as an irrigation reservoir, the lake has evolved into a major recreation center, attracting many visitors from urban eastern Colorado, as well as cities in eastern Nebraska. Nearly 860,000 visitors were recorded at state-owned facilities alone in 2002, and these visitors spent over \$420,000 that same year merely on park permits and camping fees. The total yearly value of recreation must be considerably higher, however, considering that there are several private campgrounds and marinas around the lake and that visitors make a variety of expenditures both near the lake and in the nearby city of Ogallala. Commercial and residential properties around the lake are currently valued at >\$88 million, and they produce at least \$1.5 million in tax revenues yearly, to which an unknown amount of tax revenue from total lake-related tourism could be added. Construction of additional multimillion-dollar developments is now underway along the shoreline. In the late 1990s 1-acre residential lots near the lake were selling for as much as \$100,000, although prices have since fallen to below that level.

The yearly flow of money associated with recreation and private property around the lake are probably in the

Table 1. *Lake McConaughy statistics.*

Length:	22 mi or 35.4 km (full storage)
Width:	4 mi or 6.4 km (maximum)
Depth:	140 ft or 43.3 m (maximum)
Area:	35,700 acre or 14,459 ha (full storage)
Volume:	1,743,000 acre-ft or 214,389 ha-m (full storage)
Shoreline:	105 mi or 169 km (full storage)

same order of magnitude as the yearly price of irrigation water, engendering markedly different spheres of interest. One of these spheres includes tourists, lake residents, local business operators, and developers, whereas the other includes irrigators and resource managers. The expectations of lakeside residents and developers on one hand and the lake’s irrigation-district managers on the other have always differed to some degree, and that difference has perhaps intensified during the drought years following 1999. During the drought, the lake level fell by more than 18 m from its normal pool elevation of 995 m, and by the end of 2003 doubts about the supply capabilities of the lake were expressed publicly (Table 2). The October 2003 pool level was within 2.3 m of the all-time low pool elevation during the drought of the middle 1950s. Significantly, the all-time low lake level also occurred during a major episode of drought on the Great Plains (Table 2).

Shoreline erosion has been a significant concern at Lake McConaughy since the 1950s. The original operating pool level of 3,270 ft (996.7 m) promoted widespread erosion, but the newer Federal Energy Regulatory Commission (FERC) certified level of 3,265 ft (995.2 m) has facilitated erosion control by moving the swash zone slightly lakeward from some actively mass-wasting cliffs. CNPPID originally purchased large tracts of land from private owners in preparation for the construction of Kingsley dam. “Excess” land not felt to be necessary for the completion of the project was gradually resold at a loss, but, in an understandable oversight for the times, erosion rights were not reserved. Thus, erosion has continued to be a source of conflict at some level.

Over the years, sea walls or rip-rap have been installed, or beach and upland slopes along the lake have been re-graded to retard erosion. Two recent legal proceedings indirectly involving shoreline erosion have transpired in the past 5 years in both county and district courts in the area, but there have been multiple out-of-court discussions between CNPPID and private landowners regarding erosion. In many cases, a proactive approach to erosion mitigation by CNPPID has been met positively with landowner cooperation; in other cases, interactions have been less cordial.

During the 1999–2003 drought, evidence of erosion along Lake McConaughy’s shoreline became more readily apparent than usual, offering an exceptional opportunity to assess geomorphic processes. Prior to this paper, the processes and products of shoreline erosion were understood primarily at an anecdotal level. Some erosional features, such as prominent platforms extending lakeward from shoreline headlands, are particularly striking when viewed at low pool levels and could casually be interpreted as evidence for extraordinary rates of progressive cliff recession (as much as a few hundred meters within six decades). Rather, with close inspection, these features appear to have more complicated, although much less spectacular, histories. Comparisons of 1938/1939 air photos with present-day observations, for example, show that pre-reservoir valley-slope geomorphology had a determinative, although not uniform, effect on subsequent shoreline landscapes, especially platforms. Furthermore, it is impossible to precisely differentiate erosion that took place during the filling of the reservoir from that which took place at high pool level once it was first achieved. These issues and the general problems of data paucity and resolution render the determination of a simple rate of shoreline recession very difficult and indicate that shoreline erosion around such a large reservoir must be examined in a more comprehensive geomorphic framework.

An additional complication in the realm of shoreline-related conflict at Lake McConaughy will be the developing issue of habitat designation for two endangered species, the least tern (*Sterna antillarum*) and the piping plover (*Charadrius melodus*), both of which nest in the area. A recent management plan for the lake included provisions for the monitoring, protection, and potential moving of nest sites (Central Nebraska Public Power and Irrigation District, 2002a, 2002b).

Other manifestations of change around the lake may create future conflicts or problems, and in the least exemplify the manifold local to regional effects of large reservoirs. Depositional landforms such as beach ridges, beach dunes, and a delta have been made clearly visible by falling pool level. These features have very clear-cut origins as purely lake-related phenomena, as they lack pre-1941 analogs. The lake has also induced morphometric changes in the upstream stretch of the North Platte River, which are useful for comparison with basin-wide river changes associated with relatively nebulous causative factors. Soil salinization associated with Lake McConaughy is noteworthy in its implications for local hydrogeologic systems, but a disjunct hydrogeologic effect actually extends a few hundred kilometers from the lake site into lands irrigated by lake waters, where water tables have risen considerably since the late 1940s.

The purposes of this paper are twofold. First, we provide the first scientific account of shoreline geo-

Table 2. *Chronology of events for Lake McConaughy*

1913	Diversion of Platte River waters for irrigation suggested by C. W. McConaughy of Holdrege, NE.
1936	Construction of Kingsley Dam begins with \$43 million in grants and loans (equivalent to >\$500 million in 2002, relative to Consumer Price Index); original intent of river impoundment is provision of irrigation water.
1941	Completion of Kingsley Dam across North Platte River.
1942	Kingsley Dam face washes out; repairs attempted.
1943	Kingsley Dam face washes out a second time; repaired again.
1951	Peak storage levels first reached in Lake McConaughy.
late 1960s	Anecdotal references to engineers’ concerns about erosion on south side of lake.
1971	Record high water storage attained.
1972	Erosion of dam (May 1) due to large waves generated by strong westerly storm winds.
1984	First hydroelectric power production at Kingsley Dam.
1999	Onset of recent drought conditions.
2003	Extreme drought conditions declared in western Nebraska; lake level decreases to 18 m from maximum pool level (October).
2003	Central Nebraska Public Power and Irrigation District (CNPPID) directors seek voluntary reduction in number of irrigated acres and announce that ability of lake to supply water beyond 2004 irrigation year is uncertain (November).

morphology and erosion at Lake McConaughy, as well as an explanatory model for the processes of erosion. This model is based on limited historical data and our own field observations. We concentrate on the southeastern shore, because erosional effects on exposed bedrock are prominent there, and because numbers of expensive residential properties have been built within a kilometer of the shoreline. Second, we discuss other geomorphic and environmental changes around the lake, including artificially elevated water tables around the lake and soil salinization along exposed parts of the lake floor. Results from this study are significant because they provide an instructive case study, not merely in terms of shoreline geomorphology, but also in terms of conflicting human needs, interests, and perceptions. The importance of these observations is amplified by the comparatively large local economic impact of the lake.

MATERIALS AND METHODS

The scale of shoreline features (a few tens to hundreds of meters) at Lake McConaughy is too small to be resolved in great detail on historical aerial photos. The largest of these features are barely visible in 1993 digital orthophoto quadrangles (DOQs), and therefore a fine-grained time series of shoreline recession could not be constructed. Nonetheless, we were able to hypothesize a very general concept of the history of shoreline erosion

from stereo aerial photos of the lake area taken episodically during the period 1938–1993. Delta progradation was more easily resolved because of the relative size of the feature being observed.

Shoreline features were described and mapped at ground level in multiple phases during 2000–2002 on both paper maps and on-screen with a laptop computer. For on-screen mapping, we used as bases U.S. Geological Survey 7.5-minute topographic digital raster graphic maps (DRGs) and DOQs loaded into an ArcView GIS 3.3 geographic information system (GIS) file. Historic aerial photographs were image warped to DOQs in ArcMap. Point locations collected with a differentially corrected global positioning system (GPS) were also loaded into this GIS file.

GEOGRAPHIC SETTING

Lake McConaughy fills a part of the North Platte Valley defined by high, steep, loess-mantled bedrock uplands to the south and the gentler slopes of the southern margin of the Nebraska Sand Hills to the north. Prior to the filling of the lake, relief from the valley floor to the upland table on the north exceeded 105 m. The lake has over 150 km of shoreline, which varies considerably in its geomorphic characteristics. Spectacular canyons eroded in some of the thickest Quaternary loess deposits in the Great Plains (~60 m) appear within a few kilometers landward of the southwestern shore, where there are remnant (pre-1941) alluvial fans and possible terrace deposits from the North Platte River. The southeastern shore is rocky: NNW-SSE-trending ridges terminate in NW- to NE-trending bedrock-cored spurs forming headlands that project into the lake. The northern shore is the southern boundary of the Sand Hills dune field and has more limited bedrock exposures.

The WNW-ESE orientation of Lake McConaughy and its relatively large size contribute to the potential fetch of winds arising from anywhere in the northwest quadrant. Such winds are typically the strongest in the central Great Plains, and, theoretically, a wind from the WNW could have a fetch equivalent to the entire length of the lake.

GEOLOGIC INFLUENCES ON GEOMORPHIC CHANGE

Bedrock Lithology

Lake McConaughy's southeastern shore, where bedrock erosion is dominant, and near which many private residences are concentrated, is a nearly continuous exposure of the Ash Hollow Formation of the Ogallala Group (Upper Miocene), with small outcrops of soft siltstones of the upper Brule Formation (Upper Oligocene) at its western boundary (Pabian and Diffendal, 1981; Diffen-

dal, 1984; Swinehart et al., 1985; and Diffendal, 1991). Along this shore, the Ash Hollow Formation consists of three main facies in order of volumetric dominance: (1) structureless to weakly horizontally stratified sandy siltstones and silty sandstones (fluvial bar and overbank deposits, in beds as much as 3 m thick), which are friable and erode easily (dry specimens slake rapidly in water); (2) weakly cemented, cross-stratified, medium to coarse sandstones to pebbly sandstones, with rare lenses or sheets of pebble conglomerate (fluvial channel deposits); and (3) thin (typically ≤ 1.5 m) but elongate lenses of thinly laminated calcareous silts or very silty limestones (slackwater fluvial or pond deposits). Within facies (1) and (2) appear much more erosion-resistant cemented strata, which are usually less than 1–2 m thick. Resistant strata include (1) horizons of fine-grained calcium carbonate (calcrete), which are laterally continuous over tens to hundreds of meters; (2) horizons of large, hard, siliceous rhizoliths, which are also bound together by innumerable, fine, siliceous and calcareous rhizoliths; and (3) fine-spar, cemented, cross-stratified sandstones. The distribution of these resistant strata in any given stretch of shoreline controls the pattern of erosion. Pre-reservoir (1938/1939) aerial photographs (which have poor resolution overall) show that some hill slopes on the future southeastern shore of the lake had sharp breaks in slope along the outcrop line of resistant strata at or very near the present high pool elevation. Aerial photographs indicate that a few of these slopes even had stepped profiles (Figure 2) because of the outcropping of multiple resistant strata in the Ash Hollow Formation. A large part of the future southeastern shoreline, however, had relatively smooth slopes with less pronounced breaks in slope prior to the attainment of maximum pool level in 1951.

Bedrock Fractures

Fractures can be observed on eroded bedrock platforms in the Ash Hollow Formation (see discussion below) along the southeastern shore of Lake McConaughy. NW-SE, WNW-ESE, and ENE-WSW trends can be identified (Figure 3A). These fractures appear to be preexisting planes of weakness that are activated by progressive erosion. On a given eroded bedrock platform (see discussion below), open fractures (several meters long) in exposed horizontal strata trend nearly parallel to the margin of the platform in the area of observation. These fractures are the sites of active, small-scale mass wasting (collapse of resistant layers by undercutting; see discussion below). Toward the interior of a platform's surface, fractures are less prominent, frequently appearing as mere hairline features, which are typically prominent only in friable siltstones. Individual cemented strata in the Ash Hollow Formation are indeed coherent, but are not known to exhibit well-developed jointing elsewhere.

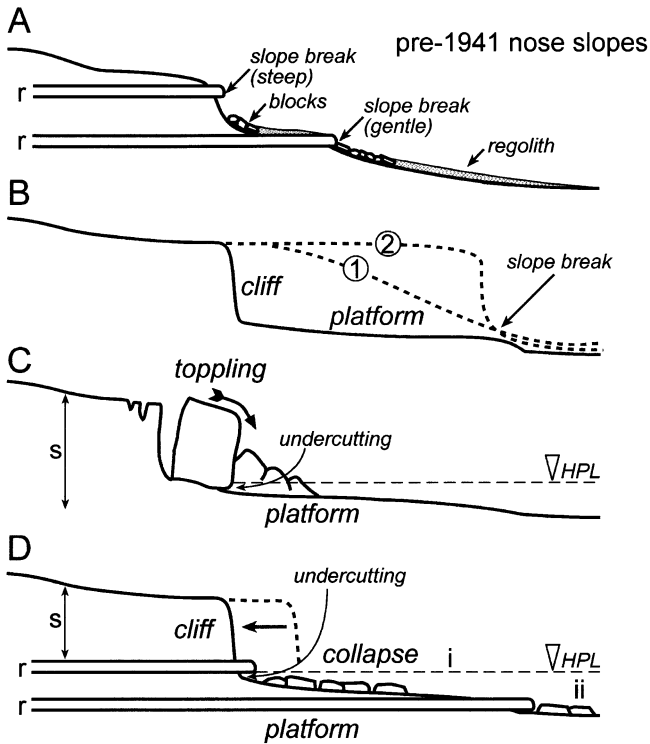


Figure 2. Development of shoreline cliffs and platforms and mechanisms of shoreline retreat at Lake McConaughy. A) Model for pre-1941 configuration of lakeshore nose slopes with preexisting slope breaks forming stepped profiles. Aerial photos from 1938/1939 show that both steeper and shallower slope breaks were present where resistant strata (r) cropped out at the eastern end of the southeastern shore of the lake, although many slopes were smooth and lacked outcrops. Regolith, mostly colluvium and slopewash, possibly with small amounts of loess and/or eolian sand, very likely covered part of stepped slopes, as shown, and all of the smooth slopes. Wave erosion and subsequent mass wasting produced erosional platforms immediately below and in front of pre-1941 slope breaks. B) Post-1941 erosion of platforms by retreat of either (1) a low-angle nose slope, or (2) a preexisting scarp/steep slope break. Aerial photo sequences suggest that both processes took place. C) Toppling of large blocks of soft bedrock (s) and soil after undercutting by wave action at high pool level (HPL), as observed in recent serial visits to the shoreline. D) Undercutting of resistant strata (r) within softer bedrock (s) by wave action at high pool level (HPL), also observed in serial visits to the shoreline. Cliff retreat similar to that shown in B (2) is also interpreted to occur simultaneously.

Differential Weathering of Bedrock

Both sandstone and siltstone strata in the Ash Hollow Formation show a conspicuous preferred direction of differential weathering, which we refer to hereafter as cementation grain (Figure 3B). With the exposure and differential erosion of many of these strata along the lake's shore, a pronounced pattern of elongate, low, rounded, WNW-ESE- and ENE-WSW-trending ridges becomes visible in bedding-plane view. These ridges are 10–50 cm wide and several meters long (Figures 3B and 4). These ridges are the upper surfaces of irregular, rod-

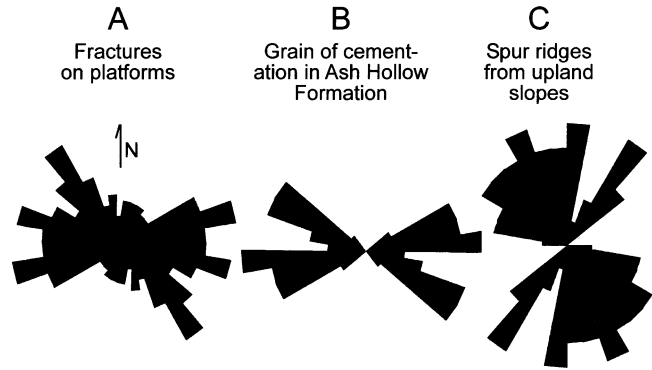


Figure 3. Rose diagrams showing orientations of features measured in the field (A, B) and on maps (C). A) Preferred NW-SE, WNW-ESE, and WSW-ENE orientations of fractures measured on erosional platforms. B) Preferred WNW-ESE and WSW-ENE orientations of grain of cementation (i.e., rod-like cemented masses) in Ash Hollow Formation exposures around shore of Lake McConaughy. C) Orientation of spur ridges from upland slopes along the southeastern shore of the lake, which terminate as lakeshore headlands and are eroding landward. Note similarity between orientations in (A) and (B).

shaped masses that are more strongly cemented with calcite than the sediment surrounding them. Similar cemented features (so-called pipy concretions) have been described in great detail from other Tertiary strata in western Nebraska and have been attributed to ancient groundwater flow patterns (Schultz, 1941).

SHORELINE GEOMORPHOLOGY

Aerial photos from 1938/1939, before Kingsley Dam was completed, show slope breaks associated with the outcropping of resistant strata on nose slopes and side slopes along the southern side of the North Platte Valley, which would eventually become the southeastern shore of the lake. These slope breaks range from slight (barely discernible) to sharp (obvious scarps). Today, similar hill slope morphologies can be viewed on the south side of the valley outside the present area of the lake. Nose slopes on dominantly NNW- to SSE-trending spur ridges (Figure 3C) are being actively eroded by waves on the southeastern shore of the lake.

The most prominent geomorphic features exposed by low lake levels during 1999–2003 are bedrock platforms extending lakeward from headlands on the shore (Figure 5). Other lake-related landforms can also be observed. The geomorphic features on the southeastern shore are listed below, in approximate order of prominence.

1. Platforms (Figures 5A, 5B, and 6) are nearly flat to gently lakeward-sloping (1° – 10°) bedrock surfaces that extend from vertical cliffs outward into the lake. Platforms appear on the nose slopes of spurs extending from upland ridges, which are now headlands



Figure 4. Pronounced grain of cementation (rod-like masses) in Ash Hollow Formation along shore of Lake McConaughy. Preferred orientation of cementation is shown in Figure 3B. Field of view in foreground is about 3 m wide.

projecting into the lake. The landward termini of platforms at the bases of cliffs or shoreline scarps are block aprons, or piles of mass-wasted blocks with angles of repose of 12° – 25° . Platforms would be entirely covered by water (and therefore invisible) at maximum pool level, and their landward termini at the bases of cliffs correspond with the maximum-pool water line. Platforms are partially covered by large (as much as 4 m in maximum dimension) tabular blocks of resistant strata that correspond with a continuous, *in situ* resistant stratum upslope in the associated cliff face. The arrangement of blocks is a loosely fitted pattern, illustrating that they were let down *in situ* by the removal of soft sediments underneath the resistant stratum upslope and then remained essentially unmoved by wave action. This process can be observed in action at many places.

Many platforms appear to consist of a single sloping surface, but several show two distinct levels separated by a low scarp (<1.4 m high), and some appear to show multiple levels (at least four). No preferred geographic distribution of multiple-level platforms could be discerned. Rather, they exist in close proximity to

single-level platforms. Any given platform as a whole, whether multi-level or single-level, ends lakeward with a low scarp of 15° – 31° . Platforms range in total shore-normal length from 20 to 266 m, but almost all are between 20 and 80 m long. Some of the longest platforms appear where the slope of dominantly NNW- to SSE-trending spur ridges (Figure 3C) is shallowing lakeward, and the thickness of erodible bedrock above lake level is therefore decreasing.

2. Shoreline scarps and cliffs are present over much of the lake's southeastern shore. Some, but definitely not all, were slope breaks before the reservoir existed; others are definitely features that have appeared since 1941 (Figures 7A, 8A, and 9–12: NS), and in some places 1938/1939 steep slope breaks were actually buried by beach sediments or bayfills. At nine sites pre-1941, slope breaks could be matched with shoreline scarps, cliffs, or headlands in the 1993 DOQs. In these positions, the 1993 slope breaks were landward of their pre-1941 equivalents. Therefore, it can be concluded that slope breaks eroded landward as lake level rose and as wave erosion continued because recession occurred parallel to the original scarp line

A



B



Figure 5. Erosional bedrock platforms on southeastern shore of Lake McConaughy. A) A well-developed platform 113 m in length, and an associated retreating cliff about 10 m high, on the east side of Ogallala Beach (see Figure 10); paving of large blocks (foreground) covers the next platform to the west. Note the pocket beach between adjacent platforms. B) Platform, about 50 m in length, and cliff immediately northeast of the corner of sections 4, 5, 8, and 9, T.14N., R.38W., looking east-northeastward (see Figure 12); note single-story dwelling (right) atop spur ridge from which cliff has been eroded. Several dozen private residences have property lines that abut lakeshore; at least four residences have recent construction work designed to compensate for or slow beach erosion.

and because no causative factor other than wave erosion can be identified. Measurements made on-screen within a GIS project indicate headland recessions at these points ranging from 12 to 61 m, with a mean of 35 m. These recessions clearly took place between 1939 and 1993.

Topped blocks are comparatively large (some exceed 10 m^3) and have roughly equal dimensions or are slightly taller than wide, setting them apart from the tabular blocks produced by undercutting. Topped blocks appear at retreating cliff fronts and typically consist of relatively very soft sedimentary rocks and soil (Figure 13), rather than resistant strata. They almost always have an upper surface covered by soil and turf, which invariably includes living grass. Furthermore, recently dead or still-living fallen trees appear along cliff fronts adjacent to some blocks.

3. Steep, blocky shoreline segments (Figure 7A) are, in effect, laterally continuous block aprons along the side slopes of spurs extending toward the lake from upland ridges. They have relatively high slopes ($\geq 15^\circ$). The blocks covering these shoreline segments are again derived from the resistant strata described previously, but the blocks are more random in their orientation and have a less fitted arrangement than those that pave platforms. There are a few shoreline segments that are practically intermediate in characteristics between platforms and steep, blocky shores; in other words, they are short platforms with very pronounced landward block aprons. Where true steep, blocky shore

segments exist, however, there are no sheer cliffs landward. Many of the steep, blocky shoreline segments match with pre-reservoir breaks in slope.

4. Pocket beaches are small ($\sim 50\text{--}150 \text{ m}$ wide), arcuate, sand-dominated beaches positioned between, but a few to several meters below, adjacent wave-cut platforms (Figures 5A, 7A, 7B). They partially fill small, drowned valleys between spur ridges extending down from the uplands. Whereas platforms are erosional in origin, pocket beaches are the corresponding depositional features built by the redeposition of resultant sediments. Pocket beaches grade in size into larger bays, where upland drainages, typically ephemeral in flow, enter the lake. Bays, too, have partially filled with sediments derived from adjacent headlands.

Pocket beaches slope lakeward at gentle angles ($2^\circ\text{--}5^\circ$), merging smoothly with the lake shelf, the sand-veneered, shoreline-parallel zone lakeward of the margin of bedrock platforms. At maximum pool level, the lake shelf zone is under more than 10 m of water in most places. The lake shelf varies in slope (approximately $5^\circ\text{--}30^\circ$) in accordance with the hill slopes along the shoreline.

The stratigraphy of pocket beaches is complex, and at least 2 m of beach sediments exist under most pocket beaches. Alternating layers of well-sorted medium sand—sometimes with clear, low-angle ($1^\circ\text{--}2^\circ$), lakeward-dipping cross stratification (primary beach stratification)—dominate, but decimeter-scale layers of rounded pebbles to cobbles of soft siltstone and

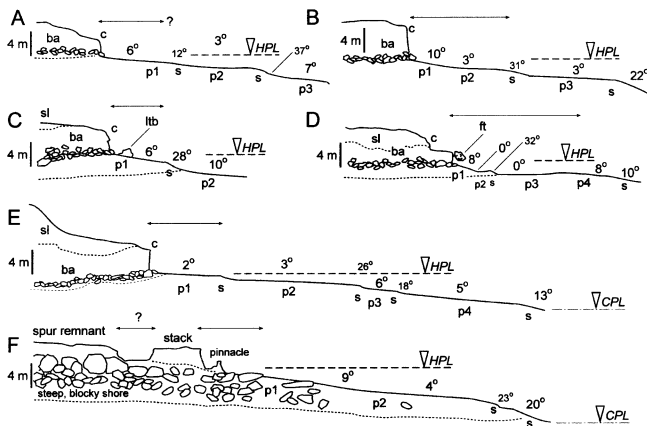


Figure 6. Profiles of selected bedrock platforms (p), intervening small scarps (s), associated cliffs (c), vegetated nose slopes (sl), and block aprons (ba) relative to high reservoir pool level (HPL) and 2002 level (CPL); all are arranged with the lake to the right (approximately north). Horizontal, double-headed arrows delimit the area most likely to have been produced by active cliff retreat since 1941, whereas the remainder of the platform is more likely to have been produced by pre-lake erosion and/or erosion during filling of the lake. Successive platform levels are numbered (e.g., p1, p2, p3). A) Platform at “Alcatraz” (see Figure 12), drawn from reversed photomosaic. B) Platform on west side of Ogallala Beach (see Figure 12). C) Platform in NW ¼ NW NW ¼, section 8, with large, recently toppled block (ltb) in front of cliff (see Figure 11). D) Platform and cliff with fallen, but still living, cedar tree (ft) indicating recent mass movement of large blocks, near point “V” in Figure 12. E) Platform in SW ¼ NE ¼ NW ¼, section 8, T.14N., R.38W. (see Figure 11). F) Platform in NE ¼ NE ¼ NE ¼, section 9, T.14N., R.38W. (see Figure 12). Erosion of the spur ridge from the upland has produced a small stack and pinnacle, as well as part of a platform. To the south (left), the platform merges into steep, blocky shoreline that is probably in large measure a pre-1941 relict landscape feature.

sandstone are also common. Pebbles and cobbles are typically flat owing to the grain of original sedimentation and cementation. These pebbles are also usually scattered over the sandy surfaces of beaches and locally form small patches or “shingle beaches” by themselves. None of the characteristic sediment on beaches and in bays was present before 1941.

Beach erosion scarps (Figure 7A, 7B) as high as 1.5 m are ubiquitous near the shoreline. These scarps were observed in the process of formation during serial visits throughout the extreme drawdown period of 1999–2003, and there is no evidence that they existed prior to that time. Shore-parallel crown cracks were repeatedly noted within 2 m landward from a given scarp. Two modes of failure were witnessed directly on time scales of hours to a few days: (1) undercutting of scarp toes by waves, causing collapse of slabs of wet beach sediments; and (2) slumping of the scarp edge as groundwater seeped downslope out of pocket beach sediments—in effect, small-scale groundwater sapping.

Beach ridges (Figure 7C) appear in all pocket beaches and bays, and are even visible in the 1993

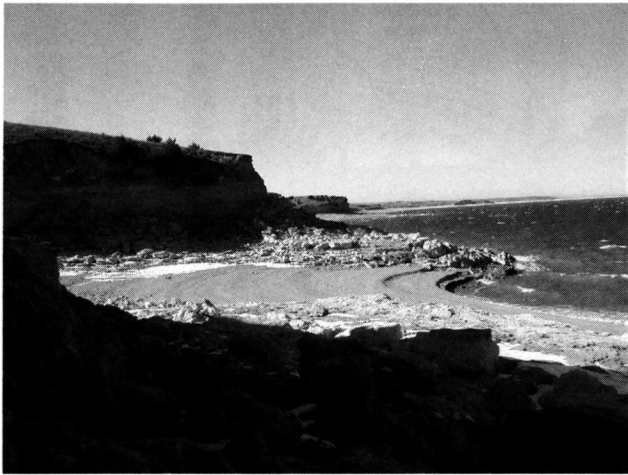
orthophoto quadrangles, wherein beach ridges in bays are as long as 400 m, and equivalent shore-parallel features along non-embayed stretches of coastline can be traced for at least 1400 m. At ground level, beach ridges are well-delineated, low terraces about 10–50 cm high and 100–200 cm wide. They appear in concentric groups of 10–20 and are spaced 3–10 m apart. They corresponded to successive lake stands as drawdown progressed.

5. Caves and shallower alcoves extend horizontally under sheer cliff faces, frequently at the landward termini of wave-cut bedrock platforms, but also along the side slopes of some lakeward-extending spur ridges marked by either narrow platforms or cliffs. They are 1–3 m high at their openings and narrow very rapidly into the cliff side: none of them are extensive, although several are large enough to barely accommodate several seated persons. Cave and alcove development occurs in soft siltstones or sandstones that are overlain by slightly more resistant layers, usually a horizon bound loosely by calcareous and siliceous rhizoliths. All caves appear just above the maximum pool-level waterline, where wave erosion would be concentrated. Shallow alcoves are the most common of the two features. Caves are subject to collapse and blockage by block fall as shoreline mass wasting proceeds. The most extensive caves seen in the study were, in fact, blocked by mass-wasting debris from the overhanging cliff within 2 years after our first observation.

Small, shallow caves (alcoves and rock overhangs) are common on the south side of the North Platte Valley near the study area but away from the lake. Ash Hollow Cave, a larger cave feature south of the western end of Lake McConaughy, has yielded Native American artifacts dating back to the Woodland Period (around 1–2 ka), but may itself be as old as mid-Holocene (Champe, 1946; Rob Bozell, Nebraska State Historical Society, personal communication). Such caves are larger and more extensive than the shoreline caves at Lake McConaughy, and also have a much more prominent overhang of resistant bedrock stratum.

6. Dunes (Figure 8) have formed near the western end of the southeastern shore and westward onto the southwestern shore, where the shoreline is smoother and where extensive low-angle sandy surfaces are relatively unbroken by platforms and block aprons. Direct observation by one of the authors (R.F.D., Jr.) and interviews with local residents indicate that these dunes did not exist on formerly submerged surfaces prior to recent, sustained falls in pool level. These new dunes are not covered by vegetation and were observed in the process of growth and migration during the period 1999–2003, as sand was blown from adjacent, exposed beaches and lake shelf. Late Pleistocene or Holocene

A



B



C



Figure 7. Pocket beaches and related features. A) Pocket beach between two eroded platforms, looking westward. Three successive beach erosion scarps, representing progressive levels of reservoir drawdown, are visible. Note short erosional platform and cliff in background, which trend into a steep blocky shoreline to the left (south-southeast). B) Close-up of actively eroding pocket beach scarp in (A), photographed in November 2000. R. F. D., Jr., is 1.7 m tall. C) Beach ridges, partially delineated by rows of vegetation, in the bay infilling with sand, W $\frac{1}{2}$, NW $\frac{1}{4}$ of section 7, T.14N., R.38W., and E $\frac{1}{2}$ NE $\frac{1}{4}$, section 12, T.14N., R.39W., looking westward (see Figure 10). Field of view is roughly 200 m wide. At least 20 beach ridges, representing successive lake levels, are visible (September 2001).

dunes existed on the floor of the North Platte Valley prior to flooding by Lake McConaughy, but these features appear to be inactive and completely vegetated in late-1930s aerial photographs.

Eolian reworking of exposed beach sediments occurs today all around the lake's shore, as evidenced by ubiquitous wind ripples (or adhesion ripples on exposed, moist surfaces immediately adjacent to the current lake shore); localized pebble lags (where rare pebble conglomerates of the Ash Hollow Formation have supplied coarse sediment to beaches); and small (<20 cm high) drifts formed in the lees of eroded bedrock blocks and other obstacles.

The most common dunes are (1) low (<30 cm) and coppice-like that form around vegetation and (2)

similar low (10–30 cm) but broad-crested (80–250 cm) dunes with wavelengths of 8–11 m that form between immature cottonwoods on newly vegetated parts of the shore. Much larger dunes appear near the western boundary of the rocky southeastern shore (N $\frac{1}{2}$ SW $\frac{1}{4}$, section 2, and immediately adjacent part of section 3, T.14N., R.39W.) against the sheer cliffs (Brule Formation siltstone overlain by a resistant basal calcrete of the Ash Hollow Formation) of a projecting NNW-SSE-trending headland. A discontinuous linear dune 3 m high has accreted directly at the foot of the cliffs and within 5 m of its base. A seawall built in this area was partially covered by windblown sand within a year of its completion.

A



B



Figure 8. Dunes along the southeastern shore of Lake McConaughy. A) Linear dune approximately 3 m high forming along the cliff containing contact between the Brule Formation (below) and Ash Hollow Formation (above) in S $\frac{1}{2}$ NE $\frac{1}{4}$ SW $\frac{1}{4}$, section 2, T.14N., R.39W. (September 2001). B) Wind-rippled, coppice-like dunes forming among sparse cottonwoods (*Populus deltoides*) along exposed beach nearby; a 2-m measuring rod is in the foreground (August 2002).

The reworking of exposed beach and lake shelf sands has been observed directly on multiple occasions. During a 2-day period of sustained northwesterly winds exceeding 30 kph November 28–29, 2000, for example, we recorded the migration of wind ripples; the movement of sand over small, coppice-like dunes; and a layer of rolling and saltating sand on the exposed beach and lake shelf visible from distances of 2 km.

7. Stacks are rare erosional knobs or pinnacles of bedrock isolated from the shoreline/uplands and surrounded by beaches and bedrock platforms. All indications suggest that they were attached to the spur ridges of upland slopes prior to the existence of the lake, and 1938/1939 air photos show that some of these features were preexisting knobs. The surface on which at least one of the stacks lies slopes landward, as if a saddle originally existed on the spur ridge from which the stack was formed.
8. Potholes are very minor but common features and provide further evidence of recent erosion. They are roughly circular holes atop bedrock platforms and are as much as 3 m in diameter and as much as 50 cm deep. Potholes are usually developed in very soft, sandy siltstones immediately underneath a resistant stratum and sometimes contain pebbles or cobbles that were either passively trapped or served as erosional tools under the influence of waves.
9. Gullies, surprisingly, are only rarely observed on the exposed shoreline and lake shelf since the fall of 2000. Only in a few places has overland flow been concentrated to the point of producing significant erosion.

In one case a gully 1.5 m deep eroded headward from the exposed lake shelf and threatened to undermine a 30-cm thick poured-concrete boat ramp. This gully was filled in and does not appear to have created additional problems since.

The distribution of erosional features and dunes on the southeastern shore is shown in Figures 9–12, which are derived from the GIS project.

PREVIOUS OBSERVATIONS OF EROSION

Background quantitative data relevant to the finer points of shoreline erosion at Lake McConaughy, to our knowledge, do not exist, and a consistent and reliable oral history of shoreline erosion proved exceedingly hard to find. R. Knaggs, retired superintendent of Kingsley Dam, observed the following aspects of shoreline erosion around Lake McConaughy merely between 1982 and 2001:

1. Undercutting, collapse, and disintegration of a 12 \times 15 ft (3.7 \times 4.6 m) steel-reinforced concrete boat-landing slab extending from a bedrock headland at the K-1 Cabin Area (see Figure 12). This site was visited by one of the authors and now shows only jumbled fragments of the slab, in such a state of ruin that they give no indication of the original design of the structure.
2. Wave erosion of an isolated bedrock stack called “Alcatraz” or “Monkey Point” (W $\frac{1}{2}$ NW $\frac{1}{4}$ SW $\frac{1}{4}$, section 3, and E $\frac{1}{2}$ NE $\frac{1}{4}$ SE $\frac{1}{4}$ SE $\frac{1}{4}$, section 4, T.14N., R.38W.; see Figure 12) on the south side of the lake near Kingsley Dam. This feature was

Change Around Lake McConaughy

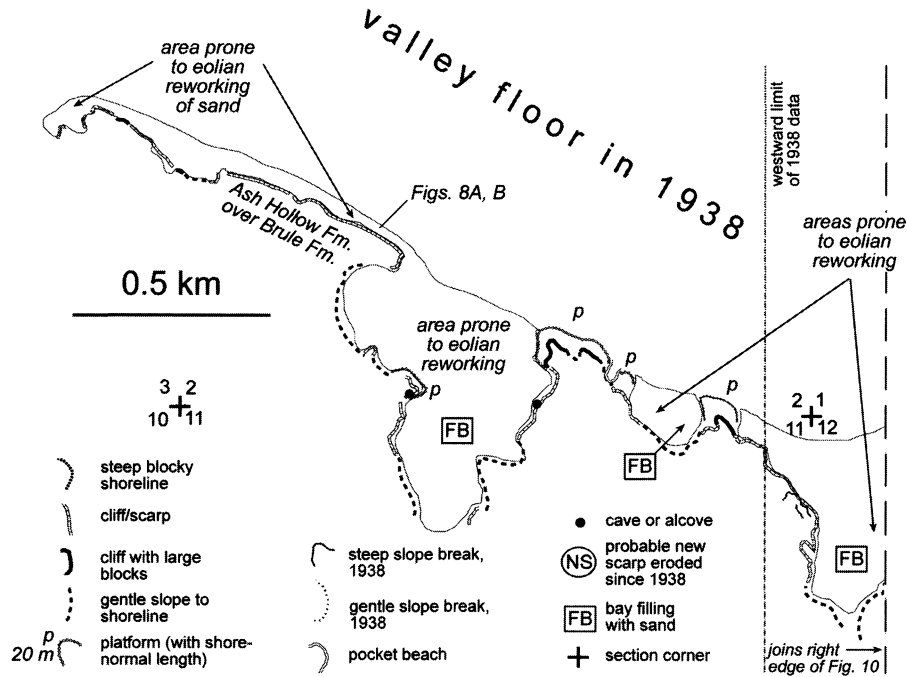


Figure 9. Map of first segment of southeastern shore of Lake McConaughy (see Figure 1 for location). In Figures 9–12, NS refers to new slope breaks that have formed since Kingsley Dam was completed in 1941.

formerly a projecting headland and is now a bedrock platform (underwater at normal pool level) with a low lakeward prominence (barely emergent at normal pool level). Together, the two features become a tombolo at low to very low pool levels. A 1941 oblique aerial photo of the site in Richter (2002, p. 64) shows that this area was a steep rocky slope prior to the filling of the lake, and that there was no platform at that time.

3. Complete erosion of now-unidentifiable bedrock stacks at Brown's Bay and Million Dollar Bay (see Figure 12).
4. Erosion of a 50–75 ft wide (15.2–22.2 m) stretch of sand beach at Van's Campground near the middle of the south-central shore of the lake.

Systematic data about waves on Lake McConaughy are also lacking. Nonetheless, the erosive potential of wind-generated waves is strikingly illustrated by the results of high winds (as much as 65 mph, or 104 kph) blowing parallel to the long axis of the lake during a singularly noteworthy storm May 1, 1972 (Anonymous, 1972; Eddy, 1972; and Richter, 2002). At the time, one authority sensed “no imminent danger of failure,” yet the intensity of wave erosion during the event was clearly high. Wind-driven waves (according to some observers about 3.5 m high) broke over the crest of Kingsley Dam, and the estimated volume of materials washed out of the face amounted to only 0.2 percent of the total volume of fill in the entire dam, although they were in a critical position

within the structure. Nebraska Highway 61 (which crosses the dam's crest) suffered major damage and was temporarily closed, and residents of the community of Keystone, NE, below the dam were evacuated.

GROUNDWATER AND SOIL SALINIZATION

Monitored wells in alluvial sediments along the North Platte River showed progressive rises in the water table as the lake filled in the 1940s and 1950s (Figure 14), but these changes are not readily apparent on a county-scale map (Figure 15). There are anecdotal references to springs developing down gradient from the lake, but these claims could not be verified. Major rises in local water tables have occurred 170–250 km east-southeast from the lake along canals that are a part of the CNPPID irrigation system, of which Lake McConaughy is the key element (Figure 16).

One indirect consequence of elevated water tables near the lake is the soil salinization that has appeared on tracts of exposed lake floor near the western end of the reservoir (Figures 17 and 18). These areas were formerly underwater, but water tables remain high even after drawdown and exposure, and groundwater is being discharged diffusely by capillary wicking and evapotranspiration. Widespread, fluffy surface efflorescences of thenardite (Na_2SO_4) appear in these areas between rainfall events in dry weather, and the exposed lake floor has also been colonized by patches of redroot flatsedge (*Cyperus erythrorhizos*) since

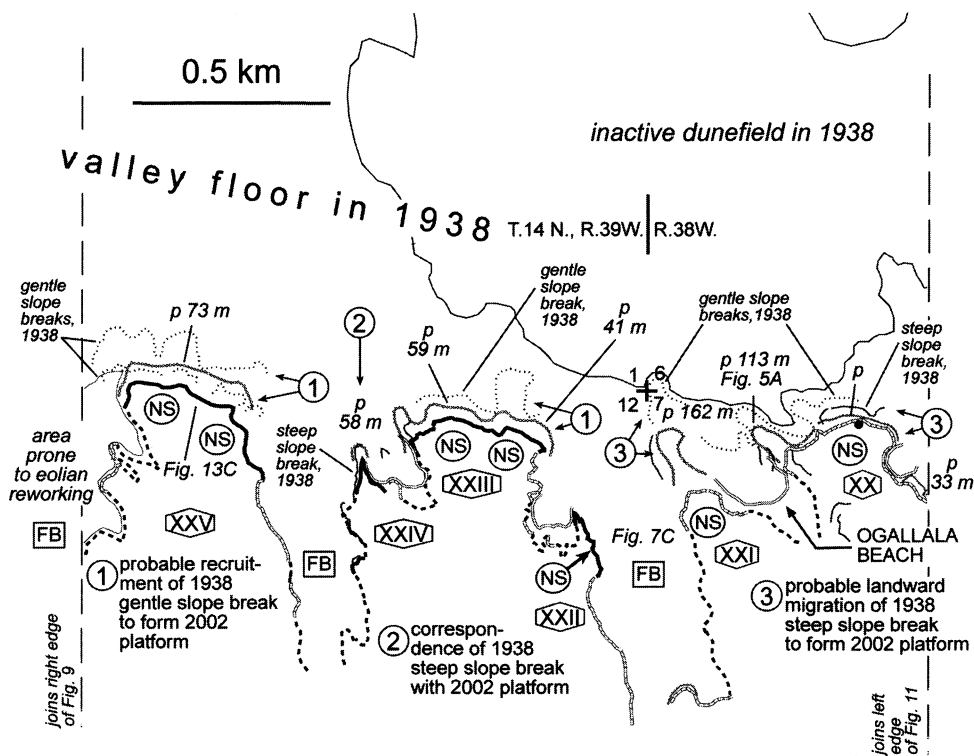


Figure 10. Map of second segment of southeastern shore of Lake McConaughy (see Figure 1 for location). Inactive dune field on floor of North Platte Valley probably dates to Holocene and was vegetated in 1938/1939. Points useful as landmarks, numbered westward from Kingsley Dam, are identified by Roman numerals. Circled Arabic numerals refer to particular scenarios of shoreline feature development. See Figure 9 for general symbol key.

its exposure. Horizons of microbial sulfate reduction appear just below the exposure surface as long as the soil remains moist (Figure 18).

On a smaller scale, mild erosion by small channels, fed by groundwater discharge as lake levels are being drawn down below the level of pocket beaches, could be observed along most of the southeastern shore in August 2002. Common, small (10–30 cm deep and as much as 200 cm wide) channels with amphitheater-like headwalls appear as groundwater is discharged along the present shoreline. Headwall erosion by groundwater sapping can be observed directly in these features. Water tables elevated by the presence of the lake are thus falling continuously as drawdown proceeds, and groundwater is returning to the lake as surface runoff. In comparison, gullying of exposed beaches and lake shelf by rainfall-fed overland flow is rare, although individual cases are dramatic, sometimes producing channels over 1 m deep and partially undermining concrete slabs or other structures.

NORTH PLATTE RIVER AND DELTA

Major changes have occurred in the North Platte River at the western end of Lake McConaughy and upstream. The most prominent of these changes are (1) decreases

in the braiding, number of channels, and total width of the North Platte River immediately upstream from the western end of the reservoir; and (2) the appearance of a sandy delta at the western end of the lake (Figure 19). A single bedload sediment analysis of a sample taken at Lewellen, NE, immediately upstream of Lake McConaughy (U.S. Geological Survey, undated) indicates that the delta should be dominated by coarse sand.

Channel width in the North Platte River immediately upstream from the future Lake McConaughy ranged from 460 m in the broad, shallow stretches lacking large, semi-permanent sandbars to 700 m in the intervening, highly braided intervals (Figure 20A). Braided intervals were characterized by 10–13 channels separated by multiple, mobile bars generally 20–80 m in width. By 1952, when the lake was filled for the first time, the width of the stream was comparable to 1938, but the number of through-flowing channels had decreased, and most of the braided intervals and bars were generally 70–170 m in width (Figure 20B). Examination of air photos indicates that these changes took place through the abandonment of smaller channels, the stabilization of bars by vegetation, and the resulting amalgamation of small bars with larger ones (Figure 20B: ab). By 1960, most of the change in the North Platte River had occurred: braiding

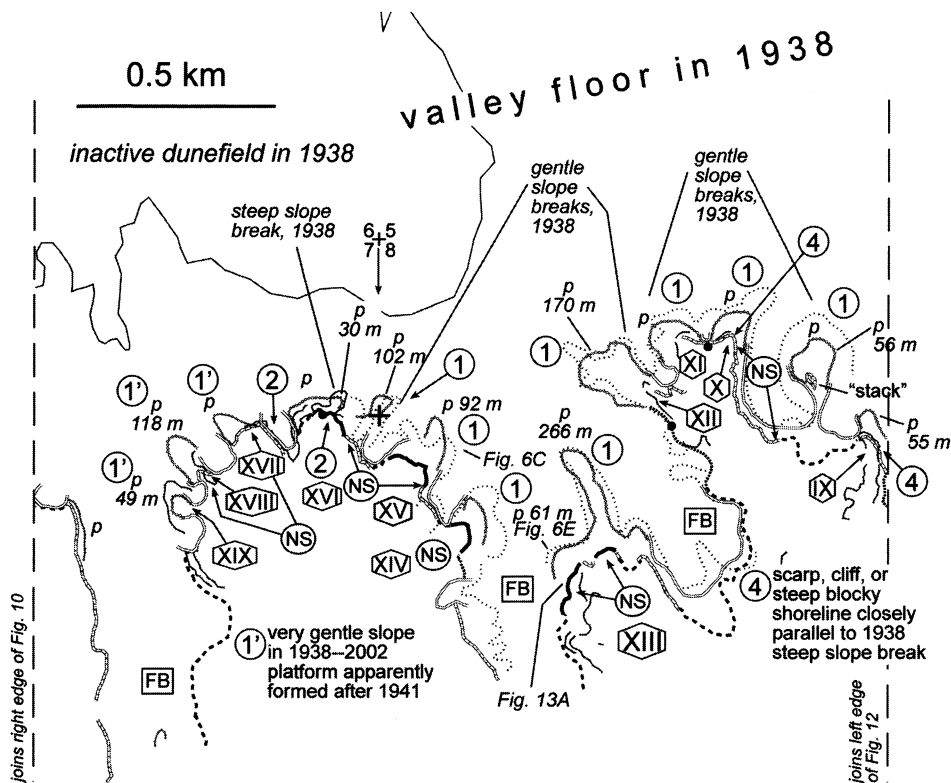


Figure 11. Map of third segment of southeastern shore of Lake McConaughy (see Figure 1 for location). Points useful as landmarks, numbered westward from Kingsley Dam, are identified by Roman numerals. Circled Arabic numerals refer to particular scenarios of shoreline feature development.

had decreased markedly and stable islands had formed from amalgamated bars (Figure 20C: si). By the 1990s, channel width had fallen to 180 m or less in unbraided stretches and 450 m in braided stretches (Figures 19A, 19B, and 20D). At that time, five or fewer channels were present in the braided stretches, and the number of bars had decreased dramatically, and stable islands had taken their places (Figure 20D: si). Only two distributary channels (Figure 20D, dc1 and dc2) feed the delta today.

The North Platte delta probably prograded at least 4 km between 1952, a year after peak storage was first reached, and 1993, although changing lake levels in different aerial photographs render an exact assessment of delta size very difficult. Significant stream morphometric changes at the head of the incipient delta are visible in 1952 air photos: in addition to the changes described above, the incipient delta also shows the formation of numerous, small accessory channels (Figure 20B: ac) that link multiple, relatively straight distributaries.

DISCUSSION

Shoreline Erosional Processes

The following discrete processes have been determined to be active on the basis of serial visits to the lake's shore over a period of years:

1. Undercutting of cliffs by the erosion of soft sedimentary rocks underlying resistant, carbonate-cemented and/or rhizolith-bound layers. Wave action is the dominant process in undercutting, the visible effect of which is typically a horizontal notch along the shoreline at normal pool level. Landward, piping may also contribute to this process. Undercutting produces generally rectangular talus blocks a few meters long, which litter the surfaces of platforms; these blocks are typically slab-like because of the tabular geometry of the resistant beds from which they are derived. Wave refraction by headlands and submerged platforms can be observed directly in historic aerial photographs (Figure 21). This relatively moderate refraction around projections from headlands is comparable with the interaction of much larger waves with both headlands and submarine ridges along marine coasts (Coastal Engineering Research Center, 1984, pp. 2–73).
2. Undermining and collapse of single resistant strata on and at the landward termini of the relatively low-angle bedrock platforms. Resistant strata can be surmised to undergo gradual *in situ* collapse as soft siltstones or sandstones are eroded from underneath them. Eroded blocks of resistant strata are typically several decimeters to a few meters in maximum dimension and

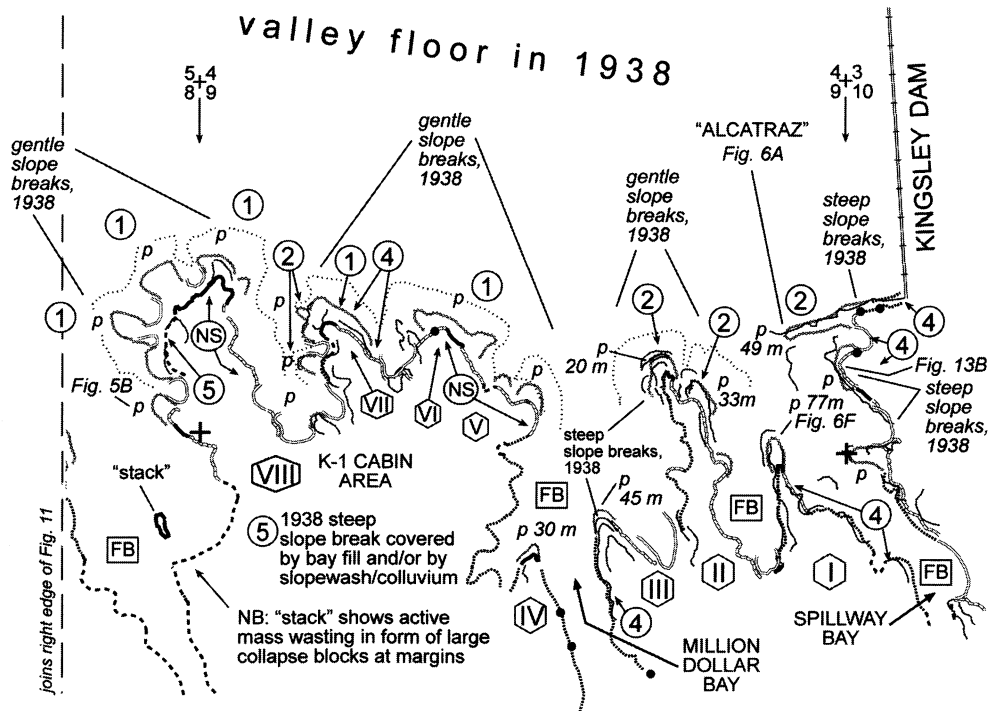


Figure 12. Map of fourth segment of southeastern shore of Lake McConaughy (see Figure 1 for location). Points useful as landmarks, numbered westward from Kingsley Dam, are identified by Roman numerals. Circled Arabic numerals refer to particular scenarios of shoreline feature development. See Figures 9 and 10 for symbol key and explanation.

are too massive to be moved by lake waves. Once collapsed, they probably have a slight armoring effect with respect to further erosion, but spaces between blocks still allow the erosion of other softer materials underneath, much like the erosion expected from an inadequate filter blanket installed on an artificial embankment.

3. Activation of fractures as the recession of cliffs proceeds landward. The exact origin of fractures remains unclear, but the coincidence of roughly WNW-ESE orientations in fracturing and cementation grain with the overall trend of the lake's shore seems to enhance shoreline mass wasting. Failure along these fractures can be observed directly.
4. Toppling of blocks on cliff faces following undercutting (Figure 13). Most of these blocks consist of materials that are soft enough to be slowly but steadily disintegrated by rain splash, overland flow, and slaking (at high pool levels). In 2 years of observation, some large blocks either were activated for the first time or rotated measurably during the several months between serial visits.
5. Freeze-thaw is likely to accelerate erosion near the shoreline, particularly in soft, porous sedimentary rocks that crop out near normal pool level. Such a process was not directly observed, but is likely to play a role given the presence of standing water and the typically cold winters in the region.

The present observation of these processes demonstrates that shoreline erosion is active and can explain part of the development of platforms and the retreat of the shoreline as a whole. It is likely that only the landward-most parts of platforms, usually identifiable by a break in slope (Figure 6), result from post-1952 recession of scarps or cliffs along the headlands. The independent estimation of 12–61 m of shoreline recession at nine points is much less than the >250 m length of the longest platform, although this range of estimates is comparable with the 20–80 m length of most platforms. Therefore, the landward movement of the lakeshore during 1941–1951 and the erosion associated with it must be called upon to explain some part of platform formation, rather than attributing the process to post-1951 wave erosion alone.

Post-1941 Evolution of Southeastern Shoreline

Platforms have no fully homologous equivalents on nose slopes along the North Platte away from the Lake McConaughy shoreline. Nonetheless, many nose slopes away from the lake today, and multiple nose slopes along the future lake shoreline in 1938/1939 aerial photographs, have stepped profiles that include relatively flat slope segments (Figures 2 and 9–12). These profiles resulted from the long-term differential erosion of strata of variable resistance within the Ash Hollow Formation

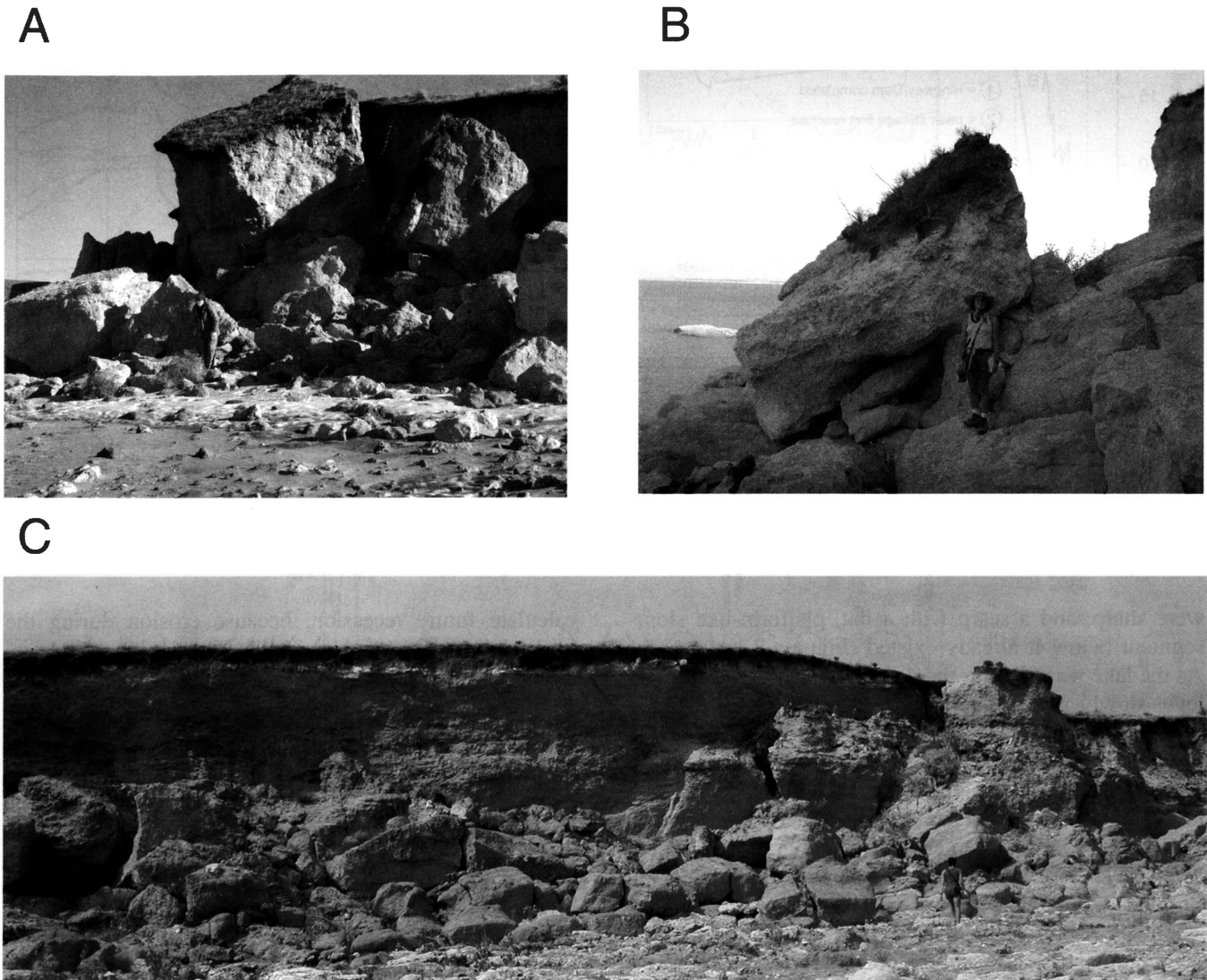


Figure 13. Recent topples of large undercut blocks along southeastern shore of Lake McConaughy. A) Large blocks of soft Ash Hollow Formation strata and soil, with intact turf cover, on cliff face at landward terminus of large erosional platform in S $\frac{1}{2}$, SW $\frac{1}{4}$ NE $\frac{1}{4}$ NW $\frac{1}{4}$, section 8, T.14N., R.38W. (November 2000; see Figure 10). R. F. D., Jr., is 1.7 m tall. B) Large, undercut block of partially cemented Ash Hollow formation, lying atop previously eroded blocks in SW $\frac{1}{4}$ NW $\frac{1}{4}$ SW $\frac{1}{4}$ SW $\frac{1}{4}$, section 3, T.14N., R.38W. (see Figure 12); Jamie Taylor is 1.55 m tall (August 2002). C) Very large toppled blocks of soft Ash Hollow Formation eroding from WNW-ESE trending headland in S $\frac{1}{2}$ NE $\frac{1}{4}$ NW $\frac{1}{4}$ NE $\frac{1}{4}$ and S $\frac{1}{2}$ NW $\frac{1}{4}$ NE $\frac{1}{4}$, section 12, T.14N., R.39W. (see Figure 10); Jamie Taylor (right foreground) is 1.55 m tall (August 2002). Prominence of mass wasting here probably resulted from coincident orientation of cementation grain and fractures (see Figure 3A and 3B).

and the tendency of resistant strata to produce low-angle slope segments. Side slopes in some places today and in 1938/1939 aerial photographs exhibit similar morphologies (Figures 9–12). Large, mass-wasted blocks occur immediately downslope from steep slope breaks where resistant strata crop out on both nose and side slopes away from the lake today. Pre-existing breaks in slope were recruited by wave action to produce platforms as they currently exist.

A few 1938 to 1941 oblique aerial and ground-level photographs of the Kingsley Dam site published in Richter (2002) show slope breaks along resistant layers in the Ash

Hollow Formation but do not show denuded slopes with well-developed platforms like those visible along the exposed shoreline during the 1999–2003 drought.

The number of levels in multi-level platforms is inconsistent from place to place, and therefore cannot be related simply to particular stands of the lake during drawdown or rise. Rather, multiple levels result from multiple resistant strata in one place.

Platform formation must have occurred in a sequence of several events. Nose slopes had pre-existing breaks in slope because of the presence of erosion-resistant strata in the Ash Hollow Formation. Locally, some breaks in slope

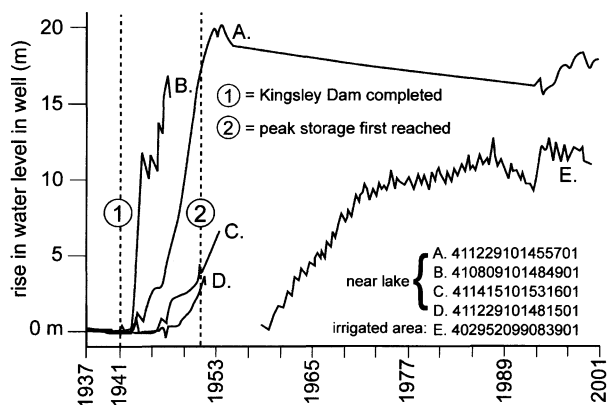


Figure 14. A–D) Hydrographs of selected monitored wells showing rising water tables around Lake McConaughy during attainment of maximum pool level (1941–1951) and thereafter (see Figure 1 for locations). E) Well in irrigated area of Kearney County showing rise in water table in vicinity of canal (see Figure 16A). Well numbers correspond to Nebraska Department of Natural Resources monitoring wells database.

were sharp, and a scarp with a flat, platform-like slope segment below it already existed (Figures 2 and 9–12). As the lake was filled in the decade following 1941, pool level slowly rose to the most prominent break in slope and was locked in at that particular geomorphic level. Two responses are likely to have resulted in such cases: a pre-existing steep slope break actually became the lakeward margin of a modern-day platform (Figures 9–12, Case 2), or a steep slope break migrated landward by wave erosion as lake level rose to form a platform (Figures 9–12, Case 3). Many nose slopes, however, were smoother and were likely to have been mantled by colluvium and slopewash; partially covered by thin loess or eolian sand (for which there is indirect evidence in 1938/1939 aerial photographs; Figures 10 and 11); or simply had not yet been eroded to produce scarps. During this first attainment of maximum pool level, however, waves along the prograding shoreline stripped regolith and soft bedrock from nose slopes and eroded landward, in some cases stepwise along horizontal planes determined by the position of resistant strata. Any existing flat slope segments atop resistant strata were readily recruited as erosion surfaces. As the lake’s level rose, inundation eventually destroyed the protective covering of sod on drowned slopes, and wave erosion continued behind the advancing shoreline as it moved landward until the former hill slope was below maximum wave base. Eroded sediment from nose slopes was rapidly moved by waves into the lees of nose slopes to produce pocket beaches and filled bays that had been produced from the valleys of small ephemeral streams draining into the North Platte Valley (aerial photographs indicated that this process was well under way by 1952). Therefore, total shoreline recession since 1941 cannot be used to

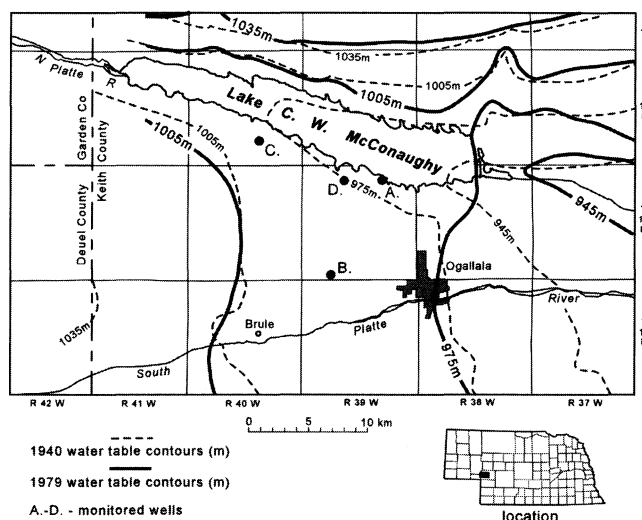


Figure 15. Water table elevations in the vicinity of Lake McConaughy in 1940 and 1979 (Source: Wenzel et al., 1941, and Conservation and Survey Division files).

calculate future recession, because erosion during the initial filling of the reservoir played a significant role.

Stacks, a special case of scarp and platform development, appear to have been inherited in even larger measure from the pre-reservoir landscape. Nonetheless, stacks are still undergoing wave erosion and mass wasting, so they are indeed being reshaped by current lake processes. Steep, blocky shoreline segments in many instances match with block-strewn slopes on pre-1941 aerial photographs. The blocks are typically far too large to be moved by wave action alone, and coupled with the relative steepness of the slopes they covered, served to “buffer” the effects of shoreline erosion, thereby showing much less geomorphic change than nearby platforms and cliffs/scarps. Furthermore, steep blocky shoreline segments tend to be along side slopes that are less subject to wave activity than are the lakeward ends of projecting headlands.

As far as we know, observers recorded none of the events we hypothesize above. However, they can be inferred on the basis of field observations, GIS work, and the examination of aerial photographs.

Other Lake-Related Changes

Rising water tables in the immediate vicinity of Lake McConaughy have been represented in a widely circulated map (Conservation and Survey Division, 2002), yet only a handful of monitored wells provided the data in the area of the lake. Therefore, a more comprehensive monitoring program would be needed before the full hydrogeologic effect of the lake could be determined. Individual wells very close to the lake definitely show

Change Around Lake McConaughy

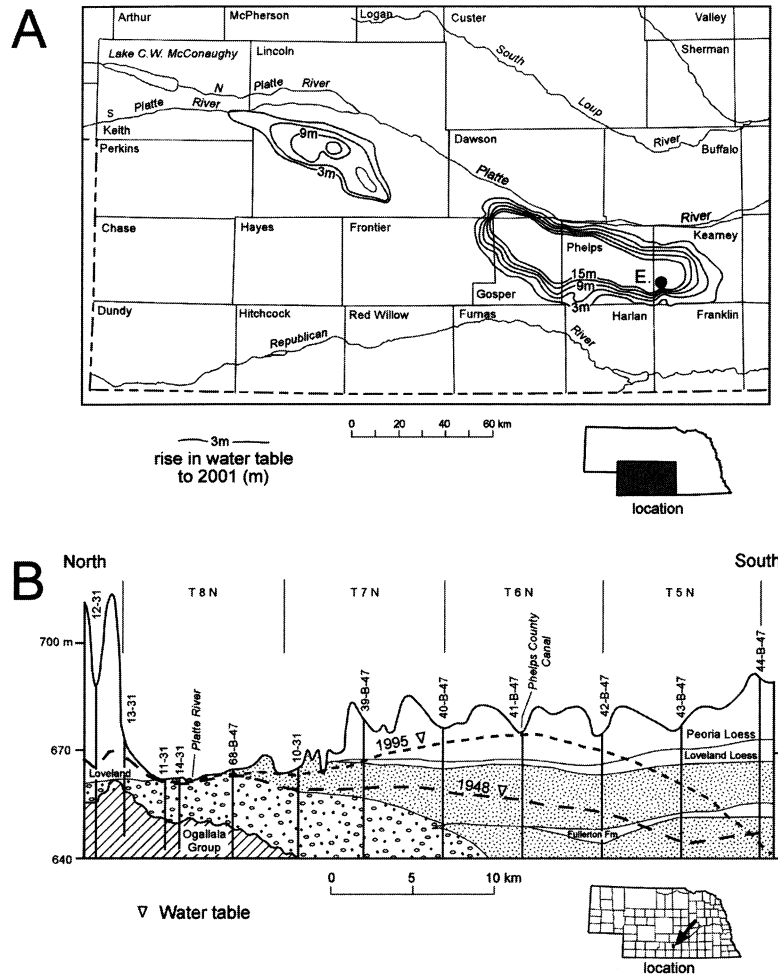


Figure 16. Disjunct hydrogeologic changes associated with Lake McConaughy. A) Historical rise in the water table of the irrigation system of which Lake McConaughy is the key element (Conservation and Survey Division, 2002); point labeled “E” is a well for which hydrograph is shown in Figure 14E. B) Rising water tables alongside an irrigation canal in the same system during period 1948–1995 (Summerside, 2003).

elevation of the water table corresponding in time with the filling of the lake. Nonetheless, the effects of the lake on county-scale water table elevations are less clear-cut, and definitely less striking (Figure 15). A more clear-cut trend, however, is the effect of Lake McConaughy–derived irrigation waters on regional water tables in Gosper, Phelps, and Kearney counties (Figure 16).

The accumulation of salts on the exposed floor of Lake McConaughy demonstrates not only rising water tables near the lake, but also the concentration of particular ions. Increasing levels of dissolved ions, coupled with the high water table created by the lake, set up the conditions necessary for the large-scale accumulation of surface salts by capillary wicking and evapotranspiration. Evapotranspiration flux is high in the Nebraska Panhandle, accounting for an estimated 81 percent of the total water output from that part of the North Platte River sub-basin in Nebraska lying upstream of the lake, according to modeling by Tangborn (1996).

North Platte River waters are relatively dilute in their content of dissolved solids, but Harvey and Sibray (2001) found that sulfate was by far the dominant ion in river waters upstream from Lake McConaughy, and several U.S. Geological Survey water analyses corroborate the observation that sulfate concentrations in the North Platte generally range from 160 to 200 ppm (U.S. Geological Survey, undated). Lake McConaughy has the potential, therefore, to enrich local groundwaters with sulfate on a large scale in the same way that irrigation canals upstream are changing the composition of shallow aquifers on a smaller scale (Harvey and Sibray, 2001). On the basis of the range of values of sulfate concentrations in North Platte River waters, the lake holds as much as 1.7 to 2.3×10^5 metric tons of dissolved sulfur at its maximum storage capacity. The prevalence of sodium sulfate (thenardite) in efflorescences on the lake floor reflects the movement of sulfur as sulfate ion through the local to regional hydrologic system. By promoting the activity of

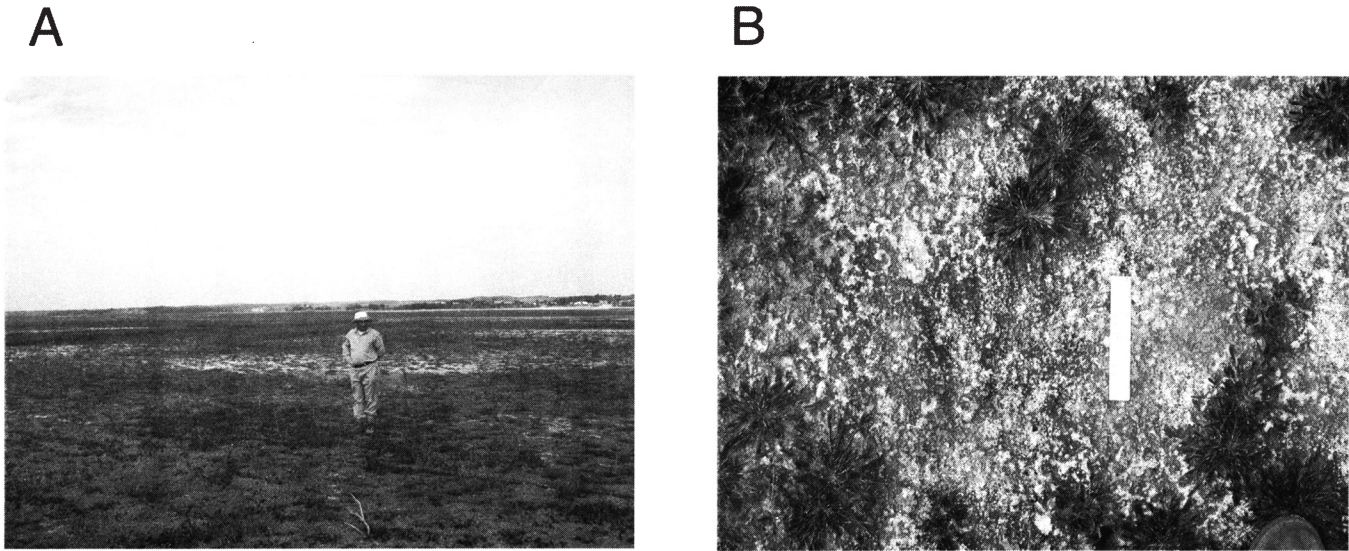


Figure 17. Surface salt accumulation, in essence anthropogenic salt flats, on exposed floor of Lake McConaughy (September 2001). A) Patchy efflorescences of thenardite (Na_2SO_4) and patches of flat sedge (*Cyperus erythrorhizos*), looking northward. B) Close-up of ground surface in the same area featuring fluffy masses of thenardite underlain by gleyed soil horizons showing evidence for sulfate reduction (see Figure 18). Scale is 15 cm long. Horizons of microbial sulfate reduction appear just below the exposure surface as long as the soil remains moist (Figure 16). Efflorescences are produced by evaporation after capillary wicking during dry episodes between rainfall events.

sulfate-reducing microbes in wet areas near the lake, concentration of sulfate ion can alter the fundamental ecology of polypedon-scale soil systems.

The concentration of sodium at the land surface, however, is a much larger concern in terms of soil properties, because it is the ion chiefly responsible for agricultural soil degradation in cases of anthropogenically elevated water tables (Sumner and Naidu, 1998). High concentrations of sodium sulfate salts are typically associated with the disruption and destruction of structure and the elevation of electrical conductivity/salinity, sodium absorption ratio (SAR), plant toxicity, and pH (Sumner and Naidu, 1998). However, salinization on the exposed floor of Lake McConaughy does not affect any lands currently under cultivation.

The Lake McConaughy delta grew on the remains of pre-1941 braid bars and abandoned channels. Delta growth at the western end of Lake McConaughy would have been expected under any circumstances, but the growth of the lake's delta and changes in the North Platte River immediately upstream provide a means of separating more well-defined influences on fluvial system change from influences such as climate, land use, and irrigation, whose effects are diffused across an entire basin. Historic changes in channel morphology (decreases in overall width and braiding index) have been described along much of the North Platte River (Williams, 1978; Eschner et al., 1983), but the changes described in this paper can be seen to evolve in time series in direct response to the elevation of local base level.

It appears likely that the stretch of the North Platte River immediately upstream from Lake McConaughy is

becoming an anastomosed stream (*sensu* Smith and Smith, 1980), because the islands first appearing in 1960 air photos (Figure 20C) seem to be relatively stable, as opposed to bars that would be inundated and migrate with flow at high river stage. Field observations near Wellen, NE, hint that vertical accretion may be occurring in this part of the river, but only an intensive coring study could verify this hypothesis. Lake-related channel changes exist at least 4 km upstream on the North Platte River, but separating the effects of the lake from the effects of basin-wide change more than several kilometers upstream on the North Platte River is difficult.

SUMMARY AND CONCLUSIONS

Shoreline Geomorphology

Landforms along Lake McConaughy's southeastern shore have a relatively complex history. Aerial photographs indicate that some hill slopes were already eroded according to the outcrop of resistant strata within the Ash Hollow Formation prior to the filling of the reservoir. Others, however, were not. The most characteristic pattern in erosion on the southeastern shore of the lake is (1) cliffs (typically with toppled blocks in front of them) and (2) associated platforms at eroding headland nose slopes, giving way laterally to (3) steep, blocky shore segments along side slopes. The lengths of platforms, which vary greatly, cannot be attributed solely to progressive retreat after peak storage was attained in 1951, although historical imagery indicates that a few to several tens of meters of cliff retreat probably have

occurred since the lake was filled, and observations of toppled blocks indicate that erosion is very much an ongoing phenomenon. Slope breaks corresponding to some current cliff-platform couplets already existed when Kingsley Dam was completed in 1941. Furthermore, denudation and erosional stripping of pre-existing stepped hill slopes (where resistant strata already cropped out in 1941) must have taken place as lake level rose during the period between 1941 and 1951. Our observations demonstrate that great caution should be exercised in the interpretation of shoreline erosion around a large reservoir, lest alarmist notions of exceptional rates of erosion arise. Furthermore, we conclude that soft strata with rare, thin, highly resistant layers, such as those at Lake McConaughy, can predispose a reservoir shoreline with moderate slopes to the characteristic pattern of erosion described in this paper.

Sites that now show evidence for mass wasting of large blocks of soft strata are likely to continue eroding landward as soon as lake level rises again. Most of these sites are at the ends of headlands that project into the lake, and therefore they receive the maximum wave energy imparted by winds with a northerly component.

Steep, blocky shorelines along Lake McConaughy, on the other hand, have been much more stable, and are likely to remain so for the lifespan of the lake, barring exceptional changes in management. Examination of historic air photos shows that several stretches of steep blocky shoreline have changed very little, if at all, since 1941. In these settings, large blocks of well-cemented sandstone cannot be moved by waves and erode only slowly, although water may still erode any *in situ* soft strata under the blanket of steep blocks.

The correspondence in orientation of many joint/fracture systems and the grain of cementation in soft Ash Hollow strata along the shoreline, as well as the orientation of the lake itself, appear to accelerate erosion on headlands. These factors may have been considered trivial, or more likely were unrecognized during the design of the reservoir. Cementation grain like that described in this paper could have an effect on the engineering characteristics of sedimentary rocks similar to that exerted by foliation and other secondary structures in metamorphic rocks, and probably should be considered at some level prior to the installation of a major engineering work.

Direct remediation (e.g., through the construction of seawalls or by widespread application of sprayed concrete) of even several selected parts of the southeastern shore is expensive, and therefore will always be limited in scale. Moreover, considering the magnitude of erosion, it would be impossible to effectively halt the process of shoreline erosion over a period of several decades by any reasonable scale of engineering effort. Maintenance of a lower pool level would decelerate wave erosion against headlands, but relatively rapid eolian erosion and re-deposition, as

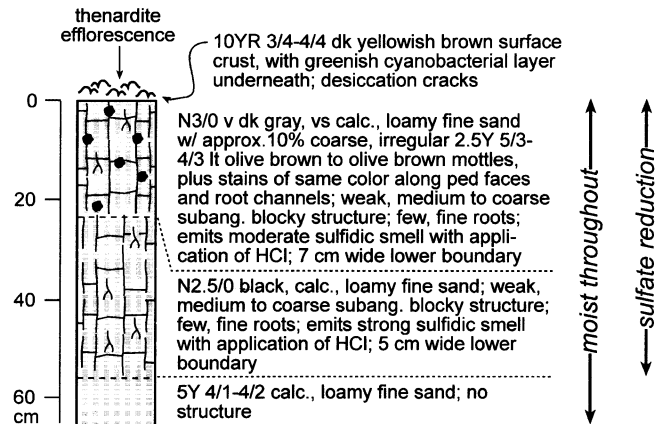


Figure 18. Soil profile under salt accumulations shown in Figure 17. Soil surface has yellowish brown microbial crust underlain by very thin cyanobacterial layer. Overall, profile is similar to saline-alkaline soils under natural salt flats in North Platte Valley of western Nebraska. Abbreviations are calcareous (calc.), dark (dk), subangular (subang.), very (v), very strongly (vs).

well as the cumulative effect of erosion by overland flow over longer time scales, of recreationally valuable beaches would partially offset any perceived benefit. Perhaps the best strategy among a number of imperfect solutions to reservoir shoreline erosion problems is the strategy of proactive prevention already adopted by CNPPID, including the condemnation of a strip of shoreline and the pre-emption of housing development there.

Other Lake-Related Changes

Lake-related depositional features, such as beaches, filling bays, and a prograding delta, are expected consequences of reservoir evolution, and these have had major effects on the local landscape. The upstream effects of delta growth at the western end of Lake McConaughy demonstrate that local base-level changes are a causative factor in stream morphometric change. The very short time scale (8 years from 1952 to 1960) of major changes in the channel pattern of the North Platte River immediately upstream of its delta is noteworthy, especially in the context of longer-term (>100 years), basin-wide stream change on the Platte system described previously by other authors. It also appears to be a potentially useful example of the rapid transition of a fluvial system from braided to anastomosed. A more detailed analysis and comparison of basin-scale versus local change might provide important answers relevant to a variety of geomorphological questions, as well as providing a model of the effects of eustatic sea-level change on fluvial systems.

Rising water tables have been observed several kilometers away from the lake, presumably because of the lake itself, whereas disjunct hydrogeologic effects—those involving the mass transfer of water over many tens of kilometers—have occurred as a result of irrigation at

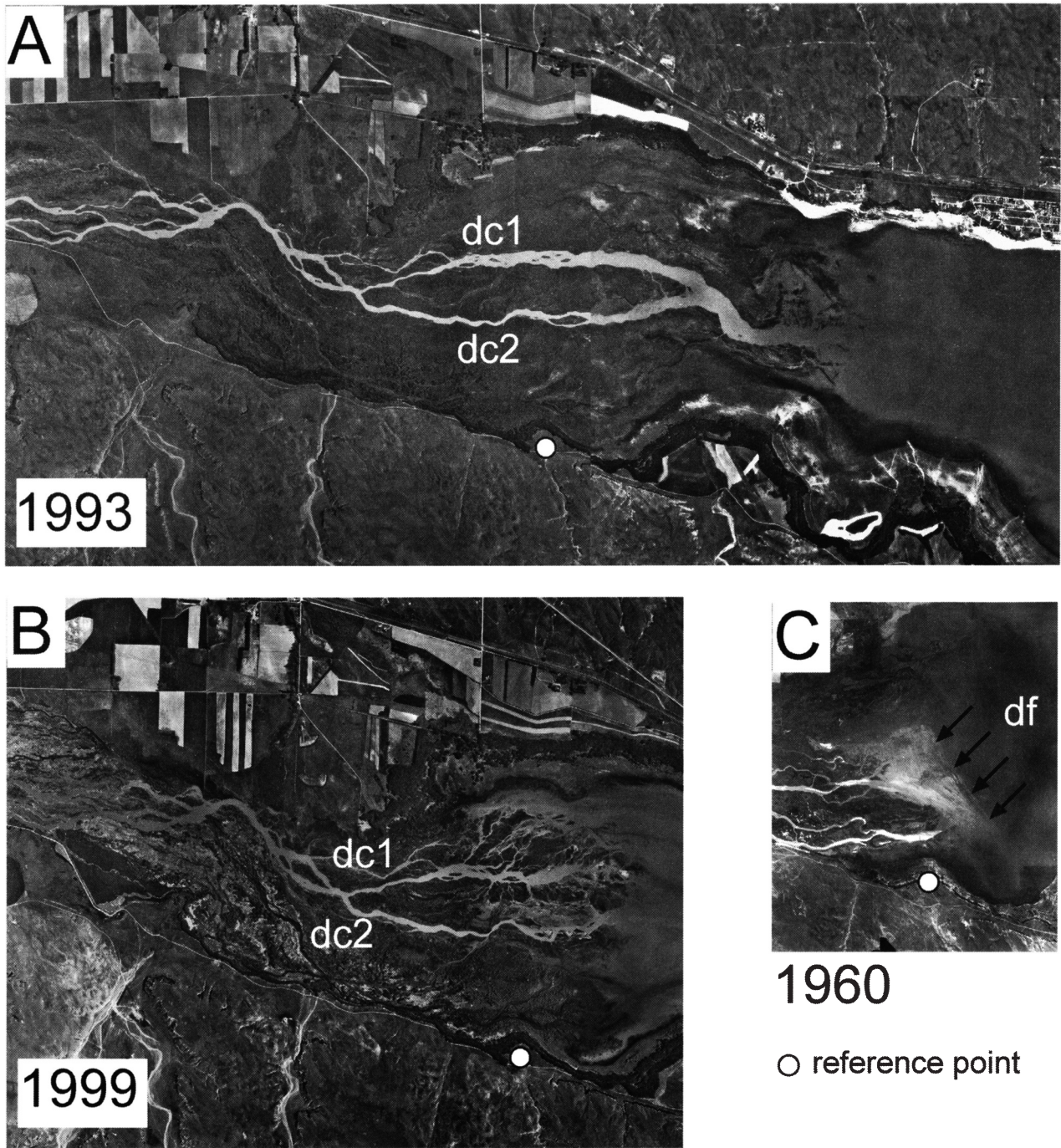


Figure 19. North Platte River delta at Lake McConaughy in 1993 (A), 1999 (B), and 1960 (C). Note the dramatic differences in the appearance of delta 1993 and 1999 due to management procedures: lake level was lower at the time of the 1993 photo, although 1993 had high annual rainfall, but lake level was higher in 1999, a lower-rainfall year. Distributary channels (dc1, dc2) are indicated. Vegetation on stabilized islands immediately upstream of the delta is sparser in 1999, leaving areas of bare sand (B), whereas delta and upstream islands are fully vegetated in 1993 (A). In the 1960 photo (C), the delta front (df) can be clearly seen; wind-driven waves appear to be diverting flow from North Platte southward, and sand is being deposited in shallow water at the delta front.

great distances from the site. Both local and disjunct effects have detectable consequences across a human time scale, and the disjunct effects, at least, may have unforeseeable results in the future. The surface accumulation of salts observed near the western end of the lake

reflects a major shift from groundwater recharge under the lake to diffuse discharge by capillary wicking and evaporation on the exposed lake floor. Presumably, continued drawdown would eventually lower the water table, whereas the re-filling of the lake would negate it.

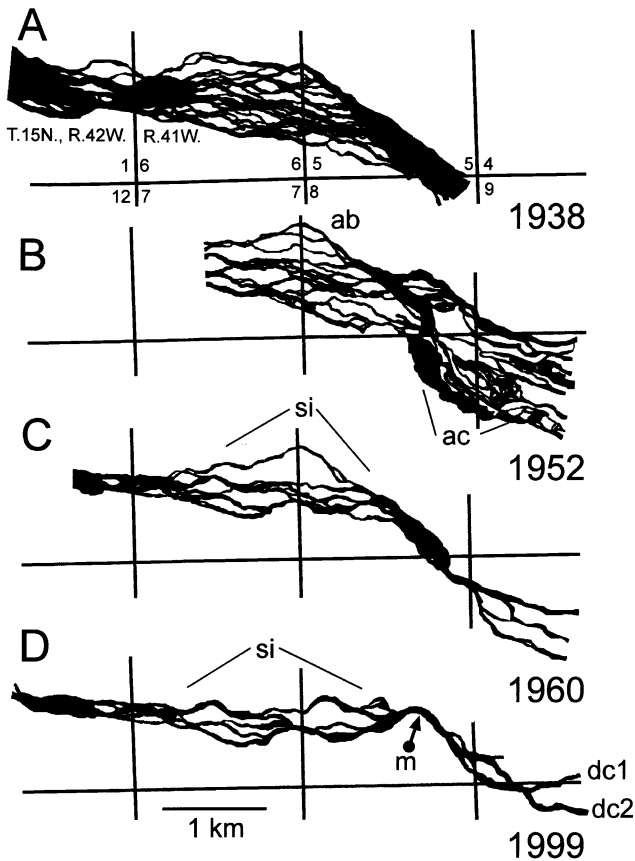


Figure 20. Changes in channel configurations immediately upstream of the North Platte River delta at Lake McConaughy, with an overlay of land section grid; flow is from left (west) to right into the lake. Aerial imagery coverage in 1938 (A) and 1952 (B) is incomplete, but partially overlaps 1999 digital orthophoto quadrangle (D). A) Channel pattern in 1938, immediately before construction of Kingsley Dam and the subsequent elevation in local base level. Note the wide, braided stretch with many braid bars between narrower, shallow stretches on either side in the original air photo. B) Channel pattern in 1952, with Lake McConaughy having reached peak storage for the first time. Note amalgamated bars (ab), which are generally larger than those present in 1938, and accessory channels (ac) that cross-link larger distributary channels downstream. River is approximately as wide as in 1938, but fewer channels are active. C) Channel pattern on June 18, 1960; relatively stabilized islands (si) have formed from bars and the number of channels has decreased markedly since 1952. D) Channel pattern in 1999. Note large, yet fewer, stabilized islands (si), fewer channels, and two delta distributary channels (dc1, dc2); channel has also migrated northward (m) at one point since 1960.

Nonetheless, the phenomenon exemplifies the potential risk of any artificial elevation of water tables throughout the North Platte Valley, a region of high evapotranspiration flux, whether because of irrigation or the impoundment of surface waters. Moreover, if Lake McConaughy were to remain at an “intermediate” level, thus continuing to expose a low-gradient land surface west of the lake, soil salinization might be a long-term, albeit localized, phenomenon.

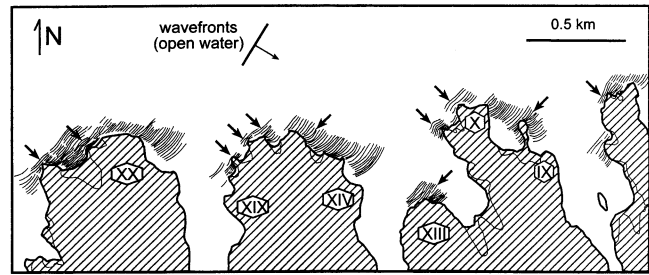


Figure 21. Interaction of waves produced by northwesterly winds with the headlands on the southeastern shore of Lake McConaughy. Arrows indicate sites of slight refraction of wave fronts around projecting parts of the headlands on the northwest-facing flanks. Fine lines within headlands represent margins of pocket beaches or other accretionary sandy shoreline exposed at what appears to be near-maximum pool level. From an aerial photograph GS-VCOP 1-48 (University of Nebraska—Lincoln Conservation and Survey Division files), taken on November 15, 1970. Reference points (Roman numerals) are as in Figures 10 and 11; see also Figure 1 for reference.

Finally, and at a very basic level of understanding, Lake McConaughy illustrates the limitations of attempts to “mitigate” drought over even moderately sized agricultural regions. Overall, the lake has served its irrigation function very well, and through several years with lower than average rainfall, but the exceptional drought conditions of recent years cast doubt on the ability of the lake to supply water beyond even the next irrigation year (2004).

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