INLAND WATERS BRANCH

Diefenbaker Lake

Effects of bank erosion on storage capacity

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TECHNICAL BULLETIN No. 10

DEPARTMENT OF ENERGY,
MINES AND RESOURCES

CANADA

DIEFENBAKER LAKE

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Cont'd)

ABSTRACT

Accelerated erosion of valley slopes by waves, as a consequence of the creation of Diefenbaker Lake, will result in a decrease in total storage capacity of that reservoir, an increase in usable storage and some increase in annual evaporation.

DIEFENBAKER LAKE

EFFECTS OF BANK EROSION ON STORAGE CAPACITY

INTRODUCTION

The creation of a surface-water reservoir exposes valley slopes, that were originally formed by glacial or runoff erosion, to the erosive energy of two or three new agents: waves, ice and, under the right circumstances, groundwater movement. This will result in accelerated erosion of the reservoir banks during the early years of the reservoir's useful life. Continued modification of shore profiles will adapt the exposed slopes to the new conditions and the erosion rate will consequently decrease with time. The effect of bank erosion in terms of reservoir economics will usually be threefold: (1) increase in the surface area of the reservoir, resulting in increased evaporation, (2) formation and increase in the width of an accumulation shelf (beach) and (3) decrease in storage capacity by deposition of erosion products.

In the following sections each of the erosive and resistive forces that play a role in bank erosion are discussed. Examples of bank erosion phenomena observed in the area of the Riverhurst Ferry on Diefenbaker Lake, Saskatchewan, are followed by a comparison of the sediment load of the South Saskatchewan River at Lemsford with accretion profiles near the Riverhurst Ferry (see Figures 1 and 2). It will be shown that bank erosion, mainly by wave action, accounts for most of the changes in the reservoir cross-section observed to date. Finally an estimate is given of the eventual decrease in storage capacity of Diefenbaker Lake to be expected from bank erosion.

Acknowledgements

The assistance of the staff of the Water Survey of Canada, Calgary District Office, in providing the sediment data contained in Figures 15 and 16 for the South Saskatchewan River and Diefenbaker Lake, is gratefully acknowledged.

EROSIVE FORCES

General Remarks

The three main agents actively contributing to bank erosion are the forces exerted by the reservoir water, reservoir ice and groundwater. The first two are activated by and derive most of their energy from a common source, wind. A minor amount of wave energy may be contributed by the passage of boats. With reference to ice, active pressures on bank material will also be caused by variations in ambient temperature.

Groundwater may contribute to erosion of relatively steep banks in fine-grained material through the build-up of excess pore pressures that may cause landslides.

Wave Erosion and Wind

The parameters that determine wave energy are: height, period, velocity and shape of the waves. These in turn depend on a number of other factors, the most important of which are the direction, duration and velocity of the winds that generate the waves.

When a reservoir is contained in a relatively narrow valley, like Diefenbaker Lake, the prevailing wind direction will be a major factor in determining the occurrence and magnitude of bank erosion. For cross-reservoir winds the fetch l_f, being the distance through which wind acts on the water surface, is usually restricted to less than two miles. Winds parallel to the valley may have a fetch of up to 15 miles.

The duration of wind at a certain velocity from a fixed direction affects the wave energy in two ways. The maximum wave height or amplitude, Z_{max}, is not attained instantaneously; the time required to develop Z_{max} increases with the wind velocity V_w. In the second place the duration of the wind determines the time during which wave erosion is active. Numerical

TABLE 1

Values of coefficients K_e, a and b for various materials, after Kachugin, 1966

Material	K_e	a
Fine sand, sandy loam, loess	$3.15\text{-}1.46 \times 10^{-5}$	0.065
Medium sand, soft loam, sandy loam with rocks	$1.46\text{-}0.49 \times 10^{-5}$	0.13
Sand with gravel, clay, heavy loam with boulders	$0.49\text{-}0.245 \times 10^{-5}$	0.39
Clayey sandstone, clay, dense marl	0.245×10^{-5}	

Material	b
No shoals in front of bank (headlands)	= 0.9
Loess banks	= 0.9
50% clay banks	= 0.8
General case, with medium shoal development	= 0.7

application of this particular aspect is difficult because waves persist for a time once they have been generated, even though wind velocity and direction change.

The following empirical relationships (after Linsley *et al.*, 1949) indicate the relative importance of the various factors.

If the wave length is λ and the depth of water D is larger than $\lambda/2$, the wave period t_o is

$$t_o = \frac{\sqrt{\lambda}}{2.27} \text{ seconds} \qquad (1)$$

For wind velocity V_w in miles per hour, and fetch 1_f in miles, the maximum wave height Z_{max} in feet is

$$Z_{max} = 0.17 \sqrt{V_w \cdot 1_f} + 2.5 - \sqrt[4]{1_f} \qquad (2)$$

The energy E_w contained in a wave of wave length λ and wave height Za, expressed in foot-pounds per foot of crest and per wave length, is

$$E_w = \frac{\rho \lambda Za^2}{8} \left[1 - 4.94 \left(\frac{Za}{\lambda}\right)^2\right] \qquad (3)$$

where ρ is the density of water. Combining the energy per wave length and per foot of crest E_w with the period t_o or the frequency $F_w = \frac{1}{t_o}$ gives the available wave energy per foot of beach and per unit of time. If the angle of incidence of the wave is α, the available energy is correspondingly reduced to $E_w \cdot \sin \alpha$.

The quantity of material Q_e that will be eroded can be related to the available wave energy E_w by another empirical equation worked out by Kachugin (1966):

$$Q_e = E_w \cdot K_e \cdot K_f \cdot t^b \qquad (4)$$

where Q_e is in cu. ft. per foot

E_w is in ft-lbs per foot shore length and per year

K_e is the wash-out coefficient, in cu ft per ft-lb

K_f is a coefficient for bank height = h_b.a

h_b is equivalent to the bank height in feet

a is a coefficient depending on bank material

t is time in year

b is a coefficient depending on the formation of shoals.

Values for the coefficients K_e, a and b were given by Kachugin. They have been converted for use in the ft-lb system and are shown in Table 1.

Part of the available wave energy is expended when depth D becomes smaller than $\lambda/2$. The waves become unstable and start breaking up or rolling. Further dissipation of energy takes place by what is called temporary infiltration in the material of the shelf or beach and also when conditions are such that an incoming wave is met by the return flow of the preceding wave. These factors may make it difficult to state how much of the available energy is actually effective in erosion of reservoir banks in a given situation.

Once material has been loosened from the banks it is transported into deeper water by the return flow of the waves and by the off-shore under-currents created by strong on-shore winds. The erosive process will be terminated when the shelf reaches such dimensions that it is capable of absorbing all the wave energy supplied.

Ice

Energy may be applied to the reservoir banks by ice in three different ways: firstly, by expansion and contraction of surface ice under the influence of temperature variations, secondly, by the "ratchet" action of water that fills cracks and subsequently expands on freezing and, finally, when ice is pushed against the banks by strong winds, either as a sheet or as loose floes or blocks.

The coefficient of linear expansion for ice in the range from 0° to 32°F is 0.00003 per degree. The actual expansion of a sheet of ice caused by a change in air temperature is usually less than that indicated by this coefficient, because the lower surface of the ice sheet is maintained at a constant temperature of 32°F. For example an ice pack one mile wide will expand only about 2.5 feet under a 30°F change of temperature and not the full 4.5 feet to be expected on the basis of the expansion coefficient. For a sheet of ice the size of a large reservoir part of the pressures thus created will be dissipated by buckling of the ice and the formation of pressure ridges.

The actual erosive effect of ice pressure and ice movement takes two different forms. The ice may loosen material from the banks, thus contributing actively to erosion (and transport), and the moving ice may destroy protective vegetation on the banks and possibly also part of the shallow-water vegetation thus contributing indirectly to erosion by increasing the potential effectiveness of wave erosion.

Groundwater

Many river valleys that now are sites of major reservoirs originally were and still may be areas of groundwater discharge. When the water level in such a reservoir rises, the water table in the surrounding area also rises. The rate and magnitude of the rise in the water table depends on the material of the "aquifers" and the original slope of the water table. If the reservoir level is lowered rapidly (say at a rate of one foot per day) after a prolonged period of constant level, bank material of low permeability may prevent a concurrent equally rapid adjustment of the water table through groundwater discharge. The resultant high pressure gradients in the bank material may be the cause of bank slides on a small or large scale.

When reservoir levels are kept constant, groundwater movement may still contribute to the erosion of reservoir banks. Such effects will be most pronounced when wave erosion creates steep cliffs in relatively competent material of low permeability, like till and shales. When the cliff reaches a certain height the increased groundwater gradient may again become a factor in the occurrence of slides.

Both phenomena can be regarded as the result of a reduction of the shearing resistance "s" per unit area of the bank which can be expressed (Terzaghi, 1950, p. 211) as:

$$s = c + (p - hw) \tan \phi \qquad (5)$$

where c = internal cohesion per unit area

p = pressure of the overburden (rock and water) per unit area at a given point P of a potential sliding surface

h = head of water at point P

w = unit weight of water

ϕ = angle of sliding friction for the surface of sliding.

When the reservoir level is lowered rapidly the effective head, h is increased if the surface-water level drops faster than the water table. Under conditions of wave erosion the normal pressure, p, on the potential slip surface is reduced, while the head, h, stays approximately constant. In addition, tensile and shear stresses in the rock body are increased. A slide occurs when the ratio of shear stress to shearing resistance exceeds unity.

The saturation of formerly unsaturated bank material may further contribute to sliding by causing a decrease in internal cohesion, c, (and thus in shearing resistance) of the material through elimination of surface tension, production of swelling in clays, or removal of a soluble cement.

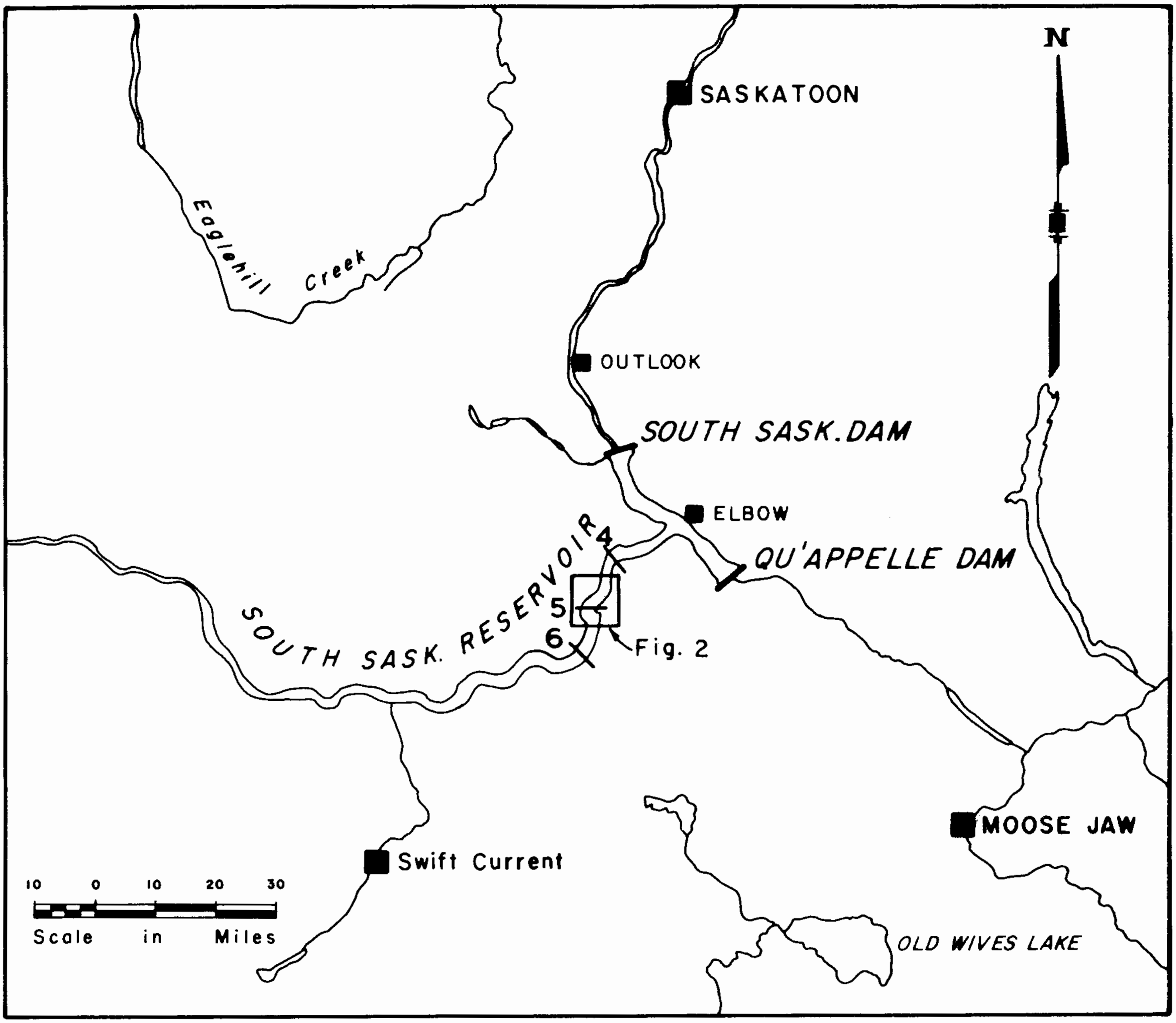


Figure 1. Location map, South Saskatchewan Reservoir, now Diefenbaker Lake, Saskatchewan. Numbers 4, 5 and 6 indicate sediment survey ranges.

RESISTIVE FORCES

Geology and Morphology

In general, coarse materials (gravel, boulders) are not as susceptible to rapid erosion as finer materials (sand, silt). The degree of cohesion between particles, by surface tension or cementation, will have a modifying effect on the disaggregation of such sedimentary rocks. Thus a well-cemented fine sand may be much more resistive than a loose coarser sand. Similarly, the presence of fractures, joints and bedding planes will decrease the erosive resistance of any given bank material.

During periods of rapid lowering of the reservoir level, very permeable bank materials will generally be less landslide prone than materials of much lower permeability. In addition, loose fine-grained deposits may give rise to failure of banks by "piping" (underground erosion) if the groundwater-discharge rate is appreciable.

When a reservoir is created in a river valley, the morphology of the valley will have a profound influence on the rate and magnitude of bank erosion. A minimum of erosion will occur if slope angles within the range of anticipated fluctuation of the reservoir are small, because wave energy will be expended mainly on rolling of the waves, temporary infiltration and on overcoming the return flow of preceding waves. Major erosion at a relatively high rate can be expected if the slopes in the fluctuation range are steep; this will be accentuated wherever they consist of loose, fine-grained material.

The relationship between shelf height Y and shelf width X for stable shelf slopes was given by Kondratjev (1966) as:

$$X = AY^2 + \frac{1}{M_n} Y \qquad (6)$$

where $$A = \frac{M_n - M_o}{20\, M_n \cdot M_o}$$

and M_n is equivalent to the slope of the stable shelf at the water edge

M_o is equivalent to the slope of the outer edge of the stable shelf

For values of Y between 0 (at the water edge) and H (depth at which erosion starts, depending on wave length and amplitude, and character of shelf material) the shelf width is

$$X = AH^2 + \frac{1}{M_n} H. \qquad (7)$$

If the level in the reservoir is lowered by a value h_1 the shelf profile is extended by a straight line from the original depth H to a point with depth $(H + h_1)$ below the original water level. The extension will have a constant slope equivalent to M_o and the width of the extension will be

$$X_1 = h_1 \left(2AH + \frac{1}{M_n}\right). \qquad (8)$$

Both M_n and M_o depend on the grain size distribution of the eroded bank material. Values given for these parameters by Kondratjev (1966, p. 811) in ft/ft are:

Fine sands - $M_n = 0.03$; $M_o = 0.005$

Gravel - $M_n = 0.2$; $M_o = 0.05$

These values mean maximum shelf slopes of about 2° and 11° for fine sand and gravel respectively. The values for M_n and M_o for silt and clay may still be smaller than those for fine sand, although cohesion will tend to make somewhat steeper shelf slopes possible.

Vegetation

Dense ground cover and the presence of shrubs or trees with a well-developed root system will retard erosion of underlying materials if intermittent submergence by waves does not result in their death. Even dead vegetation may retard erosion by dissipating wave energy and tying down soil and rock particles. Major roots of larger trees on the other hand may act in the opposite direction by causing fractures in the soil.

Emergent vegetation in the form of reeds and other aquatic plants will retard erosion of reservoir banks by dissipating wave energy before it reaches the shore line.

In the case of regular major fluctuations in reservoir level it is doubtful if any vegetation will survive in the range between low and high water; aquatic vegetation will not stand prolonged emergence, land vegetation will succumb under prolonged submergence.

BANK EROSION PHENOMENA NEAR THE RIVERHURST FERRY, SASKATCHEWAN

General Remarks

Between April 1965 and July 1967 the water level in Diefenbaker Lake (South Saskatchewan Reservoir, see Figure 1) rose from 1690 feet to 1805 feet above sea level at Riverhurst Ferry, Saskatchewan. During the above-noted period, erosion of the reservoir banks was observed near the ferry crossing during a groundwater study in the area. Photographs taken at various times since spring 1964 show some of the erosion phenomena in till and shale and indicate the magnitude of the effects. Locations of the photographs are marked on the aerial photographs, Figures 2 and 3.

Figure 2. Valley of South Saskatchewan River near Riverhurst Ferry, Saskatchewan. Note evidence of earlier landslides mainly on west bank; and sandy area on east bank inside main bend. Numbers refer to location of photographs Figures 10 to 12; arrows indicate direction of view; Roman numerals indicate sections of Figure 17. (RCAF - A15963-121/123)

Figure 3. South Saskatchewan River at Riverhurst Ferry, Saskatchewan. Pre-reservoir 'beach' and cliffs are shown at low-flow stage.

Numbers refer to location of photgraphs figures 4-9 and 13-14; arrows indicate direction of view. (RCAF - A16379-108)

Figure 4. Gravel beach and steep banks in till and shale. West bank of South Saskatchewan River, looking upstream near Riverhurst Ferry. August 1964--Water level at 1689 feet above sea level.

Figure 5. Accelerated erosion of steep banks. West bank of Diefenbaker Lake, looking upstream near Riverhurst Ferry. August 1965--Water level at 1720 feet above sea level.

Figure 6. Development of steep-angled cracks above newly eroded cliffs. West bank of Diefenbaker Lake, looking upstream near Riverhurst Ferry.
September 6, 1966--Water level at 1739.7 feet above sea level.

Figure 7. Development of large fracture in the face of the steep hill shown on Figure 4. Close up view; September 6, 1966.

Figure 8. Landslide developing in the east face of the steep hill of Figure 4; September 6, 1966.

Figure 9. The hill of Figure 4 on May 3, 1967, some time after the slide had taken place. Reports place the time of the slide sometime in February 1967. Level of ice is 1754 feet. Water dropped from 1755.5 feet on January 13 to 1737.8 feet on March 16 after which it rose steadily to the level shown.

Figure 10. Incipient cliff formation. East bank of Diefenbaker Lake north of Riverhurst Ferry. August 16, 1966--Water level at 1733 feet above sea level.

Figure 11. More advanced cliff formation. Note columnar jointing in till, resulting from desiccation; wet zone at base of cliff not fully drained. Height of cliff is approximately 11 feet. East bank of Diefenbaker Lake north of Riverhurst Ferry. August 16, 1966.

Figure 12. East bank of Diefenbaker Lake, north of Riverhurst Ferry. The high cliff on the right has already produced at least one slide; a steep fracture is clearly visible indicating the next part to go. August 16, 1966.

Description of Detail

The first photograph, Figure 4, shows the west bank of the South Saskatchewan River, looking upstream (southwest) from a point about one-half mile from the ferry. The flat beach or shelf and the relatively steep cliffs developed in glacial till and Upper-Cretaceous Bearpaw shale are characteristic of this reach of the valley in its original state.

The water level stood at 1720 feet above sea level, or 30 feet above the original river level when Figure 5 was photographed in August 1965. The cliffs show signs of accelerated erosion. Figure 6, photographed from the top of one of the cliffs in September 1966, shows development of steep fractures a few feet inward from the edge of the cliff.

The high hill of Figure 4 developed a number of fractures during the summer of 1966. Figure 7 gives a close-up view of the main fracture on September 6, 1966; Figure 8 is a view of the hill side. At that time the width of the fracture opening was 4½ inches and apparent vertical displacement 6 inches. The water level stood at roughly 1740 feet above sea level. It rose to 1754 feet by January 13, 1967, dropped to about 1738 feet by March 16 and rose again to 1754 feet by May 3, 1967, the date Figure 9 was photographed. Reports from local people place the occurrence of the slide sometime in early February, during the lowering of the lake level. Figure 9 shows the slide scar; the outer and lower parts of the hill have vanished below the water.

Figures 10 to 12 illustrate the progress of erosion above the top of the original cliffs on the east bank, north of the ferry crossing, in late August 1966. Figure 10 shows the earliest stage in the development of a new cliff face at the base of a grassy slope of approximately 15 degrees. In Figure 11 a similar cliff is shown in a more advanced state of development. "Columnar jointing", due to desiccation, is clearly visible in the glacial till that forms this cliff. In Figure 12 a slide had taken place from the cliff in the foreground approximately two weeks before photographing. The fracture to the right of the slide scar indicates the plane of failure for the next slide.

A large part of the inside of the bend in the South Saskatchewan River at Riverhurst Ferry was originally covered with sand in the form of small hills and dunes, up to 30 feet high and partly covered with vegetation. Because of the nature of the material, most of these hills were washed away by wave action before the water level started rising above 1720 feet above sea level in early August 1966. Undoubtedly this has contributed relatively large amounts of sand to the lower lying parts of the valley;

it has not affected the storage capacity of the reservoir because all the material originated below the "low" level of the reservoir.

Erosion of the bedrock shales and the glacial drift of the valley slopes produces boulders, gravel, sand, silt and clay. In addition to these, shale "pebbles" may constitute a more or less important fraction of the erosion products, as indicated by Figures 13 and 14. Figure 13 shows the "beach" at the base of the hill of Figure 4 on September 12, 1966, during the height of a storm from the east. The material in the foreground consists of shale pebbles. A view across the reservoir from the same location (Figure 14) shows accumulation of driftwood giving some protection from wave action. It also gives an idea of the size of the waves that can be expected.

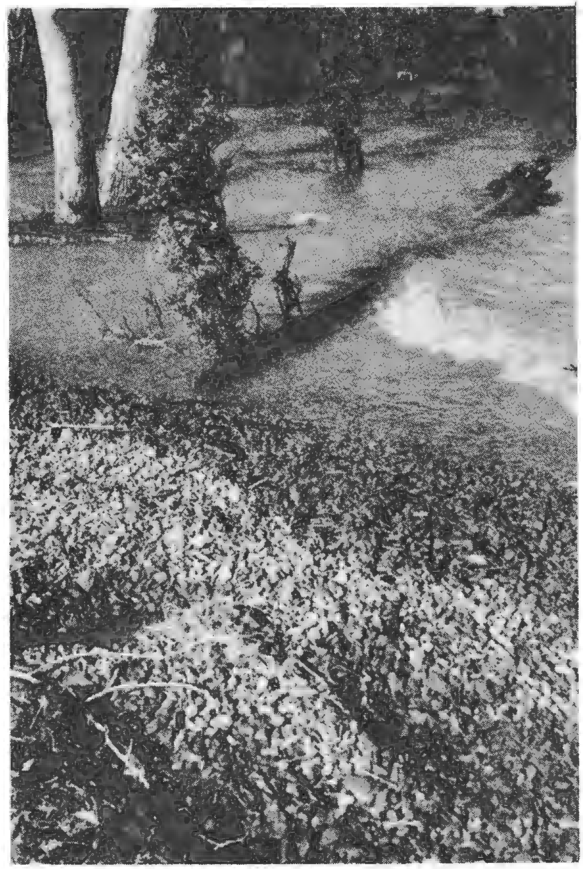


Figure 13. Accumulation of shale "pebbles" at the base of the high hill of Figure 8 during a storm on September 12, 1966. Water level at 1741.5 feet above sea level.

Figure 14. View across Diefenbaker Lake from small coulee at the base of the hill of Figure 8, during storm of September 12, 1966. Accumulation of shale pebbles and driftwood in foreground; note white-capped waves, amplitude about four feet. Water level at 1741.5 feet above sea level.

SEDIMENT OF SOUTH SASKATCHEWAN RIVER

Sediment Load

During the period from July, 1961 to September, 1966, the daily suspended-sediment load of the South Saskatchewan River at Lemsford ranged from a minimum of 14 tons per day to a maximum of 909,000 tons per day. The total suspended load for the year 1966 was 5,316,587 tons; the mean daily load was 14,600 tons and sediment yield amounted to about 118 tons per square mile of drainage basin.

In the early stages of rising water level in Diefenbaker Lake an appreciable part of these sediments were deposited at progressively greater distances upstream from the dam. Ultimately the sediment load of the river will cause the formation of an increasingly large delta at the upstream end of the reservoir. The anticipated annual fluctuation of the reservoir level of the order of 40 feet will tend to distribute delta deposits to at least 30 miles downstream from the tail-end of the reservoir.

Grain-size Distribution

Grain-size distributions for suspended sediment and bed material of the South Saskatchewan River at Lemsford are given in Figure 15. In Figure 15-a "extreme" grain-size distributions for suspended sediment are shown for the years 1962 to 1966. Figure 15-b shows a number of representative grain-size distributions plotted for bed material for the same period. Distinction between material from the two sources can easily be made on the basis of the size fractions between 1/8 and 1.0 mm.

SEDIMENTATION IN THE LOWER REACHES OF DIEFENBAKER LAKE

Accretion Profiles

For the long-term study of sedimentation in Diefenbaker Lake, a number of "sediment ranges" (cross-sections) have been established by the Inland Waters Branch. These cross-sections have been surveyed in detail with the use of water-borne depth-sounding equipment and land-based survey instruments. They are periodically re-surveyed to record changes in the reservoir cross-section caused by sedimentation.

Sediment ranges 4, 5 and 6 near Riverhurst Ferry (Figure 1) were originally surveyed on August 31, 1965 with the use of sounding line and rod. Surveys of ranges 4 and 6 were repeated in early September, 1967; this time an echo sounder was used. The results of these surveys are shown in Figures 16 a, b, and c.

Both figures 16-a and 16-c show a number of features in the central part of the valley off-set towards the left bank in 1967 as compared to their position in 1965. The elevated areas in the bottom of the valley in all three ranges represent sand bars or islands in the original river bed. It is unlikely that those in range 4 would have shifted their position after the original survey in August, 1965, because the reservoir level did not drop below elevation 1720 (water depth of 30 feet or more) at any time since. It is also unlikely that during such a shift the outline of these features and their elevation would have been preserved to the extent shown in Figure 16. Therefore, it is assumed that the difference in sounding equipment, and variations in the speed of the survey vessel during the echo-sounding runs are responsible for the apparent changes in the central part of the cross-sections.

The only instance where the possibility of inaccuracy in the survey line can be ruled out is the downward displacement of the surface on the left bank in range 6 (Figure 16-c). Only a land-based survey was involved because this part of the section is located above the water level of the reservoir. Erosion at the sides of a gully near this cross-section must account for this change in the reservoir cross-section.

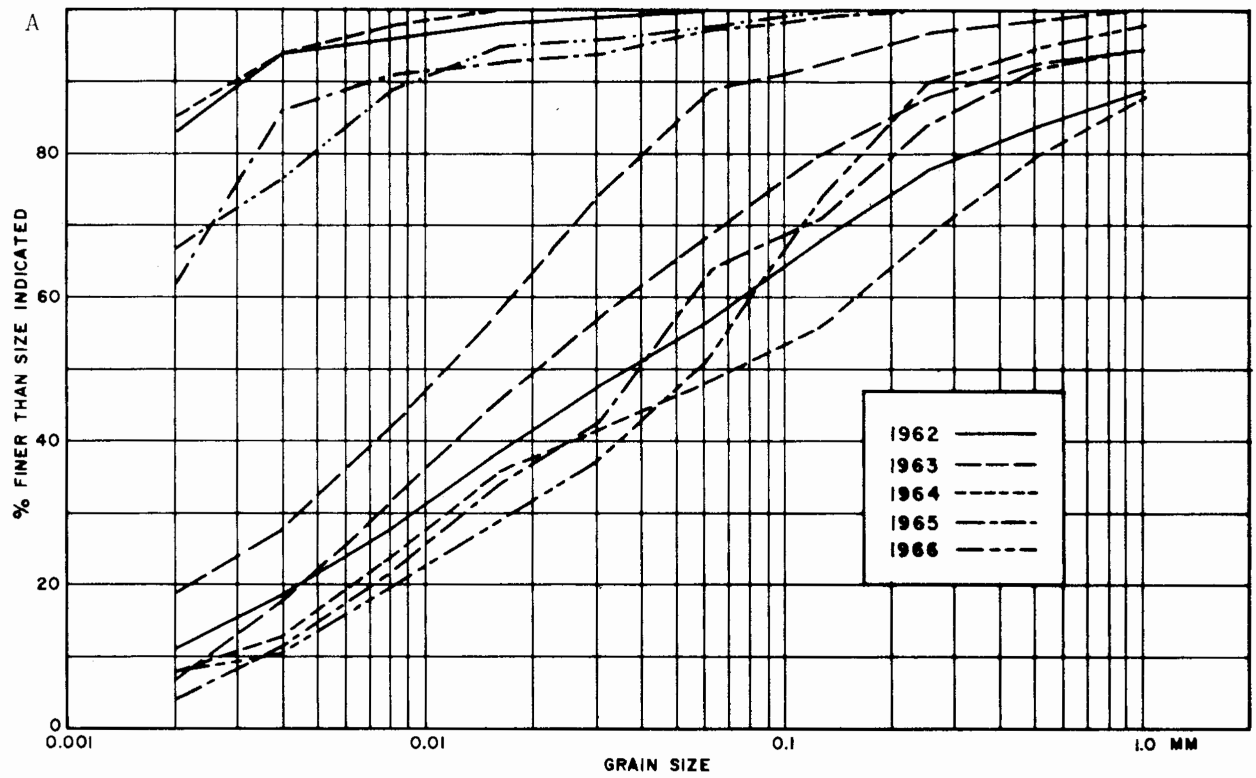
Grain-size Distribution

Grain-size distributions for samples taken at sediment ranges 4, 5 and 6 are incorporated in figure 16 a, b and c. Comparison of these with Figure 15 leads to the following observations.

1. In general, samples from the central part of the valley bottom show a grain-size distribution characteristic for bed material (Figure 15-b) (Range 4, samples 11, 12 and 14; range 5, sample 3 and 2; range 6, sample 11).

2. Samples from the remainder of the valley bottom and from the valley slopes show grain-size distributions that fall within the range established for suspended sediment (Figure 15-a).

3. Sample 15, range 4 was taken at an elevation between 1748 feet and 1752 feet. The relation between the two survey profiles at the sample location in Figure 16-a and the distance of range 4 from the tail-end of the reservoir (about 50 miles) lead to the assumption that this sample represents products of local bank erosion rather than river sediment. The materials forming the valley slopes in this area (glacial till, shale) could well produce sediment showing the grain-size distribution shown by sample 15. The distribution falls within the range for suspended sediment given in Figure 15-a.



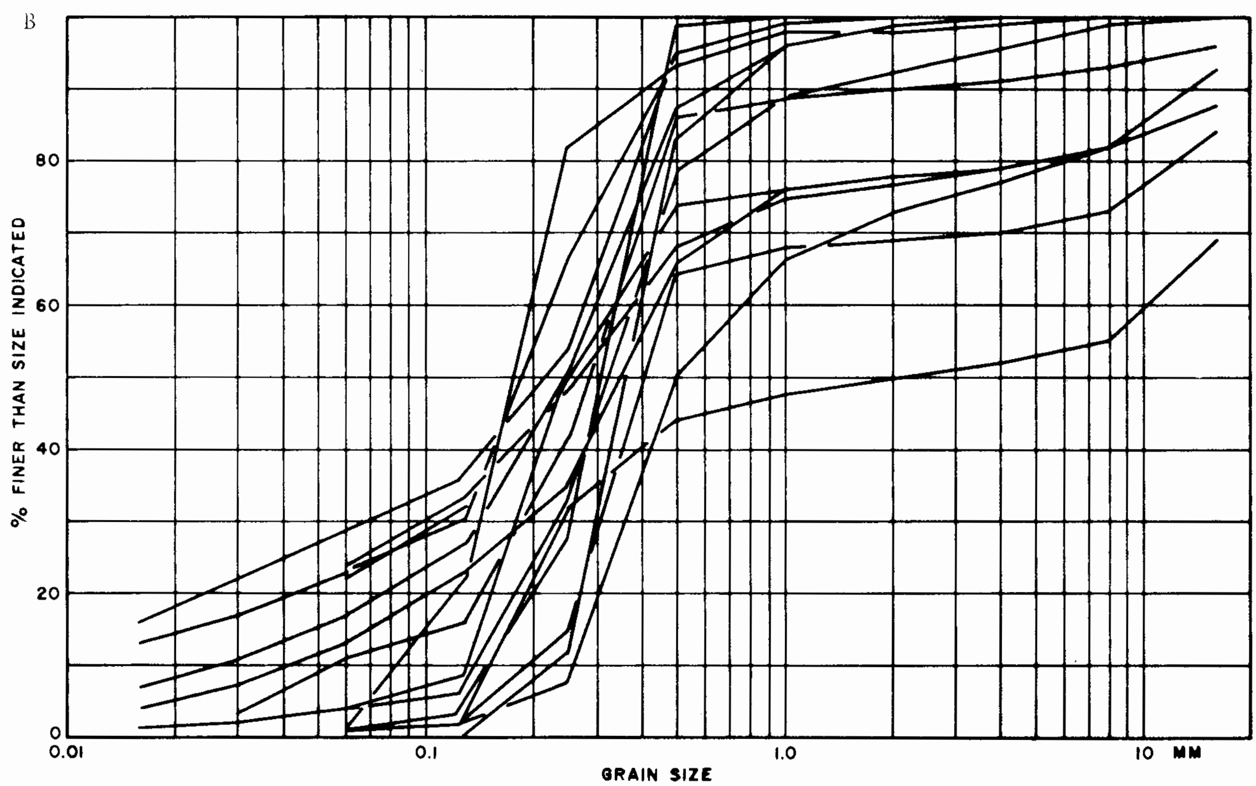


Figure 15. Grain-size distributions, South Saskatchewan River at Lemsford, Saskatchewan.
A. Suspended sediment, annual extremes for the years 1962-1966.
B. Bed material, for the years 1962-1966.

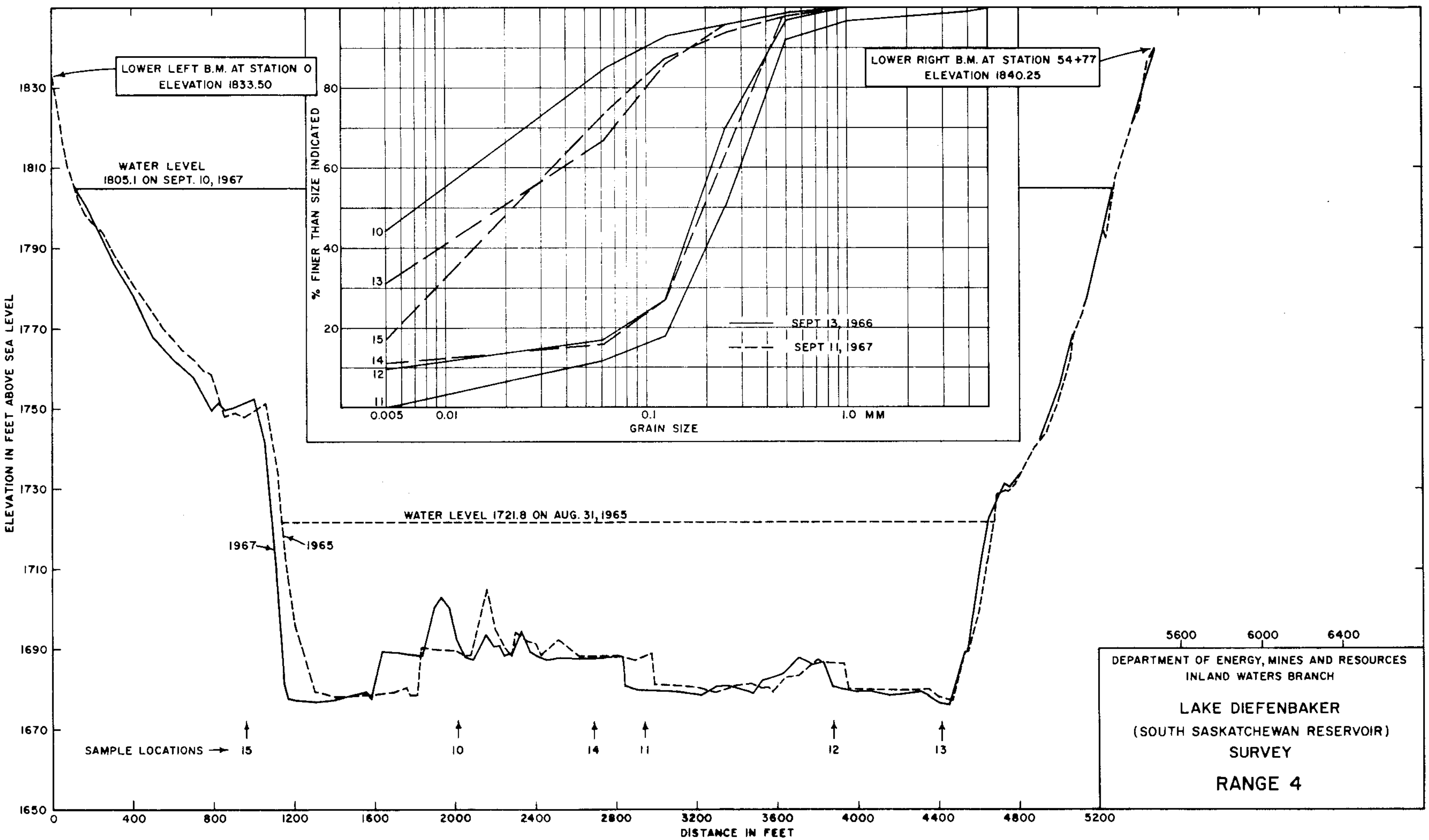


Figure 16-a. Cross-sections of Diefenbaker Lake at range 4, on August 31, 1965 and September 10, 1967.
Grain-size distributions for samples taken at locations and on dates indicated.

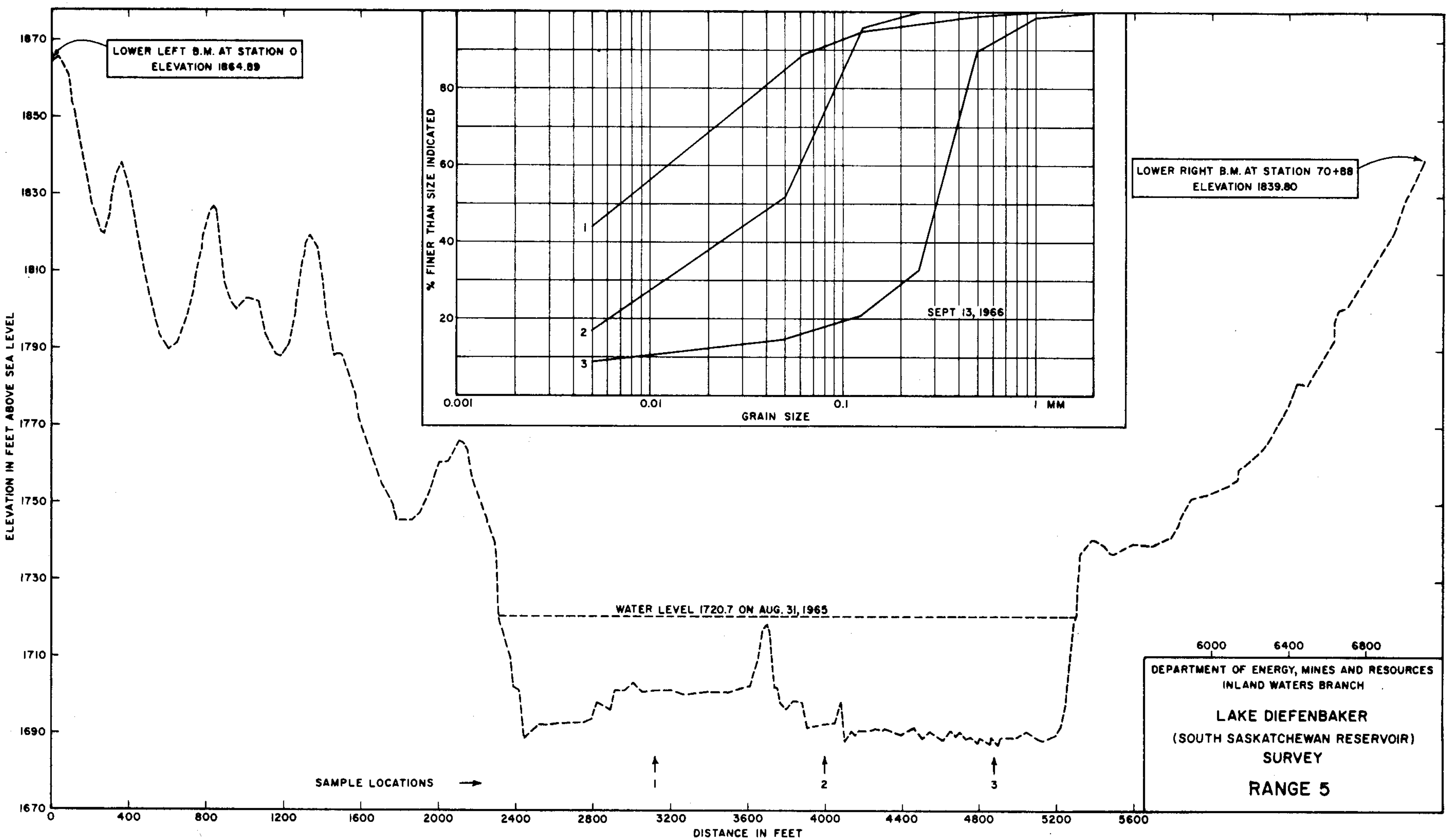


Figure 16-b. Cross-section of Diefenbaker Lake at range 5, on August 31, 1965. Grain-size distribution for samples taken at locations and on date indicated.

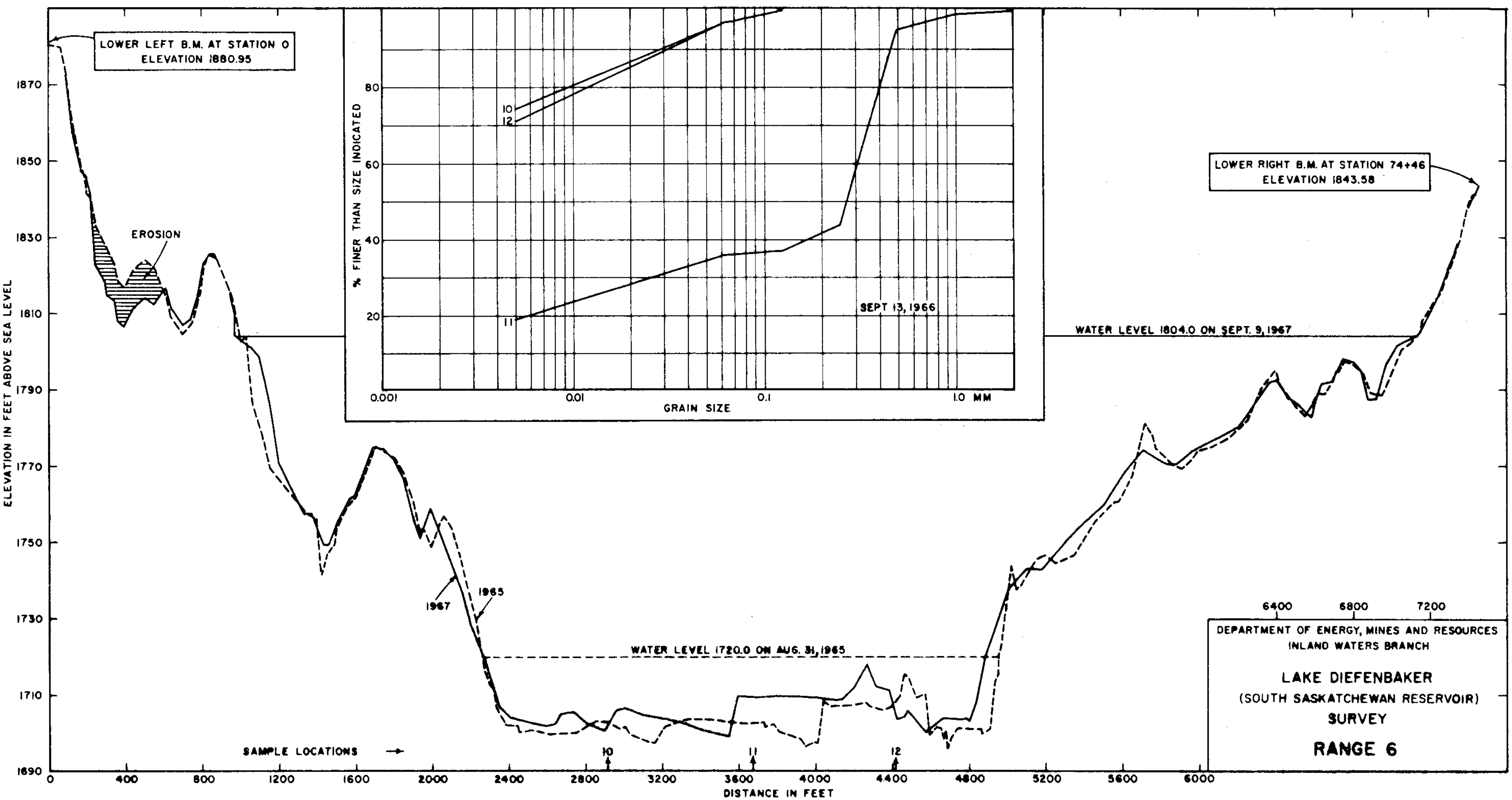


Figure 16-c. Cross-section of Diefenbaker Lake, range 6, on August 31, 1965 and September 9, 1967. Grain-size distributions for samples taken at locations and on dates indicated.

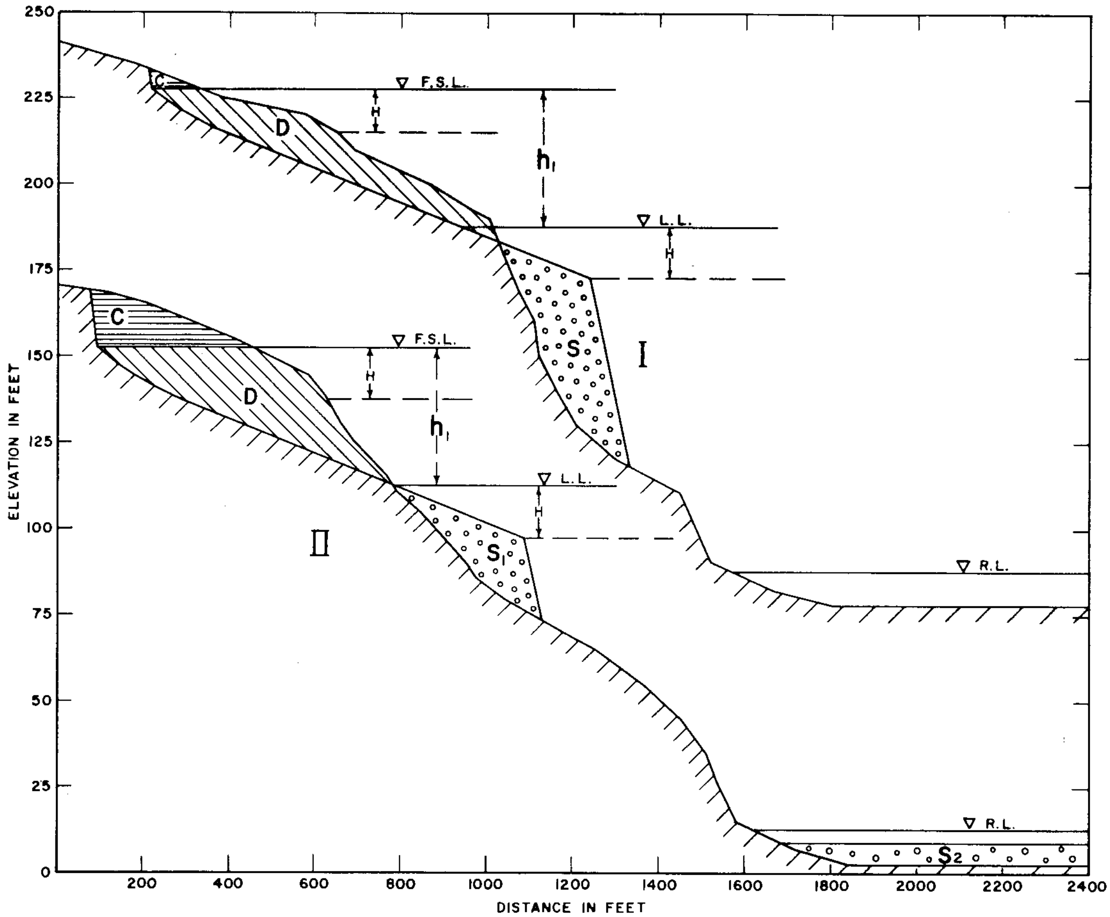


Figure 17. Erosion and sedimentation sections, west bank of Diefenbaker Lake near Riverhurst Ferry. I. Across a 'headland'; II. Through a gully. Location shown on Figure 2.

F.S.L. = Full supply level
L.L. = Low level
R.L. = Original river level
C = Theoretical extent of erosion above F.S.L.
D = Theoretical extent of erosion between F.S.L. and L.L.
S, S_1 and S_2 = Sediment derived from bank erosion.

LOCAL EFFECTS OF BANK EROSION ON DIEFENBAKER LAKE

Storage Capacity

Erosion of the banks of any newly established reservoir affects the economics of the reservoir in a number of ways.

First of all, the erosion of slopes along the valley will contribute to sedimentation in the reservoir. The material for part of the sediments will originate below low-water level. This part of the erosion-sedimentation process tends to change the shape of the reservoir's cross-section without affecting the storage capacity. The remaining erosion products (sediments) will originate either between the low and full-supply levels or above the full-supply level (hereafter abbreviated to F.S.L.). These will contribute to reduction of the total storage capacity of the reservoir available at low, intermediate and full-supply level.

The sections of Figure 17 (I - across a headland cliff and II - through a gully) illustrate these points. The sections are based on the "stable-shelf" concept of Kondratjev (1966). Assumptions made are as follows:

1. Little or no erosion occurs below low-water level.
2. $M_n = 0.1$, which is one half the value for gravel and about three times that for fine sand.
3. $M_o = 0.05$, which is equal to the value for gravel and ten times that for fine sand.
4. The outer slope of the "stable shelf" is 30 degrees, which is on the large side and tends to restrict the amount of material needed to build the submerged part of the shelf.
5. The exposed cliffs above the "stable shelf" will be able to stand slope angles of between 30 and 40 degrees, which seems a reasonable assumption on the basis of existing slopes.
6. The original shore of the reservoir consists of headlands separated by gullies, the headlands taking up about four fifths of the shorelength and the gully areas about one fifth.

The cross-sections of Figure 17 have been drawn with a vertical exaggeration of eight times.

Deposition of the material derived from above F.S.L. (C in Figure 17) reduces the total storage capacity available at F.S.L. Deposition of material derived from between low level and F.S.L. (D in Figure 17) reduces the total storage capacity available at low level. The material produced may be in excess of that needed for the building of the submerged part of the shelf (S_1 in Figure 17); in that case the excess is deposited on the bottom of the reservoir (S_2 in Figure 17).

Tentative amounts, for one side of the reservoir, in cubic feet per foot of reservoir length, derived from Figure 17 are:

Figure 17-I : C = 250; D = 7,500; S = 7,750

Figure 17-II : C = 3,250; D = 10,000; S_1 = 3,900; S_2 = 9,350

Applying the headland-to-gully ratio of 4:1 to these figures, we arrive at average amounts of

C = 850 cu. ft/ft; D = 8,000 cu. ft/ft

Assuming that three quarters of the length of the reservoir is subject to erosion over the full fluctuation range of 40 feet gives a net eroded shore length of

2 x 3/4 x 140 = 210 miles.

Reduction in total storage capacity at F.S.L., in cubic feet, thus would be

$210 \times 5280 \times 850 = 942 \times 10^6$ cubic feet or approximately 21,600 acre-feet. The decrease of the storage capacity available at low level is

$210 \times 5280 \times 8850 = 9812 \times 10^6$ cu ft or approximately 225,200 acre-feet.

These figures represent a reduction in F.S.L. storage capacity of about one quarter of one per cent, and a reduction in low-level storage capacity of about four per cent.

Notwithstanding this real decrease in total storage capacity, it should be realized that for a power and irrigation reservoir, like Diefenbaker Lake, the most important practical quantity is the usable storage, or the storage capacity of the reservoir between low level and F.S.L. As most of the erosion will remove material from the range between these two levels, the erosion phenomena may be regarded as beneficial in as far as they produce an increase in usable storage. On the basis of Figure 17, the increase in usable storage can be estimated at $8,870 \times 10^6$ cu ft, or approximately 203,600 acre-feet. This represents about 7.4 per cent of the original usable storage of 2,750,000 acre-feet.

Beach Formation

The formation and gradual increase in width of an accumulation shelf along its shore will affect the recreational use of Diefenbaker Lake. Accumulation of boulders in certain areas, resulting from erosion of glacial till, may be an undesirable feature from the point of view of boat operators. The width of the zone exposed at low level will gradually increase which may create problems with boat launching facilities. A maximum width of about 700 feet, with a slope of about three degrees can be foreseen from Figure 17. The zone will be virtually devoid of vegetation.

Evaporation

The erosion of the reservoir shore will also result in increased surface area, contributing to loss of water by evaporation. The average width of Diefenbaker Lake, with a length of 140 miles and a surface of 109,600 acres, is 1.22 miles or about 6,450 feet. Bank erosion, which had already reached 100 feet in some places by the autumn of 1967, may widen the reservoir as much as 300 feet on both sides, based on Figure 17. This means an increase in surface area of about 7,640 acres, using the same "effective" reservoir length of 105 miles as in the preceding paragraphs. Combined with a net annual evaporation of the order of 20 inches (1.67 feet), this would mean the additional loss of about 12,750 acre-feet of water per year.

CONCLUSIONS

The effects of bank erosion on Diefenbaker Lake, Saskatchewan can be summarized as follows:

1. Decrease in total storage capacity, available at F.S.L., by as much as 21,600 acre-feet.

2. Decrease in total storage capacity available at low level by as much as 225,000 acre-feet.

3. Increase in usable storage by as much as 204,000 acre-feet (or 7.4 per cent).

4. Increase in potential evaporation by as much as 12,750 acre-feet per year.

5. Creation of a horizontal fluctuation zone of up to 700 feet wide along both sides of the reservoir, with a slope in the order of three degrees, and without vegetation.

6. Creation of shallows extending up to 300 feet from the low water line, also with a slope of about three degrees.

7. A large part of these changes will occur during the early life of the reservoir. Judging by the present rate of bank erosion a period of between five and ten years from the time F.S.L. is first reached, should be adequate to accomplish up to 90 per cent of the changes.

8. Sediments from South Saskatchewan River probably do not form an important part of the sediments deposited in the lower reaches of Diefenbaker Lake at the present time. Differentitation between river sediment and sediment derived from local bank erosion, however, is difficult because of the wide variety of grain-size distributions that can be expected from the erosion of glacial deposits.

9. Experiments with solid tracers in various grain-size fractions would be useful to study the distribution, both in time and space, of the products of bank erosion.

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