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R. O. van Everdingen

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ABSTRACT

The South Saskatchewan Dam is impounding a reservoir in the valley of South Saskatchewan River, which will eventually be 140 miles long, with a depth of water at the dam of 187 feet. Piezometers were installed near Riverhurst, Sask., in three sandstone aquifers in the Upper Cretaceous formations underlying the reservoir, to determine 1) the natural groundwater movement; 2) aquifer parameters on which to base a prognosis for future changes in the groundwater regime that will result from filling of the reservoir; 3) the actual changes when they occur, during and after filling.

Aquifer tests yielded hydraulic conductivity values between 0.1 and 1.0 inch/hour; storage coefficients between 1×10^{-4} and 3.3×10^{-5}; barometric efficiency values ranging from about 20 to around 40 per cent. Discharge from these aquifers to the river was calculated to be 214 cubic feet per day per 100 feet length of the valley. The increased surface-water head is expected to reduce this amount by up to 57 per cent.

The hypothetical distribution of increases in total head for the three bedrock aquifers was determined through an electric analog model. The time needed to reach a new equilibrium (higher water levels in wells in both surficial deposits and bedrock) will be fairly long for areas not immediately adjacent to the reservoir. Additional reservoir effects may be waterlogging and increased soil salinity in some areas, improved moisture conditions in others.

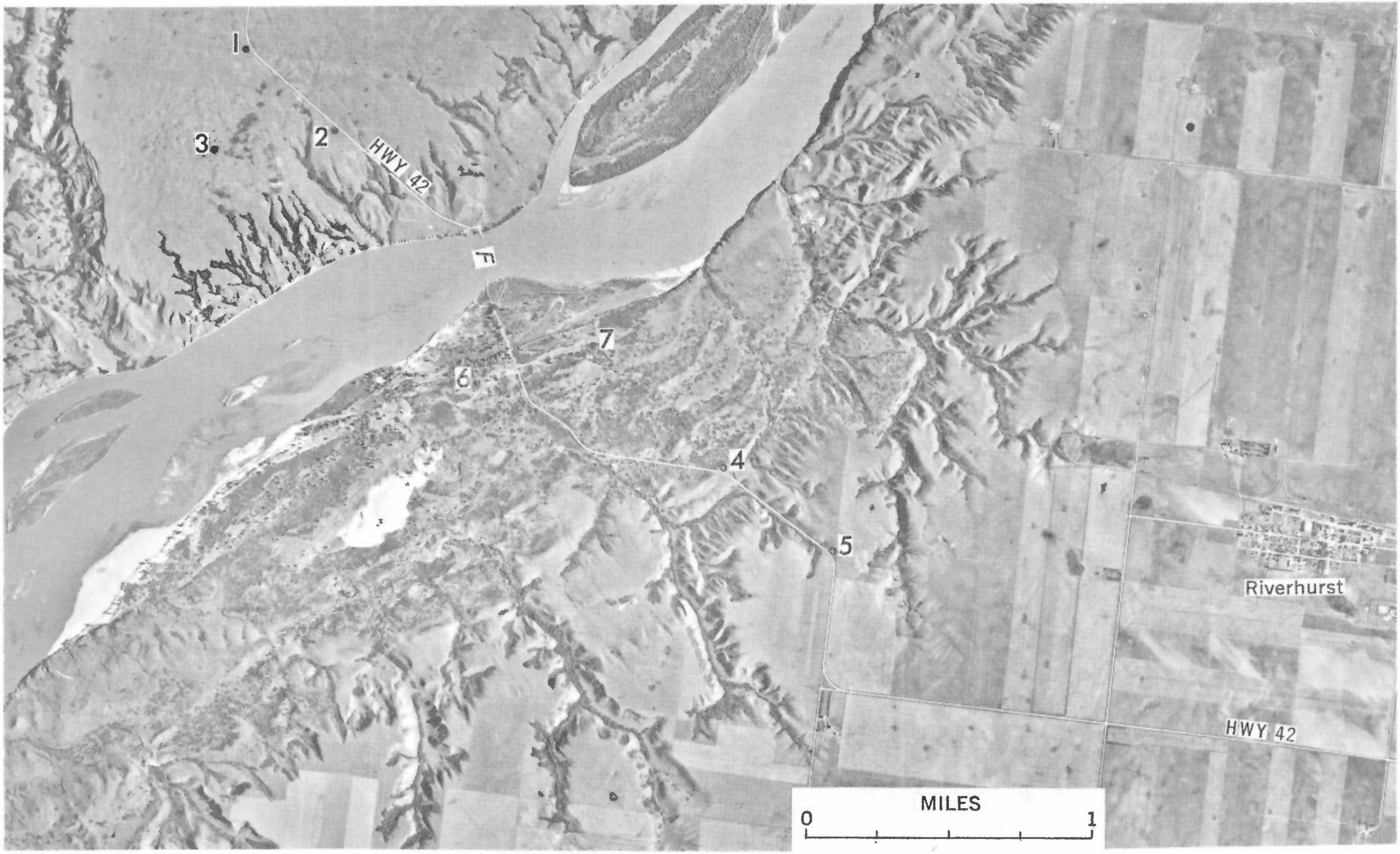

Plate I. The valley of South Saskatchewan River at the Riverhurst ferry (Highway 42), in May 1958. Piezometer nests are indicated by number (RCAF A15983-122).

THE INFLUENCE OF THE SOUTH SASKATCHEWAN RESERVOIR ON THE LOCAL GROUNDWATER REGIME. PART I. A PROGNOSIS

INTRODUCTION

In their treatise "Géologie des barrages et des aménagements hydrauliques" Gignoux and Barbier (1955) state on page 217:

> "The creation of a storage reservoir may result in an increase in the elevation of the watertable in the neighbouring area, both upstream and downstream from the dam. The increase in the watertable elevation may have important agricultural consequences, making the terrain too moist for some crops, or even inundating some areas; or conversely, improving conditions in areas that were originally too dry. This is a frequent source of litigation. In order to determine the responsibility of the construction agency it is often advantageous to carry out a series of watertable measurements before the start of construction. Also, in the case of a reservoir with strongly fluctuating storage level, the influence of rapid variations on the watertable and on slope stability should be investigated. In that case it should be kept in mind that the velocity of transmission of such variations is much higher than the velocity of ordinary groundwater flow; as a matter of fact we have to do here with the transmission of a 'floodwave', a phenomenon that has been little studied sofar".

The South Saskatchewan River Dam, under construction on the South Saskatchewan River between Elbow and Outlook, will impound a huge storage reservoir for irrigation and generation of electric power. A study was undertaken to determine the influence this reservoir will have on the groundwater regime in the reservoir area.

This is essentially a "new" problem in hydrology in the sense given to that term by Kazman (1964), in that it is concerned with an extensive man-made occurrence of hydrologic non-equilibrium.

The present report has five main sections. In the first section a short description of the physiographic setting and the geologic framework for the problem under investigation is followed by a summary of the present groundwater regime in the reservoir area as a whole.

The second section deals with the piezometer installation near Riverhurst, Sask. It describes the parameters pertinent to the present, undisturbed groundwater regime that were determined at Riverhurst (potential gradients, flow pattern, groundwater chemistry, grain size and permeability, and discharge quantities) as well as additional parameters needed for an evaluation of the influence of the South Saskatchewan Reservoir (barometric efficiency and, derived from that, the loading efficiency, coefficient of storage, and bulk modulus of compressibility of the bedrock aquifers).

The third section is a theoretical discussion of the influence of a storage reservoir on groundwater in unconfined and confined aquifers.

In the fourth section these theoretical considerations are used to determine the boundary conditions for the case of the South Saskatchewan Reservoir. These boundary conditions are applied to an analog-model study aimed at a prognosis of the distribution of the reservoir's influence on the local groundwater regime.

The final section reviews the changes to be expected as a result of flooding in the Riverhurst area, which will be checked against the prognosis by continued observations.

Acknowledgments

Valuable information was obtained through the cooperation of B. Boyson, Director, and T.W. Rey, of the Water Rights Branch, Saskatchewan Water Resources Commission; R.O. Peterson and J.G. Watson, of the Prairie Farm Rehabilitation Administration; and E.A. Christiansen, Geology Division, Saskatchewan Research Council.

Thanks are also due A. Bishop, of Lucky Lake, and W. Obarianyk, of Riverhurst, for their measurements of piezometer levels during the winters of 1962/63 and 1963/64, and to D. Matthews, P.F.R.A. Headquarters at Cutbank, Saskatchewan, for observations taken during the winter of 1964/65.

The Saskatchewan Department of Highways' Rosetown and Swift Current districts are acknowledged for their permission to install piezometers in the road allowance of Highway 42 near the Riverhurst ferry. Mr. George Bishop, of Lucky Lake, is acknowledged for his permission to install the piezometers of location 3 in his pasture south of Highway 42, as well as for his endless ferrying back and forth of men and equipment for the project.

Discussions with and advice and criticism by P. Meyboom and J.S. Scott of the Engineering and Groundwater Geology Section have greatly contributed to this study.

Drilling and installation of piezometers for the project were carried out by Sedco Exploration, Calgary, Alberta (1962), Hall Drilling, Calgary, Alberta (1963), and Stewart Drilling, Moose Jaw, Saskatchewan (1964).

Physiography

The area under study is outlined in Figure 1. It lies partly in the Saskatchewan Plains and partly in the Alberta High Plains regions of the Great Plains physiographic province (Acton et al., 1960).

Uplands within the Alberta High Plains region are Great Sand Hills (elevations between 2,200 and 2,500 feet). The Coteau (elevations from 2,000 feet to over 2,700 feet) and Vermilion Hills (elevations from 2,000 to 2,500 feet). The last two are part of the southeast-trending The Missouri Coteau. The gently to strongly rolling topography of these uplands is produced by hummocky moraine.

Uplands of the Saskatchewan Plains region within the area of study are Hawarden Hills (1,950 to 2,050 feet), and Allan Hills (2,000 to 2,250 feet). Hawarden Hills is a gently rolling plain produced by undulating moraine; Allan Hills has a gently to strongly rolling topography, caused by both undulating and hummocky moraine. All uplands mentioned reflect highs in the underlying bedrock topography, although bedrock exposures do occur only on the west flank of The Coteau and in various places in the valley of South Saskatchewan River.

The remainder of the area consists of the undulating to gently rolling surface of the Saskatchewan Plains, ranging in elevation from 1,850 to 2,000 feet; and the Alberta High Plains, with elevations up to 2,300 feet.

South Saskatchewan River, the main drainage feature, enters the area near The Forks, at the Alberta-Saskatchewan border. From there it flows in a general eastward direction until it reaches the Vermilion Hills, where the direction changes to a general northward one. The average gradient is about 1.3 feet per mile in the upstream part; 1.7 feet per mile through The Coteau, and 1.2 feet per mile north of The Coteau.

The dimensions of the valley vary from 2 miles wide and a maximum depth of 550 feet in The Coteau area, to 4 1/2 miles wide and 60 feet deep in the north of the area, near Dundurn. The actual river channel is generally close to 1/2 mile wide. It is filled completely only in the periods of maximum run-off, in late June and early July. At other times the river has the appearance of a braided stream.

Integrated drainage is lacking in large parts of the uplands. Great Sand Hills, Old Wives Lake area, and a part of The Coteau constitute interior drainage basins, without visible surface run-off. Tributary drainage to South Saskatchewan River is scarce and intermittent, with the exception of Swiftcurrent Creek.

Beaver Creek drains the area between Hawarden Hills and Allan Hills, meandering north from its origin near Hawarden. It flows through the Brightwater Marsh area and becomes tributary to South Saskatchewan River just north of the 52nd parallel, after flowing through an extensive area of sand dunes.

Eaglehill Creek, an underfit stream in a Pleistocene drainage channel, drains the southern and eastern slopes of The Bear Hills. It flows east and north from the vicinity of Rosetown, generally parallel with South Saskatchewan River, and becomes tributary to North Saskatchewan River.

Macdonald and Stonyridge Creeks drain the low areas northwest of The Coteau. Both are underfit streams in Pleistocene drainage channels. They empty in the swampy area around Goose Lake.

Aiktow Creek enters South Saskatchewan River from the southeast, near Elbow. It drains the northeastern slopes of the Vermilion Hills. A number of small creeks and coulees, draining the southern slopes of The Coteau, and the northern and northwestern slopes of the Vermilion Hills, enter South Saskatchewan River between Aiktow Creek and Swiftcurrent Creek. Among these are Snakebite Creek (from The Coteau) and Cruikshank Coulee (from the Vermilion Hills).

The only tributaries of any importance between Swiftcurrent Creek and Red Deer Forks are Antelope, Miry and Spring Creeks, joining South Saskatchewan River from the south near Cabri, Saskatchewan.

Stratigraphy and Geology

The surficial geology of Elbow map-area (NTS 72 O) has been described by Scott (1962). The glacial geology of the Swiftcurrent area (NTS 72 J/west) was described by Christiansen (1959).

The Pleistocene and Recent deposits in the South Saskatchewan Reservoir area are underlain by shales, sandy shales, and sandstones belonging to the Upper Cretaceous Bearpaw and Belly River Formations. The scarcity of bedrock exposures, combined with the incidence of slumping and landsliding along much of the valley of South Saskatchewan River, makes correlation in the Cretaceous formations difficult. Additional information obtained from drilling and electrologging of testholes has proved to be extremely useful in this regard.

Maddox has reported details on the artesian aquifers in the reservoir area, with emphasis on the Darmody-Riverhurst artesian area (1932) and on the Beaver Creek artesian area (1933).

Descriptions of bedrock stratigraphy of various parts of the area were given by Fraser et al. (1935) and Evans (1961). Information obtained from cores and electrologs from testholes near Beechy (SW corner sec. 27, tp. 21, rge. 9, W. 3) and Riverhurst (SW corner sec. 5, tp. 23, rge. 7, W. 3, and NW corner sec. 32, tp. 22, rge. 7, W. 3) was published by Meyboom (1961). A bedrock topography and water probability map for the Elbow map-area (72 O) was published by the author (1965).

The 850 to 900 feet of shales, sandy shales, and sandstones forming the Upper Cretaceous in the area between Saskatchewan Landing and Snakebite Creek were subdivided by Evans (1961) into five members. A generalized description of these in descending order is given below, while their correlation with the Beechy and Riverhurst testholes is shown in Figure 2.

<u>Vermilion Member</u> - up to 250 feet of dark grey, silty shale, containing two bentonite seams, 1 inch and 3 inches thick, at 6 feet and 7 1/4 feet, respectively above the base of the member. Only about 30 feet of the Vermilion shales are exposed in Evans' sections.

<u>Cruikshank Member</u> - 40 feet of moderately well compacted sand, light brown in exposures. The upper contact is gradational through 2 feet of sandy shale, the lower contact through about 10 feet of sandy shale. A nodule bed occurs about 12 feet below the top of the member.

<u>Snakebite Member</u> - 250 feet of dark grey shales, with seams of bentonite, horizons of nodules and layers of calcite-aragonite. The lower 55 feet are quite silty. Approximately 210 feet of this member were encountered in the testholes near Beechy and Riverhurst.

Ardkenneth Member - 70 to 109 feet of fine to very fine, well-compacted sand. Light brown in outcrops, greenish grey in fresh drill-cuttings. The lower 40 feet of this sand is crossbedded and contains some scattered nodules and an ironstone layer. The upper 30 feet contain ironstone partings. A nodule bed occurs from 2 to 3 feet below the top of the member, both in Evans' section on the north bank of South Saskatchewan River in ranges 11 and 12, and in the Riverhurst testholes. The upper contact of the member is sharp, the lower contact is transitional through sandy shales.

Beechy Member - the total thickness of this member is approximately 300 feet. It is subdivided into three shale units and two sand units.

Upper shale (5) - approximately 110 feet of dark grey, silty shale, containing a bentonite seam of 3 inches, at about 7 feet above the base of the unit. The thickness in the Riverhurst section is about 65 feet.

Upper sand (4) - 25 to 45 feet of fine to very fine, well-indurated sand, with discontinuous ironstone partings. Light brown in outcrops, greenish grey in fresh drill-cuttings. The upper contact is sharp, the lower contact is transitional through 10 to 15 feet of sandy shale.

Middle shale (3) - 50 to 85 feet of dark grey silty shales, containing an abundance of selenite.

Lower sand (2) - 15 to 20 feet (and farther west up to 40 feet) of very fine, well-compacted sand, with some nodules about 5 feet below the upper contact. Light brown in outcrops, greenish grey in fresh drill-cuttings. Both the upper and lower contacts appear to be sharp.

Lower shale (1) - 105 to 120 feet of dark grey shale in the Riverhurst section. Only about 25 feet of this unit is exposed in Evans' section. It seems to belong in part already to the Belly River Formation.

Belly River Formation - Approximately 50 feet of fine, greenish grey sand with partings of dark grey to black, hard shale were penetrated in the deepest holes in the Riverhurst section. This sandstone is probably the equivalent of the 60 feet of sand described by Fraser et al. (1935) from the upper part of the Rush Lake well, and attributed by them to the Belly River Formation.

In the Rush Lake well this sand is underlain by 230 feet of shale and a further 80 feet of sandstone.

Evans (1961) has pointed out the diachronous nature of the sands in the Upper Cretaceous in this area. Farther west, near Cabri, the lower part of what Evans described as Beechy Member of the Bearpaw Formation, is part of the Belly River-Oldman Formation. A similar diachronous trend was demonstrated by Meyboom (1961, Fig. 2) for the Ardkenneth Member in the area between Darmody and Beaver Creek (see Fig. 1), based on information contained in Water Supply Papers of the Geological Survey (1936).

The main bedrock aquifer in the Darmody artesian area correlates with the Ardkenneth Member as described by Evans (1961). Its top is encountered at elevations around 1,500 feet above sea-level, and it is overlain by up to 225 feet of shale, the equivalent of Evans' Snakebite Member. South and west of Darmody the sandstone aquifer is found at increasingly higher elevations; the rate of rise varies from 5 to 12 feet per mile. The elevation of the aquifer at Chaplin is 1,710 feet above sea-level (Maddox, 1932). Another sandstone aquifer is found 200 to 300 feet above the Ardkenneth Member in this area, correlating with Evans' Cruikshank Member farther west.

North and northeast of Darmody the top of the Ardkenneth Member is encountered at successively lower elevations (e.g. 1,350 feet above sea-level in a well in SW 1/4, sec. 30, tp. 23, rge. 3, near the Qu'Appelle dam site). Around Craik it seems to merge with the underlying sandstone of the Beechy Member equivalent. Still farther north, in the Beaver Creek artesian area, there are two separate sandstone sequences again, the top of the upper one having an elevation around 1,500 feet above sea-level, whereas the top of the lower one lies at elevations around 1,330 feet above sea-level. The upper sandstone in this area is plainly the equivalent of the Ardkenneth Member, as designated by Evans, although in this area we are no longer dealing with the Bearpaw Formation but with the Belly River Formation (Fraser et al., 1935).

The artesian aquifer encountered in drill-holes at the site of the South Saskatchewan River Dam, and designated by the P.F.R.A. staff as Belly River aquifer, must also be equivalent to Evans' Ardkenneth Member. Its top lies at an elevation of approximately 1,450 feet above sea-level (see Fig. 17). In that case the sandstone encountered at the dam site near elevation 1,700 feet would be the equivalent of Evans' Cruikshank Member.

The sandstones described by Evans in his North Elbow section (SE 1/4, sec. 5, tp. 26, rge. 6, W. 3) and south of the Outlook bridge (west bank in sec. 16, tp. 29, rge. 8, W. 3) must also be equivalent to the Cruikshank Member. In both locations they occur too low for simple correlation. It is, however, apparent from the examination of aerial photographs that the outcrops in both locations are part of slumped blocks. Field measurements at Outlook indicate an outcrop elevation of approximately 1,650 feet above sea-level, which combined with probable slump subsidence of 80 feet would indicate an original elevation of around 1,730 feet above sea-level.

The stratigraphic information available indicates that the sandstones in the western part of the area under study have a dip of 10 to 12 feet per mile in an east-northeasterly direction; in the Darmody area they show a comparable dip to the north or northeast, whereas in the Beaver Creek-Hawarden Hills area a small dip to the south or southeast is apparent.

Depending on location and topographic elevation, each of the sandstone beds in turn may have a certain importance as the aquifer supplying most domestic, municipal, and farm wells. Insofar as the sandstones do occur below the future storage level of the South Saskatchewan Reservoir, they constitute potential avenues of leakage from the reservoir. Further reference to this aspect will be made in that part of this report dealing with the influence of the reservoir on groundwater.

GENERAL GROUNDWATER REGIMEN

Groundwater Potentials and Groundwater Movement

Hubbert (1953, p. 1959) stated - "an element of water at any point possesses energy with respect to its environment which, when referred to unit mass, we may speak of as its potential Φ."

The total fluid potential Φ is expressed as total hydraulic head (h), defined as the sum of pressure head $\frac{p}{\rho g}$ and elevation head z:

$$h = z + \frac{p}{\rho g} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

where z = elevation of the point of measurement above an arbitrary datum plane;

p = hydrostatic pressure at the point of measurement;

ρ = density of the fluid (volume per unit mass);

g = acceleration due to gravity.

Losses in total hydraulic head from one point to another indicate energy consumed in overcoming frictional resistance to flow. Kinetic energy is disregarded in the above equation because it is usually negligible in groundwater systems.

In a groundwater system total hydraulic head can be measured for any point P. In a tightly cased well, ending at that point P and open at the bottom only, total hydraulic head is the sum of the elevation of the bottom of the well, and the height to which the water will rise in that well.

When total hydraulic head is known in a sufficiently large number of points in a groundwater system, surfaces of equal hydraulic head at a particular time can be constructed to illustrate the variation of total head in three dimensions at that time.

At the watertable where the fluid pressure is equal to the atmospheric pressure that acts on the whole system, the term $\frac{p}{\rho g}$ is taken as zero. Thus for any point on the watertable total hydraulic head is equal to the elevation of that point above datum. Contour lines on the watertable are thus lines of equal head, marking the intersection of surfaces of equal hydraulic head with the watertable.

Steady-state flow of groundwater is governed by Darcy's law, expressed by Hubbert (1953, p. 1967) as

$$q_z = -P'\frac{dh}{dz} \quad \ldots\ldots\ldots\ldots \quad (2)$$

for the case of vertical flow, where

q_z = flow vector in vertical direction;

P' = permeability of the rock in vertical direction;

$\frac{dh}{dz}$ = head gradient in vertical direction.

The negative sign indicates that flow is in the direction of decreasing head.

It follows that in a homogeneous-isotropic medium the lines of flow (flow vectors) are perpendicular to the surfaces of equal hydraulic head. In inhomogeneous and anisotropic media the situation is more complex, but a qualitative evaluation of the flow pattern can still be made on the basis of total-head data.

In general, the earth provides an inhomogeneous and, to a certain extent, anisotropic framework for the flow of groundwater and other fluids. The flow system will tend to follow a route of least resistance through the framework, mainly by crossing beds of low permeability as nearly as possible at right angles to the bedding planes, and travelling through the more permeable beds nearly parallel to the bedding planes over long distances.

In a flat-lying series of alternating shales and sandstones, like the Upper Cretaceous in the area of the South Saskatchewan Reservoir, groundwater will have a decided tendency to flow nearly vertically through the shales, and laterally through the sandstone beds, from the recharge areas to the stream valleys. The influence of anisotropy will probably be slight because of the preferential directions of flow caused by the differences in permeability. Flow lines and lines of equal head will, therefore, be approximately perpendicular to one another within each bed; both are refracted more or less sharply at the contacts between permeable and less permeable beds.

Topography in the reservoir area consists of a plain, which is roughly 200 to 250 feet above an incised river valley, and a number of uplands rising 150 to 600 feet above the plain. The river valley is filled to a depth of about 100 feet with unconsolidated deposits (gravel, sand, silt, clay, and till). It forms the main avenue of groundwater discharge. The groundwater may either enter the stream and leave the area as surface run-off, or flow through the unconsolidated deposits as underflow. A part of the discharge may be consumed by extensive vegetation on the flood-plain of the river (evapo-transpiration). The uplands and parts of the plain constitute the areas for recharge to the Upper Cretaceous aquifers; depressions and the valleys of intermittent creeks may act as further discharge areas for the aquifers.

Thus the general pattern of the groundwater flow is downward under the uplands; horizontal and outwards from the uplands toward depressions and river valleys; and upward under the valleys. These 'local' circulation systems may be superposed on larger, regional systems, moving at greater depth and conditioned by topographic features of a higher order of magnitude.

The difference between the recharge and discharge areas can be further demonstrated by the performance of wells. Total hydraulic head decreases with increasing depth in a recharge area, resulting in an increasing depth to water in cased wells of increasing depth. Conversely, in a discharge area total hydraulic head increases with depth, resulting in a decrease of depth to water in cased wells of increasing depth; even to the point where a well may start flowing at the surface. Therefore deepening of an existing well in a recharge area will usually increase pumping lifts, whereas in a discharge area this procedure may decrease or even eliminate pumping lifts.

Figure 1 shows the approximate piezometric distribution for the Upper Cretaceous aquifers for the eastern part of the South Saskatchewan Reservoir area, based on data collected by the Geological Survey of Canada in 1935 and published in the form of Water Supply Papers. Most of the bedrock wells in the area tap the Ardkenneth Member (or its equivalent). Some wells, however, end in the Beechy Member (or its equivalent) or even in the first sandstone of the Belly River Formation (see Figs. 2 and 6). Thus not all data available on total hydraulic head pertain to the same aquifer or to a plane of a fixed elevation. Besides, even the wells in the upper (Ardkenneth) aquifer do not all end at the same depth below the top of the aquifer. The errors caused by this are, however, largely restricted to the central part of the uplands and to the immediate vicinity of South Saskatchewan River. As few data are available in these particular places, and because no change in the piezometric contours was necessary for the addition of total-head measurements from recently drilled wells, it is felt that Figure 1 gives a good approximation of the piezometric distribution for most of the area.

The occurrence of groundwater discharge through bedrock aquifers towards the South Saskatchewan River valley indicated by the piezometric distribution in Figure 1 was demonstrated by the results of tritium analyses of South Saskatchewan River water, carried out by the Saskatchewan Research Council[1]. These results showed that groundwater contribution to river flow occurs fairly uniformly along the course of the river during the period from August to January. They account for up to 50 per cent of the mid-winter base-flow. The groundwater contributed is apparently of good quality, with a chemical composition suggesting that it originates in glacial drift. The tritium content of these waters suggests, however, that they are generally older than well-water samples of similar quality. A survey of major artesian well waters in the province revealed a uniform and consistently low tritium content for these waters.

The longer flow path to the river channel may account for the higher apparent age of the discharged water. On the other hand it may be assumed that groundwater discharge is also derived from the artesian aquifers, which would also account for the higher age. Further reference to the occurrence of groundwater discharge from bedrock is made in the description of the flow pattern for the Riverhurst piezometer installation. The general piezometric distribution shown in Figure 1 forms the basis for the assumption made in the chapter on manifestations of reservoir influence, that the ultimate potential gradients for the bedrock aquifers will still be directed towards the South Saskatchewan valley (Reservoir).

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[1]Saskatchewan Research Council, Annual Report 1963, p. 19.

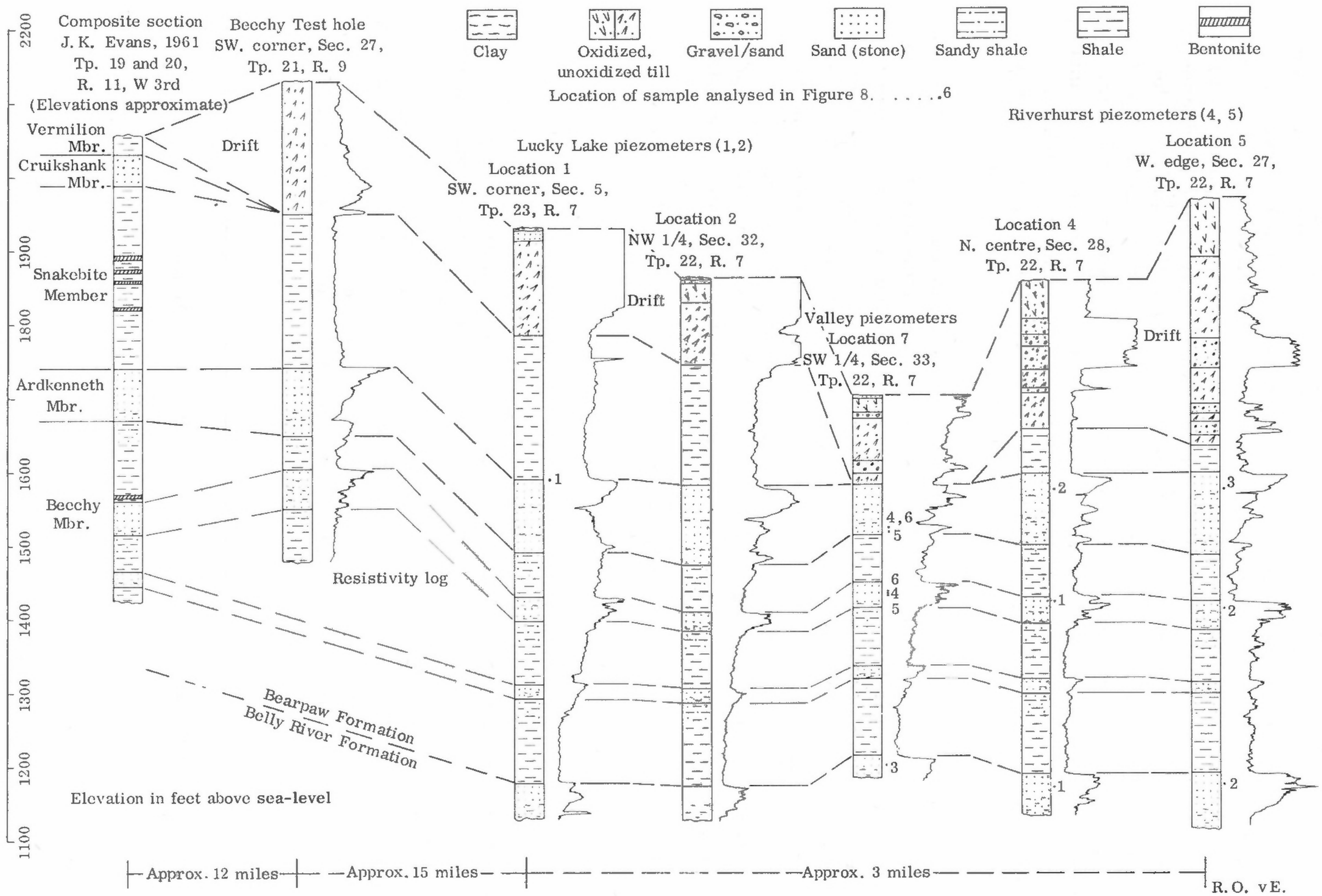

Figure 2. Stratigraphic correlation of Upper Cretaceous formations, South Saskatchewan Reservoir area

Hydrochemistry of the Upper Cretaceous Aquifers

The small number of complete chemical analyses available from bedrock aquifers in the area under study does not enable the construction of a detailed picture of the variations of ionic content. Analyses given in the Water Supply Papers of the Geological Survey of Canada enable the construction of a contour map for total dissolved solids only for the northeastern part of the area.

The contours for total dissolved solids shown in Figure 1 in a general way confirm the flow directions indicated by the piezometric contours. They indicate an increase from less than 2,000 to over 3,000 parts per million (ppm) from the topographic high of Allan Hills towards South Saskatchewan River. For the remainder of the area east and south of the river total dissolved solids usually range from 900 to 1,600 ppm. In the southwest corner of the area concentrations of up to 3,200 ppm have been recorded.

Groundwater is generally of the sodium-sulphate type in the upper sandstone, and of the sodium-chloride type in the deeper sandstones. Waters from the deeper sandstones usually contain a higher concentration of total dissolved solids. In contrast, the waters from surficial deposits are mainly of the calcium and magnesium-carbonate or sulphate type. The range of concentrations of total dissolved solids is quite large, from little over 500 to as much as 3,500 ppm. The contrasting composition of the bedrock waters is regarded as the result of exchange of calcium and magnesium ions from the drift water for sodium ions from clays and shales.

Details on the chemistry of waters from surficial deposits and bedrock in the Riverhurst area are discussed in the next chapter (the Riverhurst Piezometer Installation). They appear to fit very well in the general pattern described above. A tabulation of the chemical analyses from that area is presented in Appendix III.

THE RIVERHURST PIEZOMETER INSTALLATION

Introduction

The piezometer installation near Riverhurst, Saskatchewan, described below, was designed to serve a dual purpose: (1) evaluation of the natural, undisturbed groundwater regime near the future South Saskatchewan Reservoir, and (2) assessment of the changes in the groundwater regime due to the creation of that reservoir.

Determination of the stratigraphy of the section, and piezometric levels for the various aquifers enabled construction of a qualitative natural flow pattern. Groundwater chemistry was investigated to enable detection of future changes. Grain-size analyses were made and permeability tests run on some of the piezometers to obtain permeability values that enabled calculation of approximate amounts of groundwater discharge through the bedrock aquifers under natural conditions.

In order to make a prognosis of future changes it is required to have an understanding of the additional aquifer parameters of loading efficiency, storage coefficient and bulk modulus of elasticity that control the influence of a surface reservoir. Values for the barometric efficiency (and the related loading efficiency) reflecting the reaction of pressures in an aquifer to external loading, were determined for the bedrock aquifers. They enabled calculation of the coefficients of storage for the aquifers, as well as values for the bulk modulus of compressibility of the aquifer skeleton. The latter are used in the chapter on the influence of the South Saskatchewan Reservoir to determine probable amounts of compaction of the aquifers under loading.

In the Riverhurst area the flat-lying Upper Cretaceous strata are overlain by unoxidized (blue) till, the upper part of which is commonly oxidized to a brown colour. On the east side of the valley some extensive beds or lenses of coarse sand and gravel were encountered in the till. The thickness of these ranges up to 70 feet (location 4, Figs. 2, 3, and 6). On the west side of the valley only a few feet of surface sand and fine gravel are present.

The central part of the valley is largely filled with till, containing some gravel lenses. The upper part of the valley fill consists of Recent alluvial sand, silt and some fine gravel.

The depth to bedrock found in the valley is 120 feet in location 7 and 148 feet in location 6. The slope of the bedrock surface from location 4 to location 5 (see Fig. 6) indicates the existence of an old drainage channel in this area.

Installation, Procedure and Measurements

A total of 28 piezometers in eight nests were installed in the Riverhurst-Lucky Lake area in the years 1962, 1963, and 1964 (see Fig. 3 and Plate I). Nests 1, 2, and 3 are located on the west side of the valley, in a triangular pattern; nests 4 and 5 on the east side of the valley; and nests 6 and 7 in the bottom of the valley, on a line at right angles to the general direction of the main section.

In all but nest 3, piezometers were placed in the drift, in the sandstone of the Ardkenneth Member, in the upper sandstone (4) of the Beechy Member, and in the upper sandstone of the Belly River Formation. Nest 3 contains only two piezometers, in the Ardkenneth Member and in the Belly River sandstone. Distances between adjacent piezometers in one nest range from 15 to 30 feet.

The piezometers in glacial drift are installed in till in nests 1, 2, and 7; in gravel in nests 4 and 5; and in sand and gravel in nest 6.

In each of the nests 2 and 4 two piezometers were placed in the Ardkenneth Member, in order to provide a link between nests 1 and 5 with piezometers near the top of the sandstone, and nests 6 and 7 with piezometers near the base of the sandstone. In addition this arrangement afforded a check on possible vertical gradients within the Ardkenneth Member.

The installation procedure for the piezometers is illustrated in Figure 4. The piezometers were installed in rotary-drilled holes with a diameter of 4 1/2 inches. They consist of 2-inch steel pipe in 20-foot lengths, with a 3-foot, number 10, slotted sandpoint (except in 4A, having a 5-foot sandpoint, and 4B, having number 12 slots). Above the sandpoint a metal-petal basket or rubber basket was mounted to support the cement seal. The cement was pumped down the annulus through plastic hose or 3/4-inch steel pipe. In some cases part of the drilling fluid was washed out of the annulus before placement of the cement. After the cement seal had properly set, the inside of the piezometer was washed out, again using either plastic hose or 3/4-inch steel pipe. The piezometers were developed either by swabbing or air-jetting. Some water samples for chemical analyses were obtained at this time.

After proper development most of the piezometers were left to recover. Piezometers in nests 4 and 5 were filled with river water and the regression of the water-level to static level was recorded.

Measurements of depth to water in the piezometers are made with an electric tape at 2 to 4 week intervals. Positive head on flowing piezometers in nests 6 and 7 was measured with standard pressure gauges. Additional details regarding depths, elevations, etc. are given in Appendix II.

Sensitivity of Piezometers

The sensitivity of open piezometers is a function of the diameter of the pipe and the permeability of the material in which they are placed. Inside a 2-inch piezometer fluctuations of the water-level of the order of

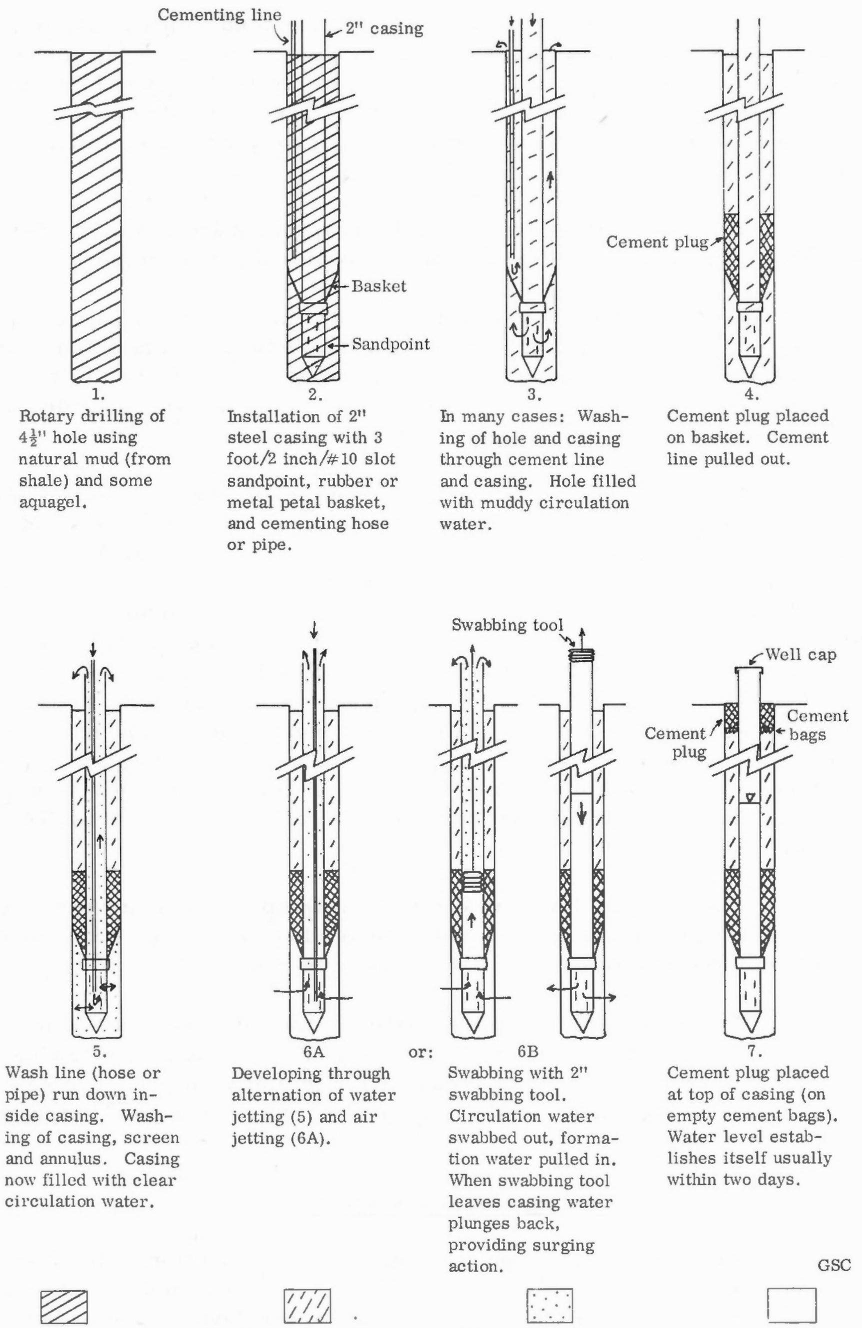

Figure 4. Installation method of deep piezometers

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1 foot are accompanied by groundwater inflow or outflow of the order of 0.15 gallon. Thus, open piezometers may be subject to a time lag varying from less than a minute to several days.

Hvorslev (1951) stated that "as a measure of sensitivity, an equalization ratio of 0.90 may be considered adequate for many practical purposes and corresponds to a time lag equal to 2.3 times the basic time-lag. An equalization ratio of 0.99 requires twice as long as 90 per cent equalization". For our purpose we use the 90 per cent equalization time E_{90}. In the section dealing with the permeability of the bedrock aquifers the basic time-lag method is used for the determination of permeability. The E_{90} times were determined from semi-log plots of water-level recovery in the piezometers after the water-level has been drawn down a few feet; the results were checked against the theoretical relation $E_{90} = 2.3$ T the basic time-lag in minutes.

For piezometers in the Riverhurst installation the E_{90} values obtained range from 8 to 78 minutes (see Table II, column 4). All but one of the nine determinations gave values for E_{90} smaller than 20 minutes.

Further reference to the significance of these low equalization times will be made in the subsection dealing with the barometric efficiency of the bedrock aquifers.

Natural Flow Pattern

Figures 5 and 6 illustrate the groundwater flow pattern for the Riverhurst section under natural conditions. The lines of equal head in these two figures are based on measurements taken during the fall of 1964. They demonstrate in a more detailed way the movement of groundwater through bedrock from both sides towards the valley of South Saskatchewan River described on a previous page and illustrated in Figure 1.

No appreciable seasonal variations in total head were recorded in any of the piezometers in bedrock since their installation. Apparently the groundwater regime in the bedrock aquifers is not affected to any significant extent by seasonal variations in precipitation and evapo-transpiration.

Fluctuations of nearly 6 feet were recorded in piezometer 6, in sand and gravel in the centre of the valley, as a direct result of the passing of the crest of the 1964 spring flood.

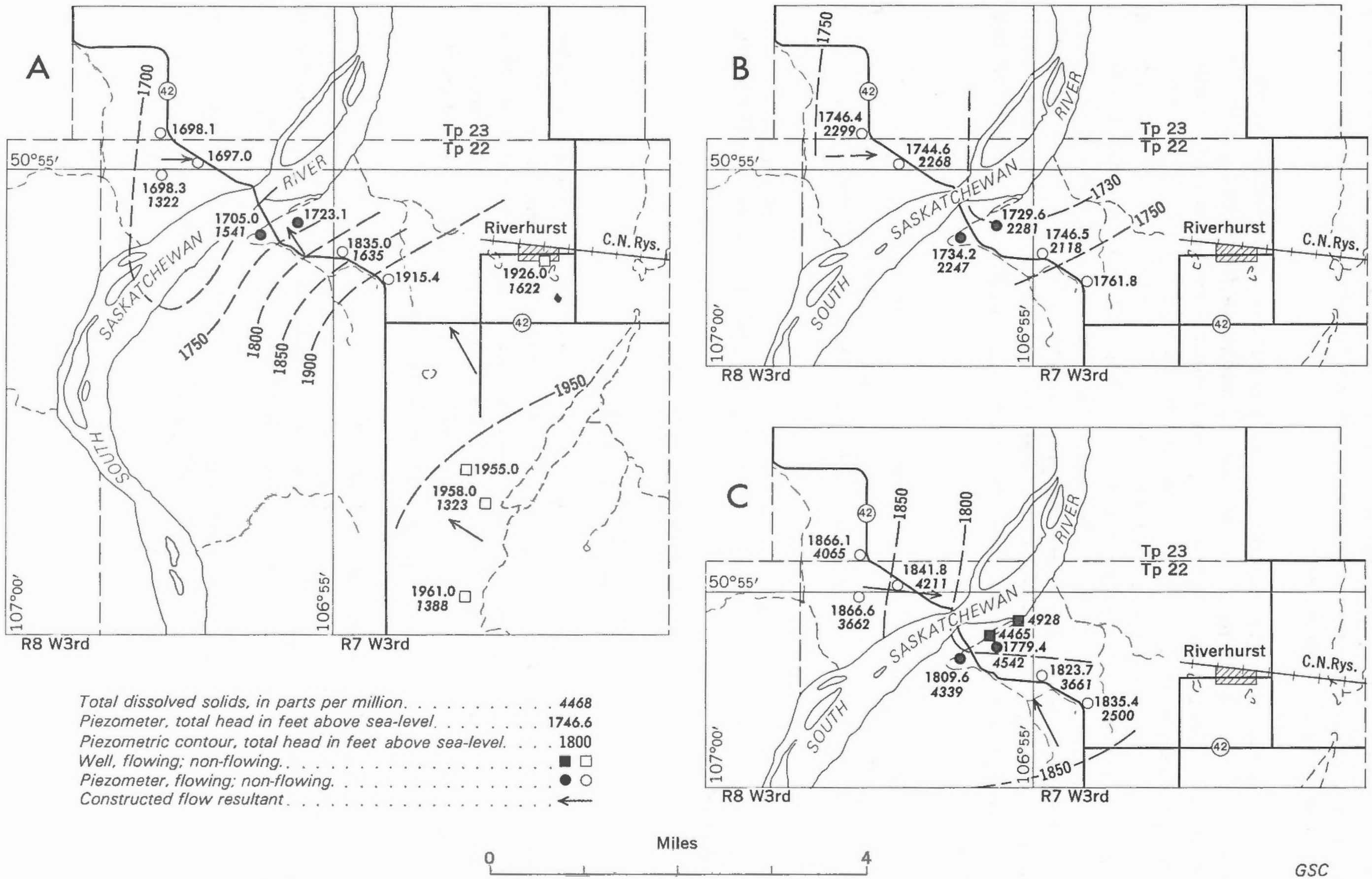

Figure 5. Piezometric contours and total dissolved solids of bedrock aquifers, Riverhurst area; A, Ardkenneth sandstone; B, Beechy sandstone 4; C, Belly River sandstone.

The head distribution in Figure 6 indicates that groundwater movement in the Cretaceous sandstones is directed toward the valley from both sides, along appreciable lateral gradients. The existence of longitudinal flow components (parallel to the river) is suggested by the configuration of the lines of equal head in Figure 5. The small head difference between piezometers 4A and $4A_1$, near the top and the base of the Ardkenneth Member, respectively, points to nearly horizontal movement of water in this part of the aquifer.

In addition to the horizontal movement of groundwater in the sandstones and in the gravels on the east side of the valley, vertical movement of groundwater must take place in the till and shales, because of the vertical gradients, both upward and downward. The horizontal and vertical gradients in the bedrock between points of measurement in the section are summarized in Table I. Downward movement prevails in the till almost all the way down both flanks of the valley. Thus the actual discharge area is restricted to the valley bottom, between elevation 1,710 on the west side and elevation 1,775 on the east side.

Table I

Range of Hydraulic Gradients in Bedrock, in ft./ft., Based on Measurements During September 1964

Horizontal gradients[1]	West side of valley	East side of valley
Ardkenneth Member	0.5×10^{-3}	3×10^{-2}
Beechy Member	1.0×10^{-3}	5×10^{-3}
Belly River sandstone	1.0×10^{-2}	1.3×10^{-2}
Vertical gradients	**Between sandstones**	**Between piezometer screens**
Ardkenneth to Beechy, east side of valley	1.37 - 2.48	0.59 - 0.94
Others	0.10 - 0.87	0.07 - 0.71

[1]In part based on Figure 6.

On the west side of the valley the downward gradient persists through the Snakebite shale in the Ardkenneth sandstone. An upward gradient exists from the Belly River sandstone, through the shales and sandstones of the Beechy Member, to the sandstone of the Ardkenneth Member. The Ardkenneth Member thus will receive some water both from above and from below.

Under the central part of the valley a continuous upward gradient is found, from the Belly River sandstone, through the Beechy and Ardkenneth Members and through the fill of the bedrock valley, to the watertable.

On the east side of the valley a more complicated pattern was encountered. A downward gradient from the watertable, through till, and an upward gradient from the Ardkenneth Member indicate that the gravel beds will receive some water from both the overlying till and the underlying bedrock. A second downward gradient, from the Ardkenneth Member, through the upper Beechy shale (5), and a second upward gradient from the Belly River sandstone through Beechy shale, show that the Beechy sandstone also receives water from both sides.

The lowest potentials measured for the Beechy and Belly River sandstones in the section lie under the central part of the valley as expected. For the Ardkenneth Member the lowest potentials were found under the western slope of the valley. The upper, more permeable part of the member has been eroded under the central part of the valley. These two facts, combined with the very high potentials in the member on the east side suggest a high resistance to movement of groundwater from the Ardkenneth Member through the valley fill on the east side of the valley. Reference to these piezometric levels and to the natural flow pattern in general will be made in the part of this report on manifestations of the influence of the South Saskatchewan Reservoir.

Chemistry of Groundwater in the Riverhurst Area

The chemical composition of groundwaters in the Riverhurst area was determined to enable detection of possible future changes in chemistry owing to the creation of the South Saskatchewan Reservoir. Samples of water for chemical analysis were collected from the piezometers and from farm and municipal wells in drift and bedrock around Riverhurst. Results of the analyses of these samples are given in Appendix III. Semi-logarithmic plots of the results, expressed in milli-equivalents, are shown in Figure 7, A to D.

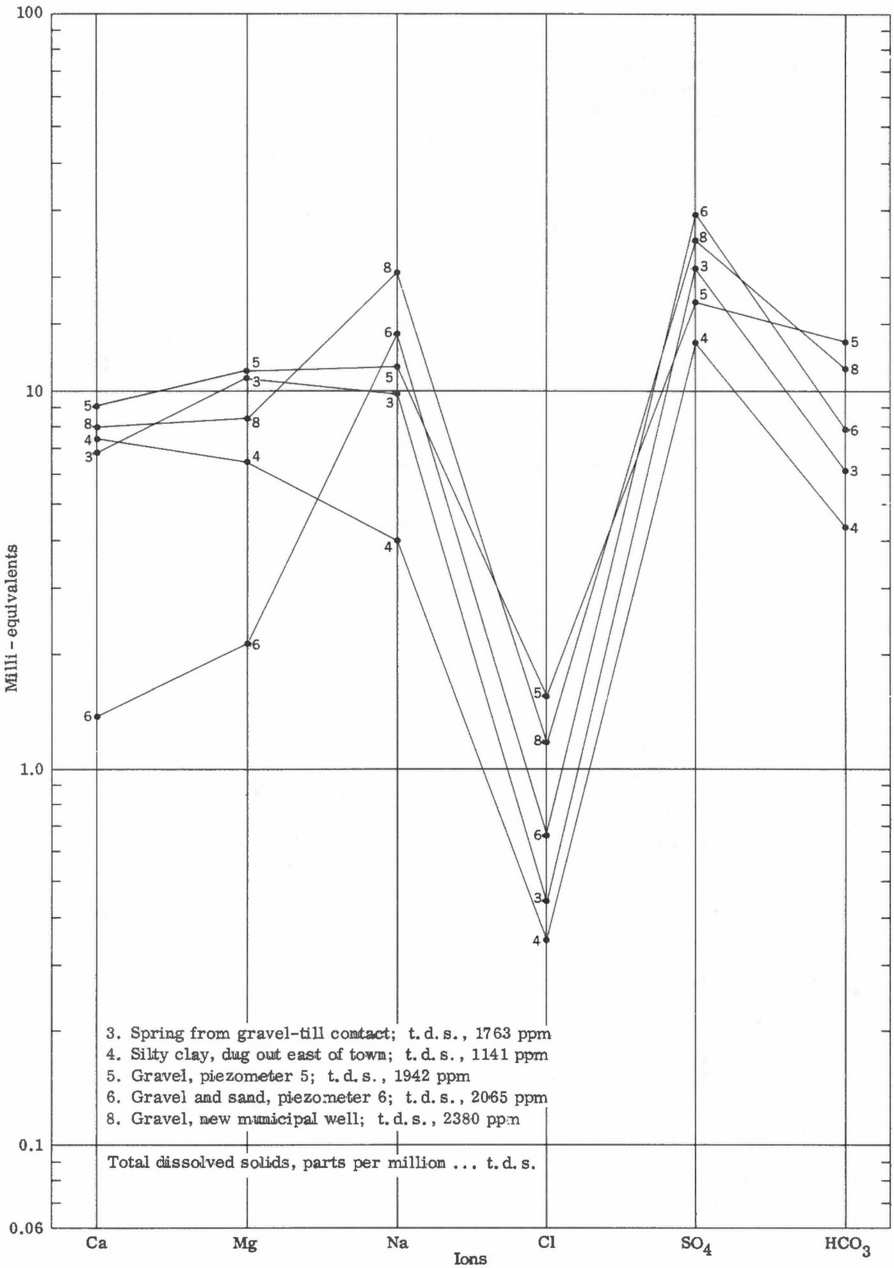

Figure 7A. Chemistry log plots of waters from Quaternary deposits, Riverhurst area.

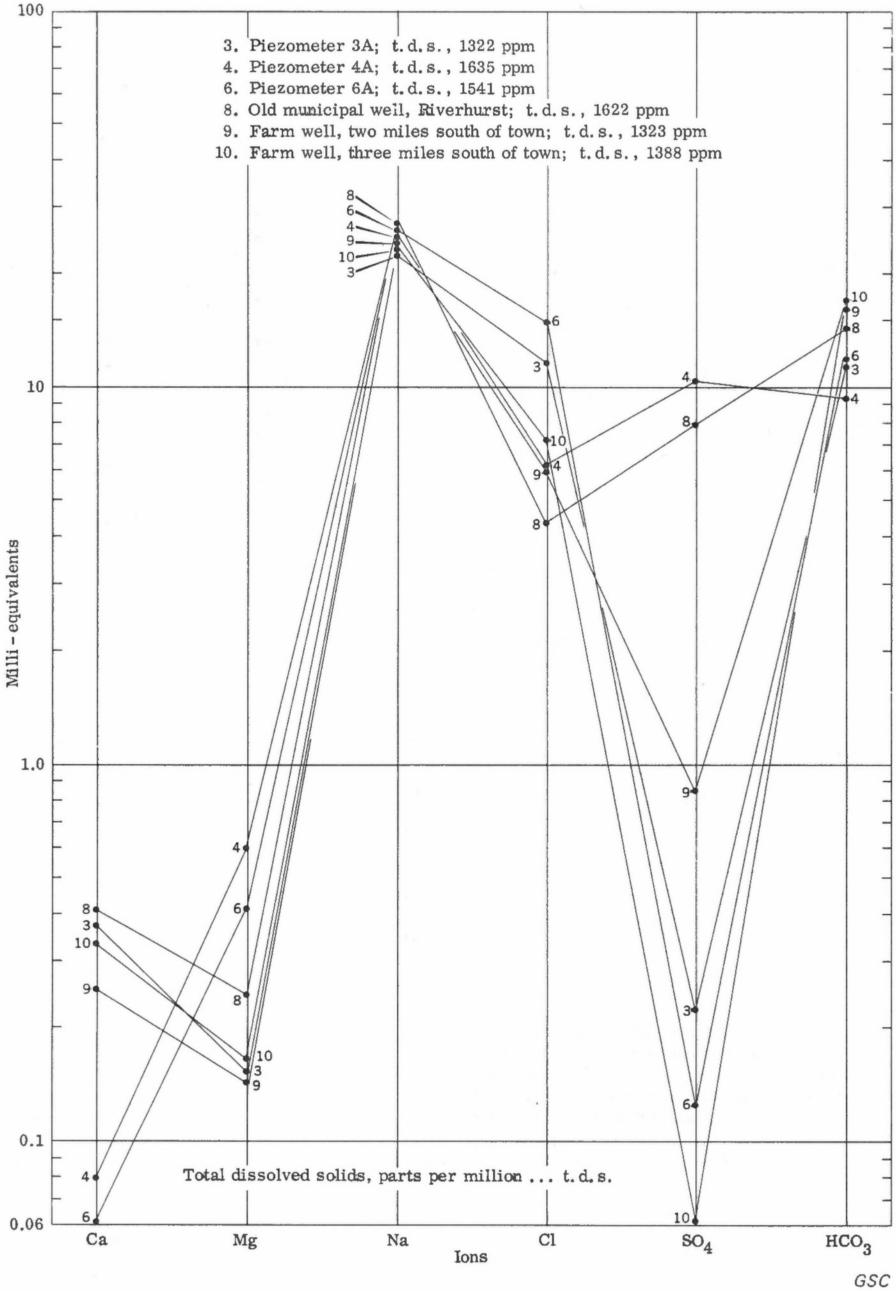

Figure 7B. Chemistry log plots of waters from the Ardkenneth sandstone, Riverhurst area.

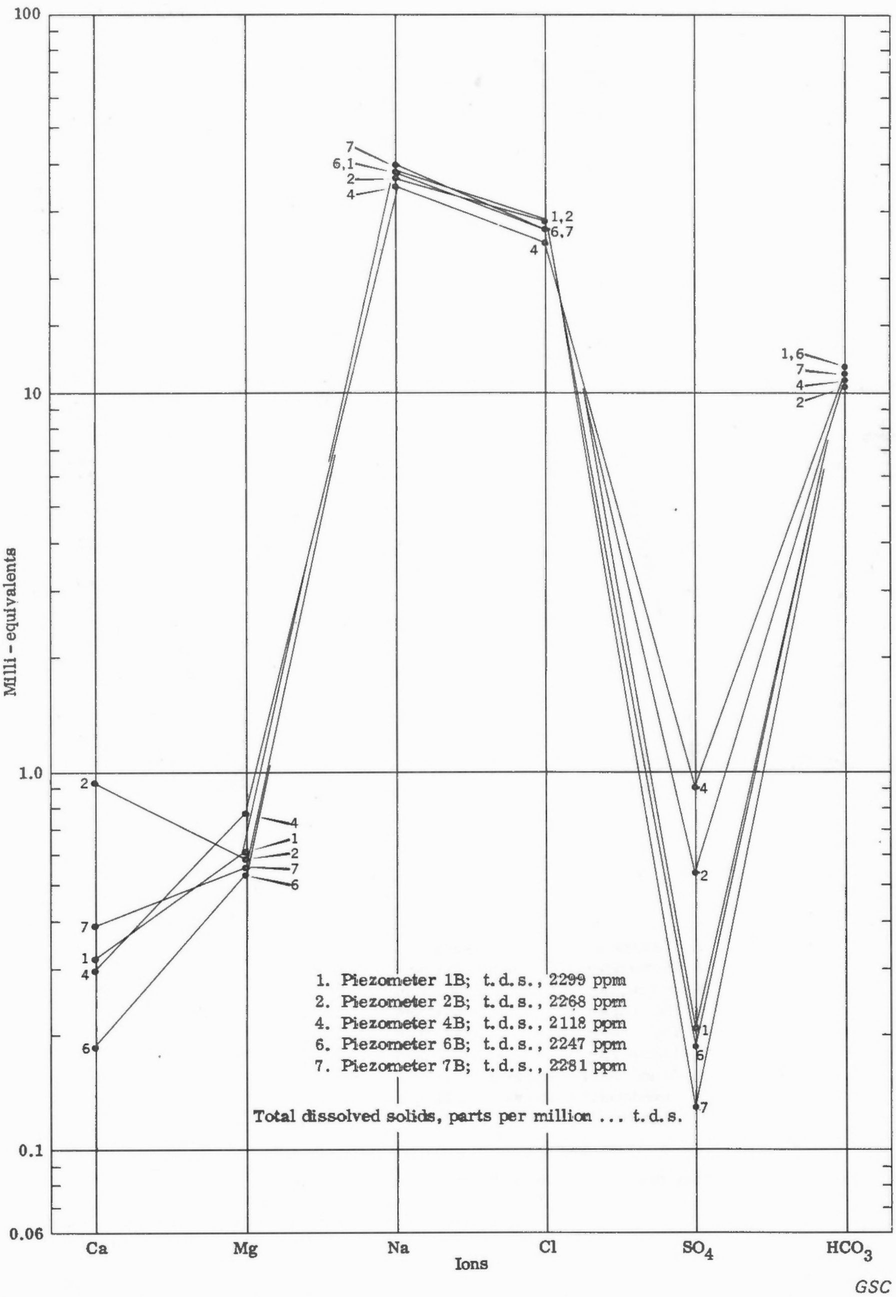

Figure 7C. **Chemistry log plot of waters from the Beechy sandstone, Riverhurst area.**

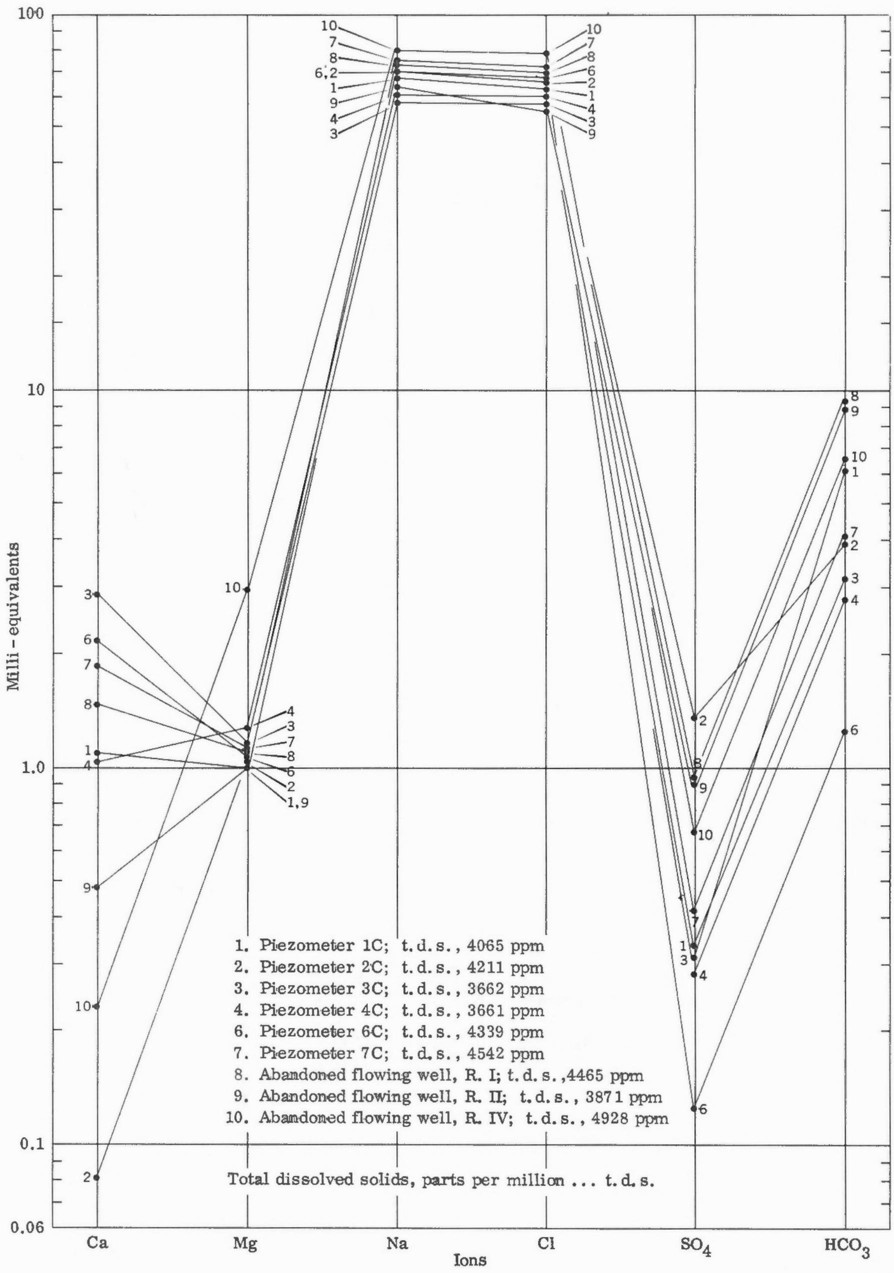

Figure 7D. Chemistry log plot of waters from the Belly River sandstone, Riverhurst area.

The amount of total dissolved solids (TDS, also indicated in Fig. 5) increases only slightly in the direction of flow in each of the aquifers in the restricted area investigated. In bedrock the amount of TDS shows a distinct increase with depth.

For the drift the TDS concentration ranges from 1,140 ppm in the dugout (see Fig. 3, W. 7) east of the town of Riverhurst, to 2,380 ppm in the gravel at 140 feet depth in the new municipal well at Riverhurst (W 5). For the Ardkenneth Member concentrations lie around 1,500 ppm, for the Beechy Member around 2,200 ppm, and for the Belly River sandstone between 3,600 and 4,900 ppm. The upward movement of groundwater towards the gravel on the Riverhurst side, suggested by the head distribution on Figure 6 is supported by the unusually high concentration of total dissolved solids found in the gravel.

Not only the concentrations of TDS but also the relative concentrations of each ion present in the waters from the various aquifers are different, as shown by Figure 7. For the samples obtained from surficial material the main characteristics are fairly high amounts of calcium (Ca), magnesium (Mg), and sodium (Na), low chloride (Cl) values, and high sulphate values (SO_4, over 10 milli-equivalents).

Compared to this the samples from the Ardkenneth Member on the west side of the valley, as well as those from wells W 9 and W 10 on the east side, show an increase in sodium, a marked increase in chloride, and a decrease in calcium, magnesium, and sulphate, the latter to less than 1.0 milli-equivalent. Water from the Ardkenneth Member in piezometers 4A and 5A, and in the old town well in Riverhurst (W 6) has the same calcium, magnesium, and sodium concentrations as the other Ardkenneth samples, but the chloride and sulphate concentrations lie somewhere between the values for these ions in driftwater and in the other Ardkenneth water. The composition shown by samples 4, 5, and 8 in Figure 7A seems, however, to be normal for the Ardkenneth Member and its equivalent, farther east. A similar chemical composition was found by Meyboom (oral communication) for water from the first Upper Cretaceous aquifer in the Arm River area.

Waters from the Beechy and Belly River aquifers in the Riverhurst area contain much larger amounts of sodium and chloride, up to 70 milli-equivalents in the Belly River sandstone. Values for calcium and magnesium are generally somewhat higher, and for bicarbonate (HCO_3) somewhat lower in the Belly River than in the Ardkenneth.

Ion ratios for waters from drift and bedrock in the Riverhurst area are given in Appendix III and summarized in Table II. The ratio Mg/Ca apparently cannot be used to distinguish the source of the water, possibly because the sampling method allowed escape of CO_2, which would influence the ratio for ions remaining in solution after filtering. The ratio Na/Mg + Ca makes it possible to recognize drift water (ratio smaller than 2.0) from bedrock water (ratio larger than 2.0). The other three ratios, Cl/SO_4, Cl/HCO_3 and Na + K/Cl enable a further distinction among waters from the three bedrock aquifers in the area. The first two ratios increase with depth, while the ratio Na + K/Cl decreases, approaching unity in the water from the Belly River sandstone.

Table II

Ranges of Ion Ratios for Waters From Drift and Bedrock in the Riverhurst Area

Ratio	Drift	Ardkenneth	Beechy	Belly River
Mg/Ca	0.13 - 1.59	0.025- 7.57	0.62- 2.80	0.36 - 13.1
Na/Mg + Ca	0.29 - 1.53	2.55 - 89.2	25.0 - 52.0	14.8 - 63.4
Cl/SO_4	0.021- 0.089	0.54 - 0.59 1.09 -117.0	27.4 -148.0	49.2 -542.0
Cl/HCO_3	0.071- 0.29	0.30 - 2.20	2.30- 2.65	5.86 - 23.8
Na + K/Cl	7.53 -23.0	1.64 - 6.10	1.34- 1.42	1.001- 1.14

Grain-Size Analyses and Permeability Tests of the Upper Cretaceous Sandstones

Grain-size analyses and permeability tests were made to obtain values for the permeability of the Upper Cretaceous sandstones. These enabled an approximation of the quantities of groundwater entering the South Saskatchewan Valley through the bedrock aquifers. In addition the permeability of the aquifers is one of the controlling factors for the influence of the future South Saskatchewan Reservoir on piezometric levels in these aquifers.

Grain-size analyses were made from samples taken from the various sandstones in the Riverhurst section. The locations of the samples are indicated by numbers on Figure 2 corresponding with the numbers on Figure 8. The results of the analyses (see Fig. 8) place the Upper Cretaceous sandstones in the fine to very fine sand to silt groups of the U.S. Bureau of Soils classification. The amounts of silt and clay in the analyses may be somewhat too high, because of contamination with drilling fluid (generated by disintegration of shale).

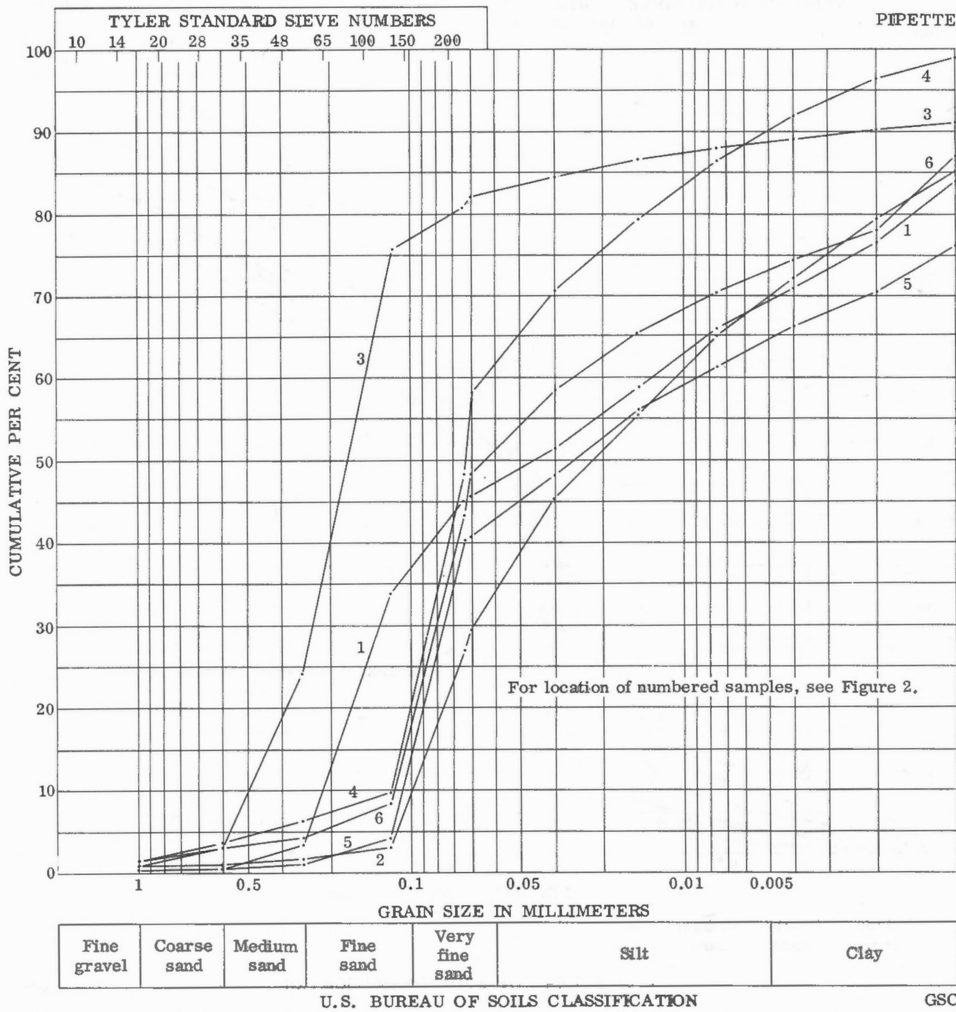

Figure 8A. Results of grain size analyses, Ardkenneth sandstone, Riverhurst area.

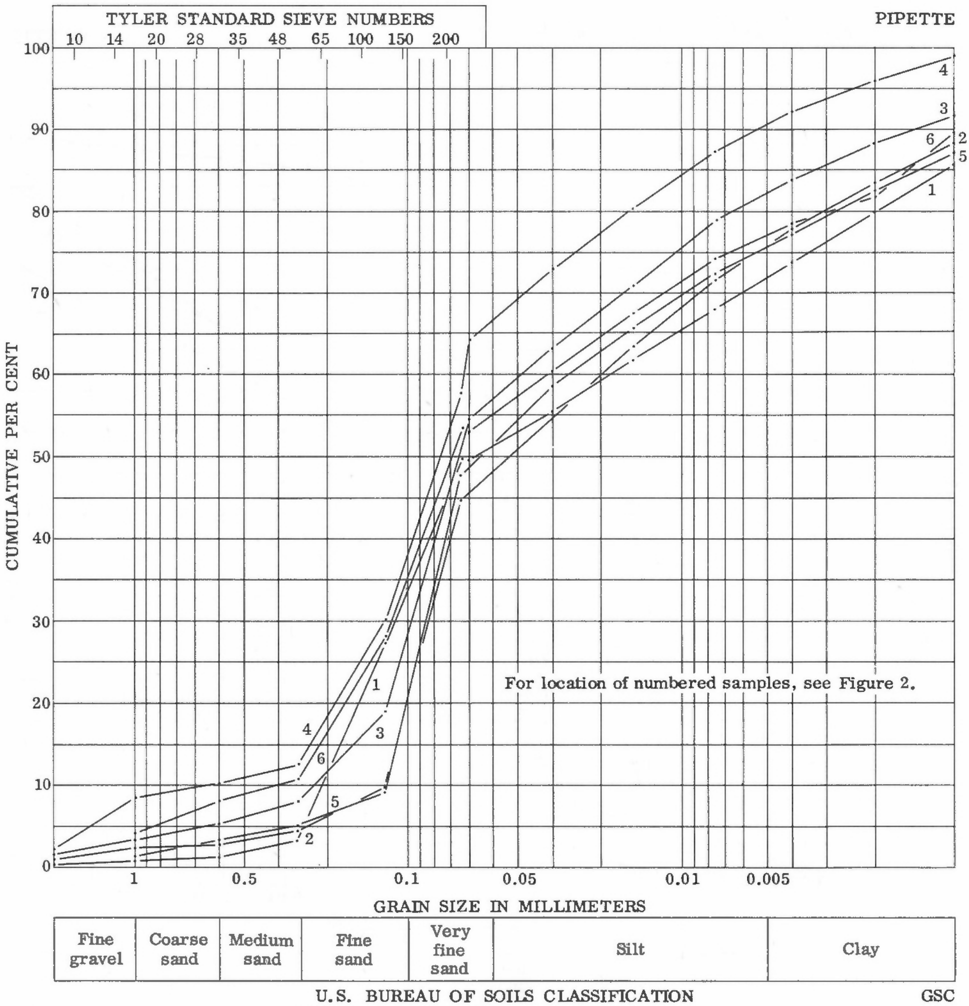

Figure 8B. Results of grain size analyses, Beechy sandstone 4, Riverhurst area.

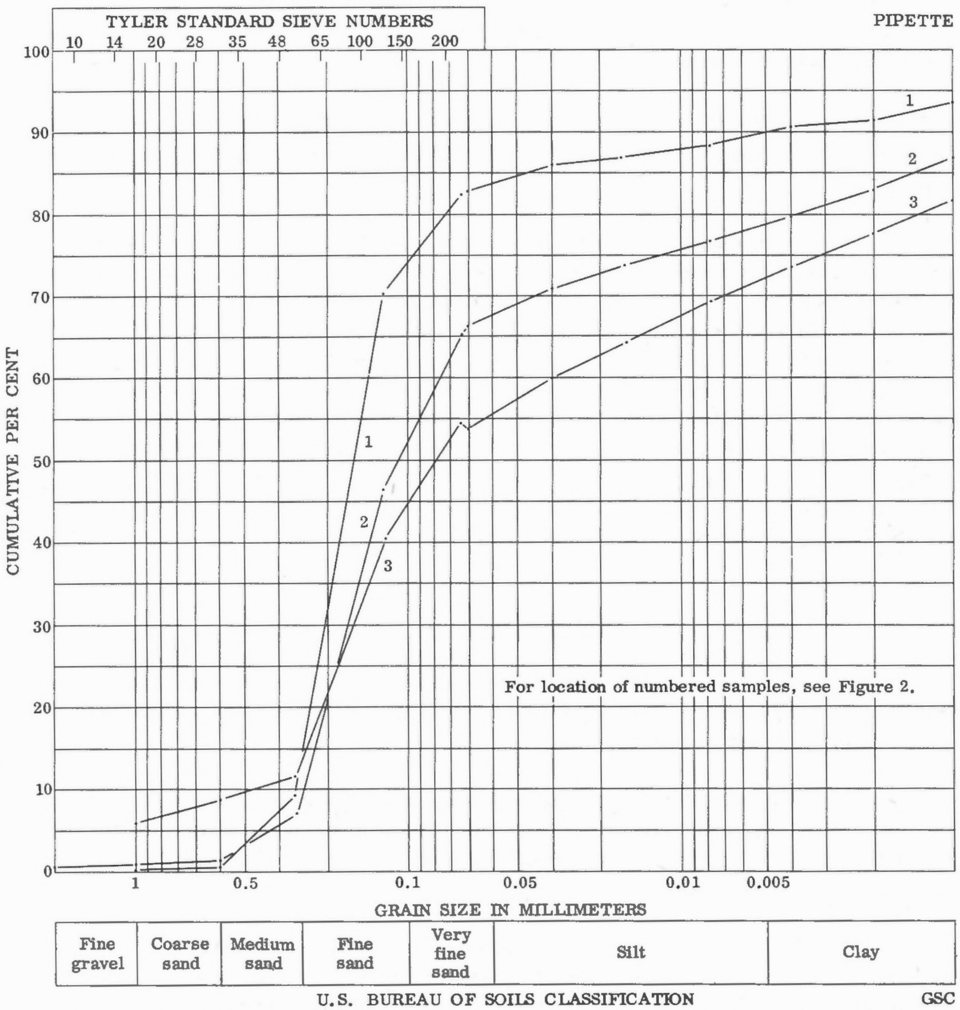

Figure 8C. Results of grain size analyses, Belly River sandstone, Riverhurst area.

The results for the Ardkenneth Member show that the upper part of the member is coarser than the lower part. The six analyses for the Beechy Member all fall within a fairly narrow zone, well inside the range for the Ardkenneth Member. The three samples from the Belly River sandstone are coarser, but they also fall inside the range for the Ardkenneth Member. It is clear that grain-size distribution can not be used to distinguish the various sandstone members.

Determination of permeability values from the grain-size distribution by Hazan's formula

$P = 0.0116\ (d_{10})^2$, in metres per second, where d_{10} is expressed in millimetres, was not possible, because in all cases d_{60}/d_{10} is larger than 5.

Permeameter experiments by P.F.R.A. (1963) consistently yielded higher permeability values than would be expected from the grain-size distribution. This is probably caused by the presence of abundant aggregates of fine particles, greenish in colour, found by microscopic examination of untreated sandstone samples. None of these aggregates was found in samples previously treated for grain-size analysis. In the undisturbed state these aggregates would account for the higher permeability (by giving a larger effective grain size), whereas they would disintegrate and add to the amount of silt and clay-sized particles in the grain-size analysis. The mineral forming the aggregates is glauconite, belonging to the chlorite group (Meyboom 1961, P.F.R.A., 1963).

Permeability Tests

Three types of field test were used for the determination of permeability or hydraulic conductivity of the Upper Cretaceous sandstones in the Riverhurst piezometers.

The test used initially, carried out directly after installation of the piezometers, consisted of filling the piezometer with water to the top of the collar and recording the drop of the water-level in the pipe till static conditions were reached.

The results of this test gave only an approximation of the permeability values. Besides, the river-water used for filling was left in the piezometers, which caused inaccurate measurements when automatic water-level recorders equipped with an electronic attachment were later used on these piezometers[1]. The advantage of the test was that it demonstrated the existence of a proper connection between the piezometer and the formation.

The second type of test, also carried out directly after installation, did have this same advantage, and only one of the earlier disadvantages, namely the unknown amount of water involved in the test. Air-jetting was used to pump the piezometers; the last water produced was preserved as a sample for chemical analysis. Recovery of the water-level in the piezometers was recorded from the moment air-jetting stopped. At the end of these tests the piezometers contained only formation water.

The third type of test was carried out some time after static water-levels had been established in the piezometers. The water-sampling outfit of the Groundwater Section (van Everdingen, 1965) was used as a bailer, to take a small amount of water out of the piezometer (2 to 3 litres). The original static water level, the maximum drawdown, and the residual drawdown at short intervals after bailing stopped, were recorded.

Values for hydraulic conductivity were calculated from the test data by the basic time-lag method, described in detail by Hvorslev (1951). Hvorslev (p. 43) stated: "The simplest expression for the coefficient of permeability is obtained by determination of the basic time-lag, T, of the installation, and use of the equation

$$k = \frac{A}{F.T} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where k = hydraulic conductivity (dimension L/T);

A = area of standpipe (dimension L^2);

F = shape factor (dimension L);

T = basic time lag (dimension T)".

Equations to calculate shape factors for various types of observation installation are given in Hvorslev's Figure 12. Assumptions are that the water-bearing material is of uniform permeability (k is k_{mean}) and infinite depth; that water and aquifer are incompressible; that artesian conditions prevail, or that the flow required for pressure equalization does not cause any

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[1]NaCl had to be added to the water in these piezometers to increase the low electric conductivity to a level where the Keck attachment could operate successfully.

perceptible change in the groundwater level. For the case of a 2-inch steel pipe with a 3-foot long sandpoint in a confined sandstone aquifer, case 8 in Hvorslev's Figure 12 gives

$$F = \frac{2\pi L}{\ln\left[\frac{L}{D} + \sqrt{1 + (\frac{L}{D})^2}\right]} \quad \ldots\ldots\ldots \ (4)$$

where L = length of intake (sandpoint, dimension L);
D = diameter of intake (dimension L).

Basic time-lag T is determined, by means of a semi-logarithmic plot of time versus head, as the time T corresponding to $h = 0.37 h_o$, i.e. when the residual head has been reduced to 0.37 of its original value. Results of the calculations of permeability by the basic time-lag method are given in Table III, column 2. Column 4 of the same table shows the 90 per cent equalization times obtained for these piezometers, giving a measure of their sensitivity.

A second calculation procedure, used as a check on the results, is the variable-head method, in which Hvorslev (1951, Fig. 18, case 9) expressed horizontal permeability k_h as

$$k_h = \frac{d^2 \cdot \ln\left(\frac{2mL}{D}\right)}{8L \cdot (t_2 - t_1)} \cdot \ln \frac{h_1}{h_2} \text{ for } \frac{mL}{D} > 4 \quad \ldots . \ (5)$$

in which D = diameter of intake (dimension L);
d = diameter of standpipe (dimension L);
L = length of intake (dimension L);
h_1 = piezometric head for $t = t_1$ (dimension L);
h_2 = piezometric head for $t = t_2$ (dimension L);
t = time, in seconds;
$m = \sqrt{k_h/k_v}$ (equal to or larger than unity for the upper part of the sandstone aquifers);
k_h and k_v = horizontal and vertical permeability (dimension L/T).

Results of the calculations by the variable-head method are given in Table III, column 3.

Table III

Hydraulic Conductivity of Confined Aquifers in the Area of the South Saskatchewan Reservoir and Equalization Time-Lag for Piezometers in the Riverhurst Area

Aquifer and Location	k_{mean}(1) inches/hour	k_h(2) inches/hour	E_{90}, minutes
Gravel			
Piezometer 4, Riverhurst	0.23	0.26	9.6
Ardkenneth Sandstone			
Piezometer 3A, Riverhurst	0.38	-	18.4
" 4A, "	0.43 - 0.49	0.59	9 - 12
" 5A, "	0.49 - 0.86	0.23 - 0.38	8 - 13
Loreburn, SE 1/4, sec. 23 tp. 26, rge. 5.	0.15 - 0.31 (3)	-	-
Strongfield, NE 1/4, sec. 26, tp. 27, rge. 5.	0.17 - 0.65 (3)	-	-
Hawarden, SW 1/4, sec. 26, tp. 28, rge. 5.	0.36 - 1.00 (3)	-	-
Beechy Sandstone			
Piezometer 2B, Riverhurst	0.61	-	11.5
Belly River Sandstone			
Piezometer 4C, Riverhurst	0.38	0.36	18
" 5C, "	0.09	0.09	7.8

(1) Determined by Hvorslev's basic time-lag method.

(2) Determined by Hvorslev's variable-head method.

(3) Determined from pump test results by the equation $P = \frac{T}{m} = \frac{264\ Q}{m.\ \Delta s}$

Determinations of vertical permeability were carried out by the P.F.R.A. on undisturbed samples of the Ardkenneth equivalent, to assess the relation between the permeability and the quantity of fine material in the samples. Results suggested that for samples containing 20 per cent or less smaller than 0.07 millimetre, the permeability of these sandstones is larger than 0.72 inch per hour; for samples containing 25 per cent material smaller than 0.072 millimetre the permeability is of the order of 0.36 inch per hour; and for samples containing 30 per cent or more material smaller than 0.07 millimetre the permeability is smaller than 0.036 inch per hour.

Grain-size analyses by the P.F.R.A. revealed two distinct zones in the Ardkenneth equivalent at the dam site: the main water-bearing zone, with 10 to 25 per cent smaller than 0.07 millimetre, and a transition zone with 30 to 45 per cent smaller than 0.07 millimetre. Permeabilities for these zones range from 6.5×10^{-5} to 6.5 inches per hour.

A pump test carried out on the artesian aquifer at the dam site by the P.F.R.A. yielded the following aquifer characteristics:

Permeability	3.6 inches per hour
Storage coefficient	0.0003

Results of pumping tests on municipal wells, tapping the Ardkenneth equivalent at Loreburn, Strongfield, and Hawarden, were obtained through the Saskatchewan Water Resources Commission. Permeability values calculated from the test data and based on a thickness of the main water-bearing zone of 30 feet, are added to Table III for comparison.

For the purpose of later calculations the average permeability of the Upper Cretaceous aquifers involved in this study will be taken as 0.4 inch per hour.

Discharge Quantities

Using the value of 0.4 inch per hour for the permeability 'k' of the sandstone aquifers, and the hydraulic gradients 'I' given in Table I, it is possible to calculate approximate quantities of groundwater that flow into the valley of South Saskatchewan River in the Riverhurst section through each of the three aquifers, by the equation

$$Q = k.I.m.L \quad \ldots\ldots\ldots\ldots\ldots \quad (6)$$

where L is taken as 100 feet.

Thus for the Ardkenneth Member:

$$Q_A = Q_{A\ west} + Q_{A\ east} = 0.8 \times (0.5 \times 10^{-3}) \times 60 \times 100 + 0.8 \times (3.0 \times 10^{-2}) \times 60 \times 100 = \underline{146.4} \text{ cu ft./day.}$$

Similarly for the two sandstones in the Beechy Member:

$$Q_B = \underline{29.4} \text{ cu ft./day}$$

and for the Belly River sandstone $\quad Q_{BR} = \underline{73.6} \text{ cu ft./day}$

This gives a total inflow of groundwater through the bedrock aquifers in the Riverhurst area of 249.4 cu ft./day/100 feet, or approximately 2.9×10^{-5} cubic feet per second per foot of valley.

A part or all of the water entering the valley area will be discharged to the river. The amounts of water that can move upward through the shale and the river fill under the 1,200 feet wide river channel can be approximated by using the equation:

$$Q_{A \rightarrow B} = \frac{k}{m_s} \times (h_A - h_B) \times 1,200 \times 100 \; . \; . \; . \; . \; . \; . \; . \; . \; (7)$$

where k is the vertical permeability of the shale or river-fill;

m_s is the thickness of the shale or river-fill;

$Q_{A \rightarrow B}$ is the amount of water moving between sands A and B;

h_A and h_B are piezometric heads in these two sands under the river channel.

In order to use this formula it is necessary to assume values for the permeability of the shales and till. For the Beechy shales a value of $k = 0.0025$ ft./day was taken; for the till in the bedrock valley a value of $k = 0.015$ ft./day was used. Values for the thickness of the shales and the till were taken from the electrologs, and minimum piezometric heads in the aquifers were derived from Figures 5 and 6. They are shown in Table IV, together with the calculated values for the amounts of horizontal and vertical flow.

The discharge figures in Table IV would indicate that most of the water from the bedrock aquifers is being discharged into the surface stream; approximately 15 per cent may move downstream as "underflow" within the Ardkenneth Member.

Table IV

Approximate Quantities of Groundwater Discharge from Bedrock Aquifers in the South Saskatchewan Valley Near Riverhurst.

	Thickness ft.	Minimum head ft.	Quantities in cu ft./day/100 ft.
River		1690	
Till	55		Q_{AR} 214.0
Ardkenneth sandstone	60	1697	Q_A 246.4 33.9 (3)
Upper Beechy shale	77		Q_{BA} 101.5
Beechy sandstone	30	1729.6	Q_B 29.4 1.0 (2)
Lower Beechy shale	205		Q_{CB} 73.1
Belly River sandstone	40	1779.4	Q_C 73.6 0.5 (1)

(1) 0.5 cu ft./day/100 ft. moves downstream in the Belly River sandstone.

(2) 73.1 + 29.4 - 101.5 = 1.0 cu ft./day/100 ft. moves downstream in the Beechy sandstone.

(3) 101.5 + 146.4 - 214.0 = 33.9 cu ft./day/100 ft. moves downstream in the Ardkenneth sandstone.

Barometric and Loading Efficiency

Both the barometric efficiency and the loading efficiency reflect the influence of changes in external loading on piezometric levels in a confined aquifer (e.g. the load applied by a full surface water reservoir). Determination of one of these characteristics further enables calculation of the coefficient of storage and the modulus of compressibility of the aquifer.

Barometric efficiency

Water-levels in wells in a confined aquifer are affected by fluctuations in atmospheric pressure. Jacob (1950) argued that these fluctuations are an index of the elastic properties of the aquifer. At the well the water is subjected to the full change in atmospheric pressure, whereas in the aquifer a part of the pressure change is accommodated by a change in the state of stress of the solid aquifer skeleton. Thus an increase in barometric pressure causes a decline of the water-level in the well and a decrease of the barometric pressure causes a rise of the water-level. The ratio between the net change in the water-level and the net change in barometric pressure, both expressed in the same units, is known as the barometric efficiency (BE) of the aquifer, given by:

$$BE = \frac{s_w}{s_b} \quad \ldots\ldots\ldots\ldots\ (8)$$

where s_w = net change in water-level, in feet;

s_b = net change in barometric pressure, in feet of water.

Measurements for the determination of barometric efficiency should be taken during a period when no pumping from the aquifer takes place nearby.

Barometric efficiency is a function of the bulk-modulus of compressibility of the solid skeleton of the aquifer (α); the bulk-modulus of compressibility of the water (β); and the porosity of the aquifer (θ):

$$BE = \frac{1}{1 + \alpha/\beta\theta} \quad \text{(Jacob, 1950)} \ \ldots\ldots\ldots\ (9)$$

This relation is used later in this report to derive values for α from the known values of barometric efficiency, in order to enable calculation of probable amounts of aquifer compaction to be expected as a result of flooding of the South Saskatchewan Reservoir.

During the summer of 1964 automatic water-level recorders (Stevens Type-F) were installed on some of the piezometers in the Riverhurst section. Keck SD-62A recorder attachments[1] were used to adapt the recorders for operation on the 2-inch diameter well pipes. Recorders were left on the piezometers for periods ranging from 2 to 5 weeks. The records are on a 1:1 vertical scale, with a time scale in which 1 inch equals 24 hours (8-day chart).

At the same time a record of barometric pressures was made with a recording barometer, installed in the Survey trailer near location 6 (see Fig. 3). The inverse graphs of the original barograph records, converted to feet of water, are shown in Figure 9, A to D, together with the piezometer hydrographs.

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[1]Manufactured by W.G. Keck and Associates, Inc., East Lansing, Michigan, U.S.A.

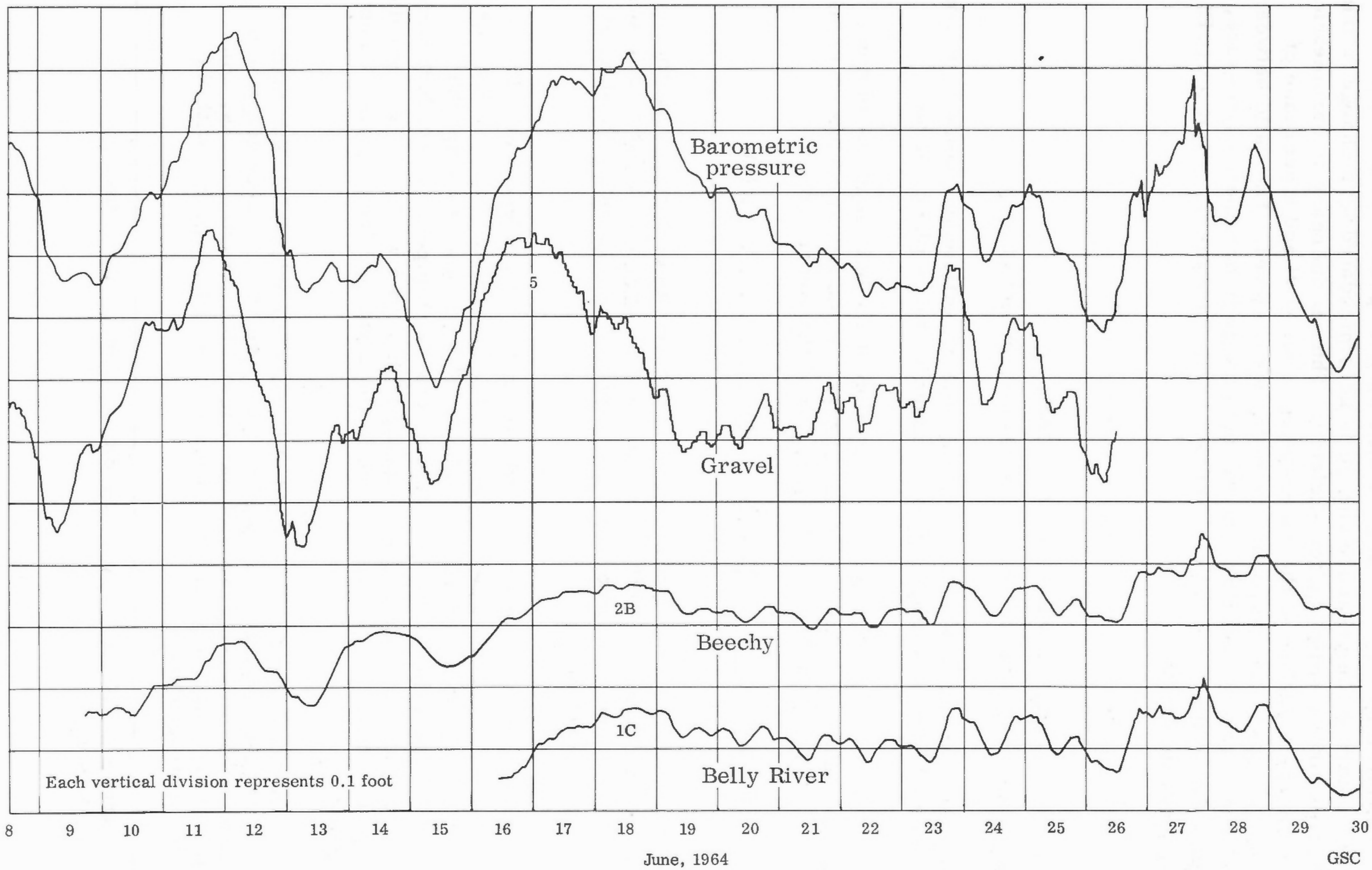


Figure 9A. Barometric variations, and hydrographs of piezometers in gravel, Beechy sandstone and Belly River sandstone, Riverhurst area

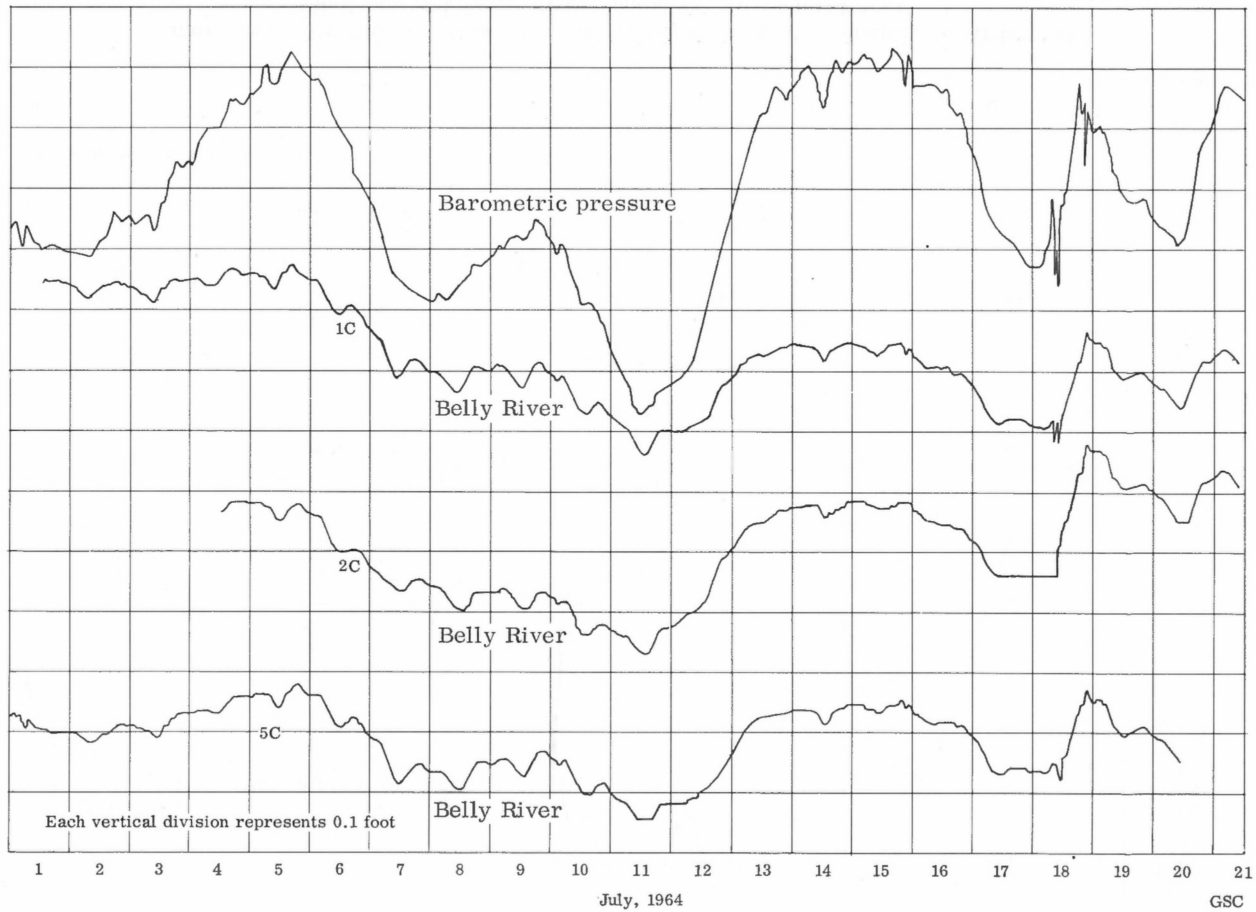


Figure 9B. Barometric variations, and hydrographs of piezometers in Belly River sandstone, Riverhurst area

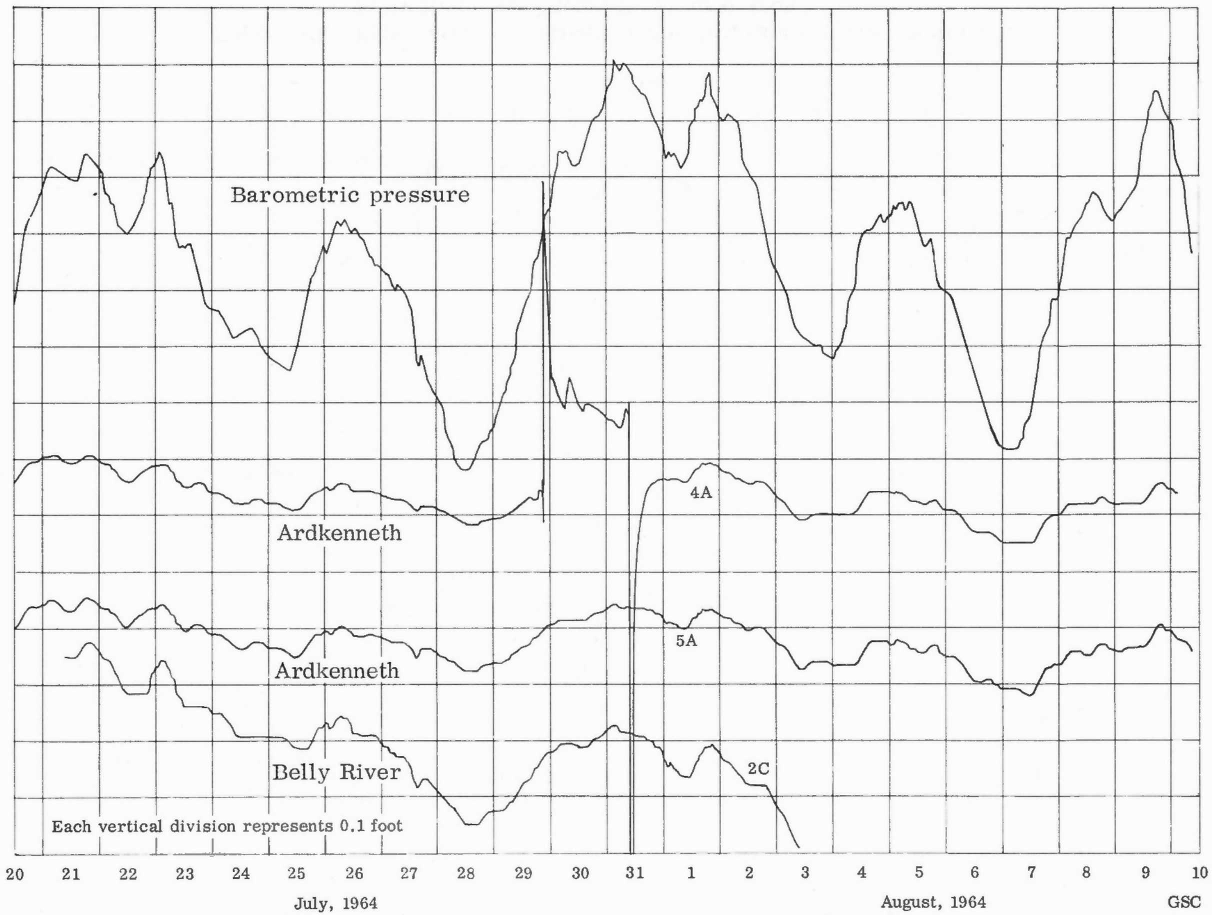


Figure 9C. Barometric variations, and hydrographs of piezometers in Ardkenneth sandstone and Belly River sandstone, Riverhurst area

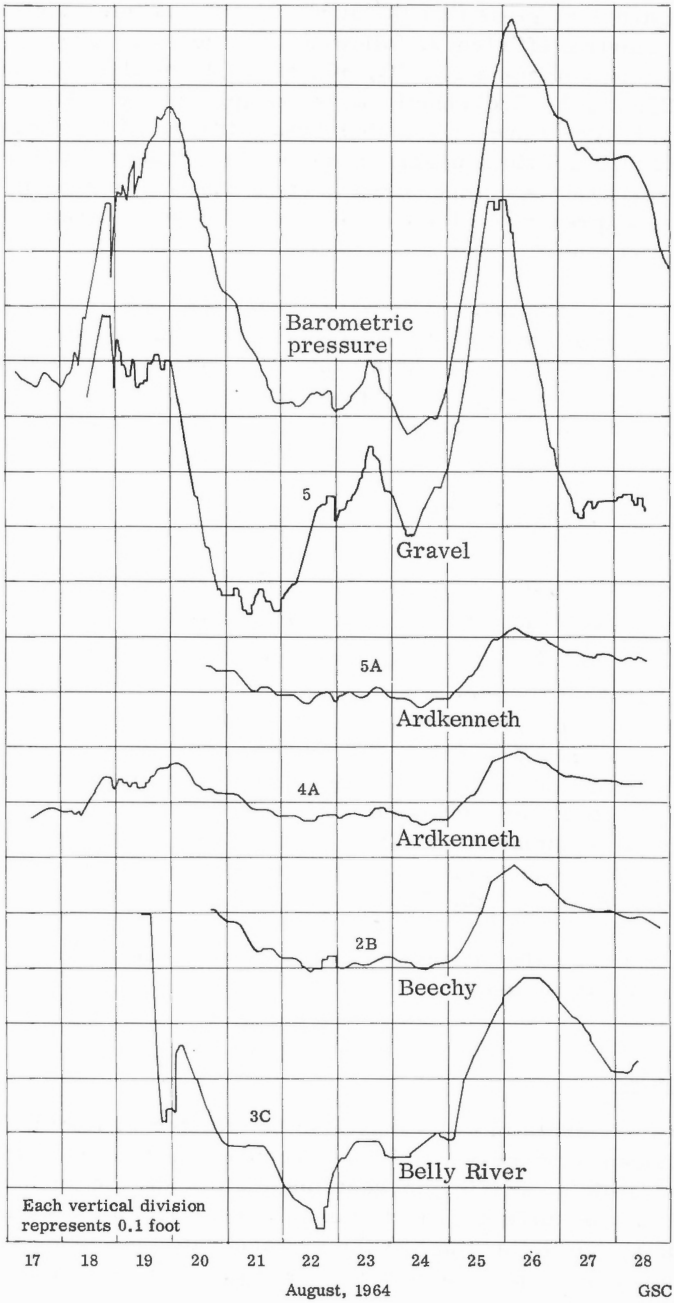


Figure 9D. Barometric variations, and hydrographs of piezometers in gravel, Ardkenneth sandstone, Beechy sandstone and Belly River sandstone, Riverhurst area

Figure 9 suggests that the surficial gravels (piezometer 5) have a very high barometric efficiency, followed in decreasing order by the Belly River sandstone (piezometers 1C, 2C, 3C, and 5C); the Beechy sandstone (piezometer 2B); and the Ardkenneth sandstone (piezometers 4A and 5A). Apart from BE, Figure 9 presents a nice demonstration of the concept of lag-time (described on a previous page). It can be seen that the changes in atmospheric pressure are compensated in the piezometers in a very short time, giving the impression, on the time-scale of Figure 9 that the response is nearly instantaneous.

All major fluctuations in water-level, as well as some of the smaller ones, were plotted in Figure 10, A to D, against the corresponding changes in barometric pressure, both expressed in feet of water. For each of the piezometers the straight line through the origin ($y = cx$) that best fitted the available points, was calculated by the least-squares method, using the equation:

$$c = \frac{xy}{x^2} \text{ for the coefficient } c \quad \ldots\ldots\ldots\ldots \quad (13)$$

where x = barometric fluctuation, the independent variable;

and y = water-level fluctuation, the dependent variable;

while $S_s = \sum (y - c_x)^2$, the sum of squares, should be a minimum for the best fit line. The best fit lines and the values for c (= BE) obtained in this way are shown in Figure 10, A to D. The narrow spread of the observed points around the line of best fit is a further indication of the great sensitivity of the piezometer installations. Figure 10 shows that piezometers terminating in the Belly River sandstone are somewhat less sensitive than those terminating in the Ardkenneth sandstone, a fact that could be expected already from the E_{90} values mentioned in the section on sensitivity of the piezometers and shown in Table III.

For later calculations the values for barometric efficiency (BE) shown in Table V will be used.

Loading efficiency

Water-levels in wells may also be affected by fluctuations in the level of an adjacent surface-water body, because of a loading effect, or because of hydraulic connection between the aquifer and the surface water. A load applied at the surface will be transmitted partly to the water in the aquifer. Thus a rise in the stage of the surface water produces a rise in the piezometric level, a drop in the surface stage produces a drop in the

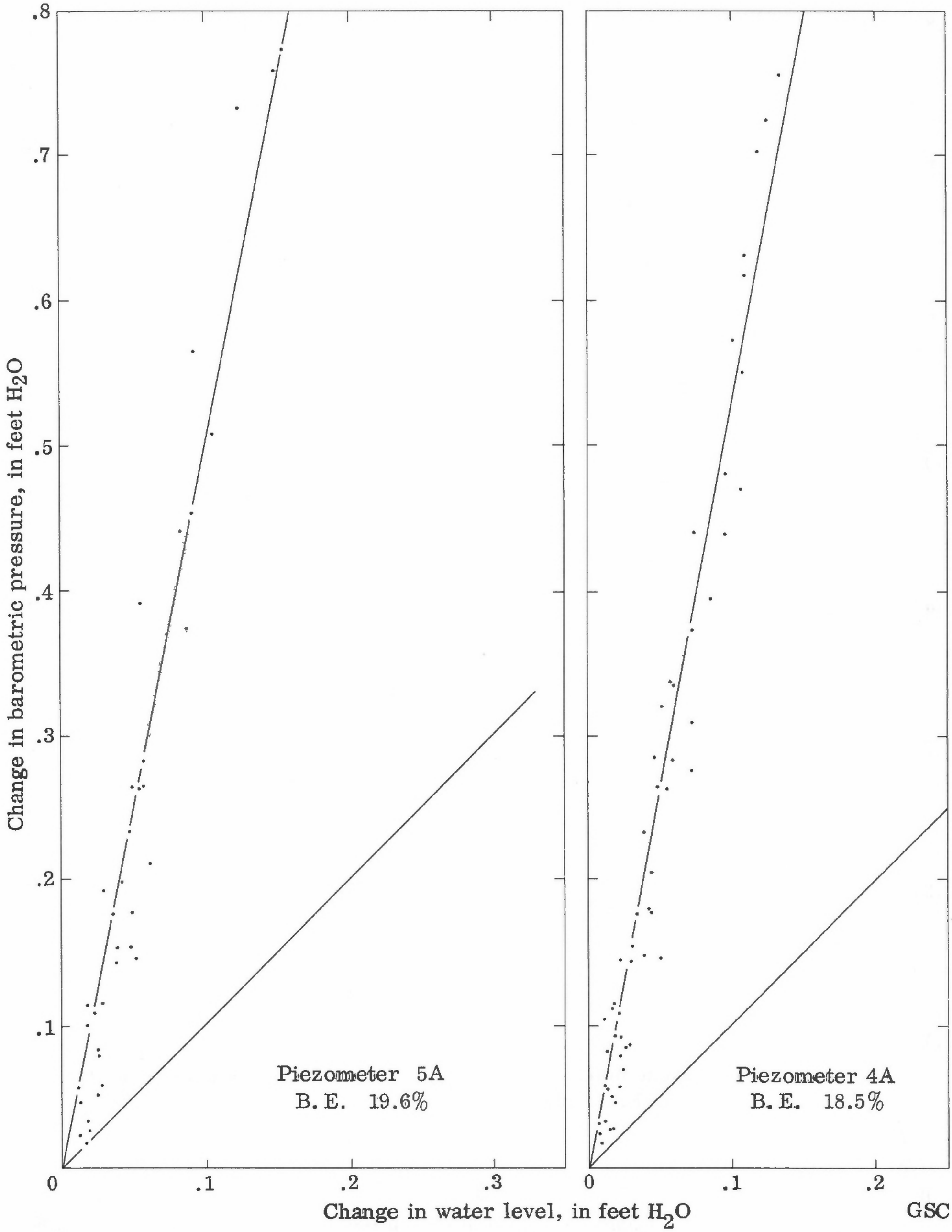


Figure 10A. Barometric efficiency plot of Ardkenneth sandstone, Riverhurst area

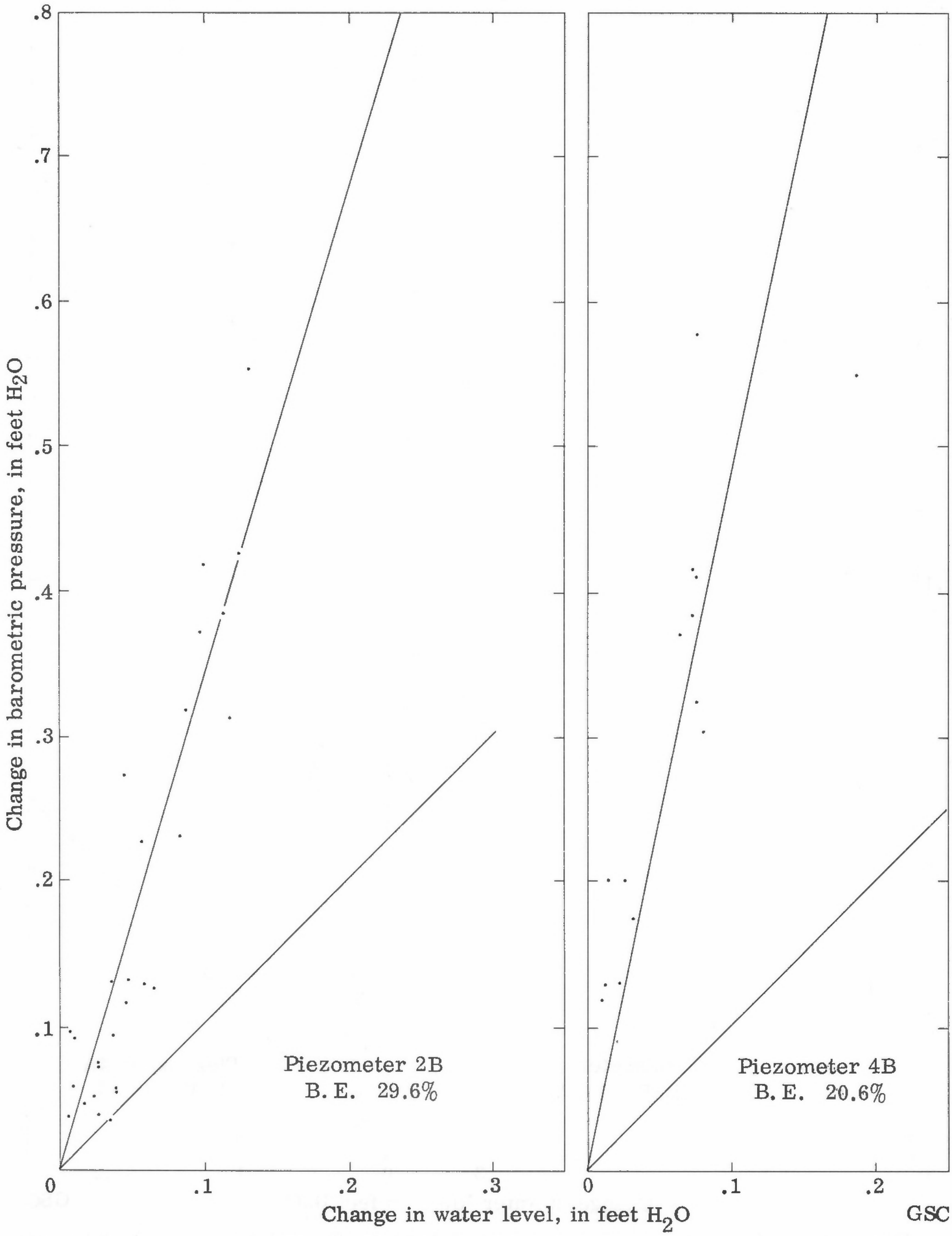


Figure 10B. Barometric efficiency plot of Beechy sandstone, Riverhurst area

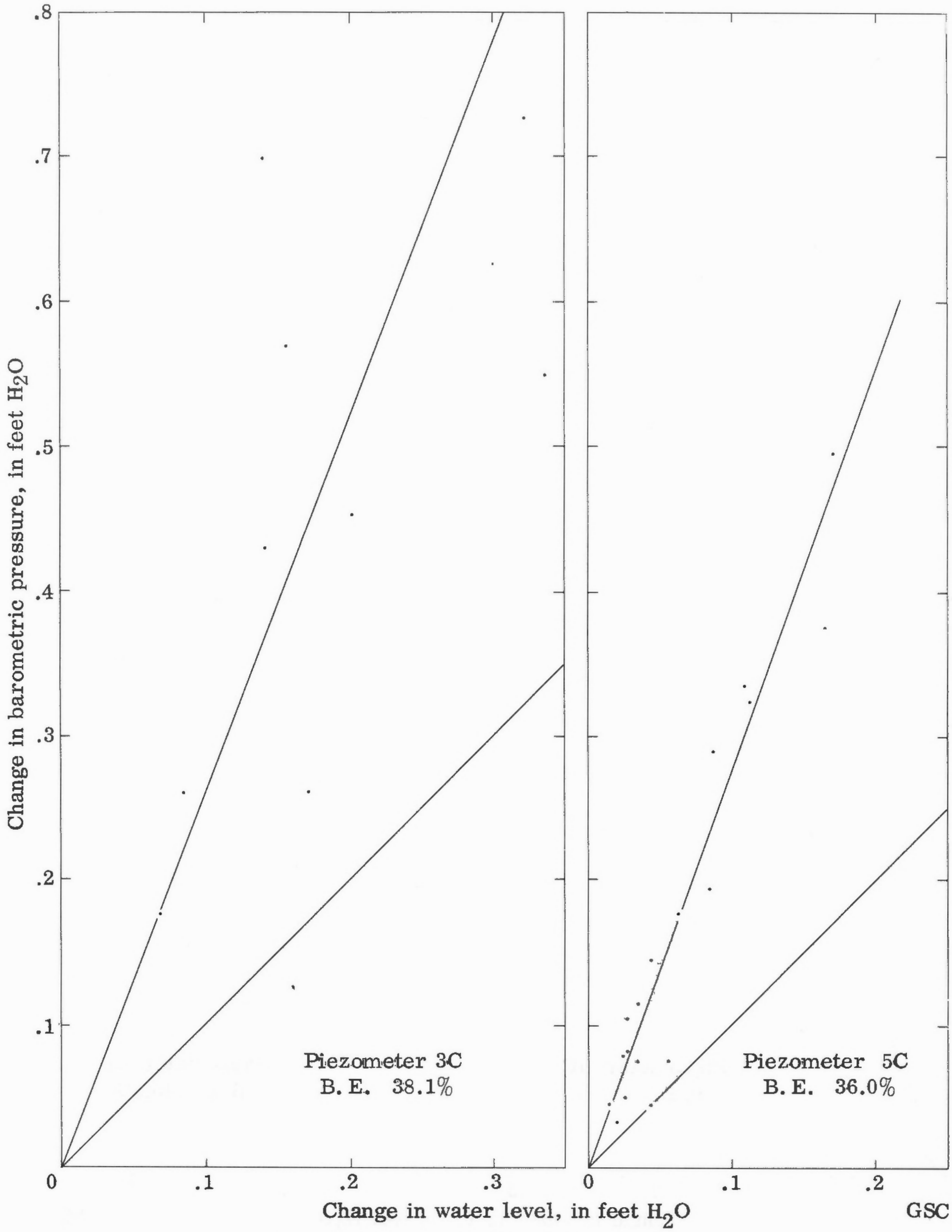


Figure 10C. Barometric efficiency plot of Belly River sandstone, Riverhurst area

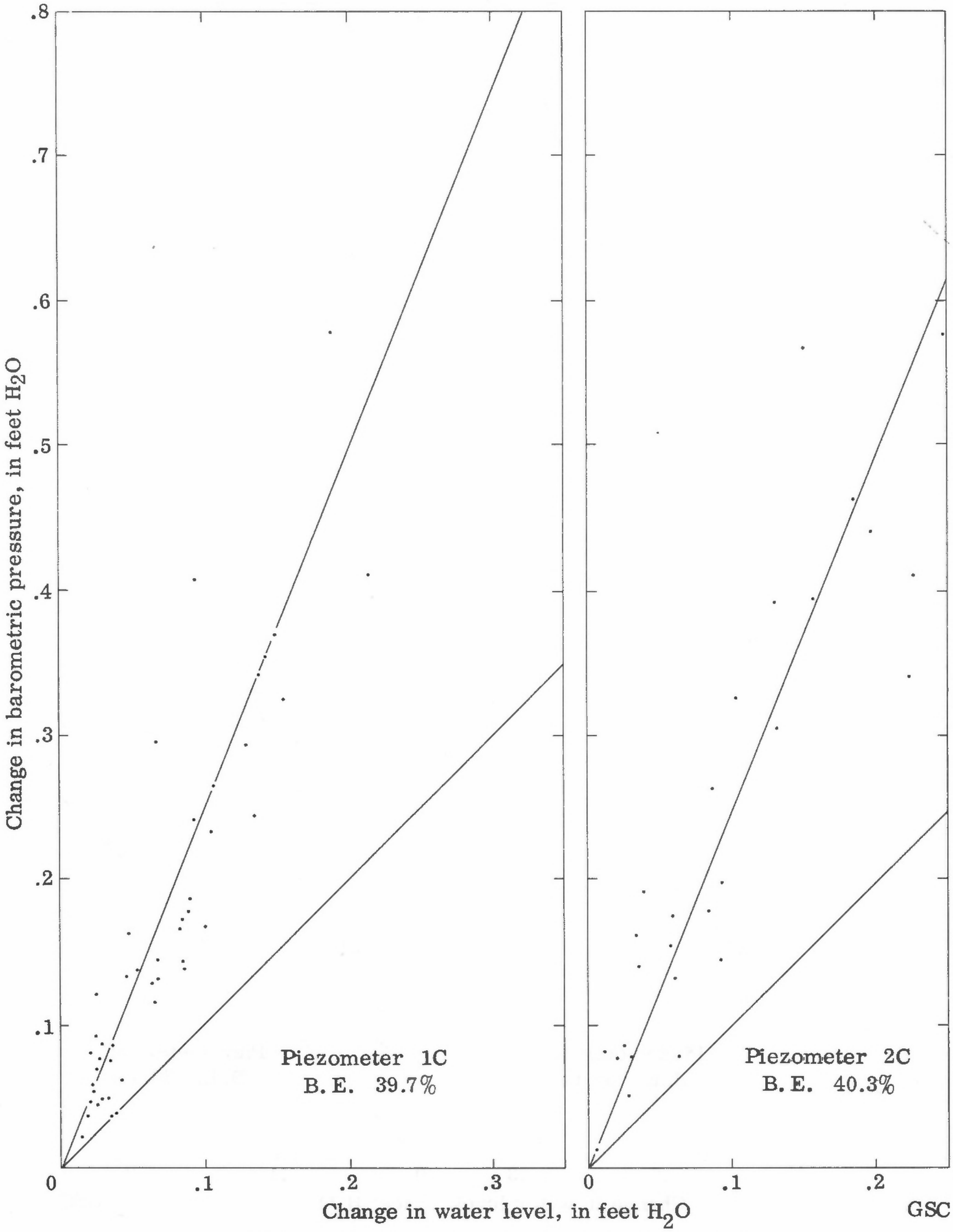


Figure 10D. Barometric efficiency plot of Belly River sandstone, Riverhurst area piezometric level. The ratio of the net change in piezometric level and the net change in surface stage is called tidal or loading efficiency (LE) in the case of a confined aquifer without hydraulic connection to the surface water.

Loading efficiency can be calculated from one of the two following equations:

$$LE = \frac{s_w}{s_t} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

where s_w = net change in water-level in the well, in feet;

s_t = net change in the level of the surface water, in feet;

or $$LE = \frac{\alpha/\beta\theta}{1 + \alpha/\beta\theta} \quad \text{(Jacob, 1950)} \quad \ldots\ldots\ldots\ldots \quad (11)$$

A comparison of equations (9) and (11) shows that loading efficiency and barometric efficiency are related by the equation

$$LE + BE = 1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

which thus enables the calculation of loading efficiency from a known barometric efficiency. The loading efficiency is used in the next two sections to evaluate the influence of a storage reservoir (South Saskatchewan Reservoir) on confined aquifers without hydraulic connection to the reservoir.

Coefficient of Storage

The distribution, in time and space, of the influence of a surface reservoir on piezometric levels in confined aquifers in hydraulic connection with that reservoir is a function of the permeability and the coefficient of storage of the aquifers. Values for the permeability of the Upper Cretaceous aquifers in the Riverhurst area were derived earlier from test results. It is possible to derive approximate values for the coefficient of storage for the bedrock aquifers, once the barometric efficiency is known.

According to Jacob (1950) the storage coefficient S and the barometric efficiency BE of a confined aquifer are related by the equation

$$S = (\gamma_o \times \theta \times m \times \beta) \frac{1}{BE} \quad \ldots\ldots\ldots\ldots\ldots \quad (14)$$

where γ_o = specific weight of water (0.0361 lb/cu inch);

θ = porosity of the aquifer, expressed as a fraction;

β = bulk modulus of compressibility of water (3.3×10^{-6});

m = thickness of the aquifer, in feet.

It was assumed that values for the porosity of the bedrock aquifers would range between 20 and 25 per cent. Values for m for the three bedrock aquifers under study were derived from the available electrologs: Ardkenneth aquifer 60 feet; Beechy aquifer 30 feet; and the Belly River aquifer 40 feet.

Using these values, and the values for barometric efficiency from the foregoing section, we find for the Ardkenneth aquifer:

$$S_A = 3.61 \times 10^{-2} \times 0.2 \times 7.2 \times 10^{2} \times 3.3 \times 10^{-6} \times \left(\frac{1}{0.19}\right)$$

$$= 9.02 \times 10^{-5} \text{ for a porosity of 20 per cent, and}$$

$$S_A = 1.13 \times 10^{-4} \text{ for a porosity of 25 per cent.}$$

Similarly for the Beechy aquifer (BE = 26 per cent, θ = 20-25 per cent, m = 30 feet):

$$S_B = 3.30 \times 10^{-5} \text{ to } 4.13 \times 10^{-5}.$$

Finally, for the Belly River aquifer (BE = 39 per cent, θ = 20-25 per cent, m = 40 feet) we find:

$$S_{BR} = 2.92 \times 10^{-5} \text{ to } 3.66 \times 10^{-5}.$$

For further calculations, averages of these values will be used as shown in Table V.

The values found here for the Ardkenneth aquifer are a factor 4 to 5 times smaller than the value for S determined from a pumptest by P.F.R.A. (1963; $S = 3 \times 10^{-4}$). It is possible that the bulk modulus of compressibility (α) would be larger for the case of the pumptest, during which a new and considerably higher stress range was induced in place of the original one over which stress had fluctuated many times (under the influence of changes in barometric pressure). Jacob (1950) argued that differences between the coefficient of storage as determined from tidal or barometric efficiency and that derived from results of a pumptest in the same formation are caused by the imperfect elasticity of confined sands.

Bulk Modulus of Compressibility

For a later evaluation of the importance of aquifer compaction (due to loading by the South Saskatchewan Reservoir) it is necessary to determine the bulk modulus of compressibility of the aquifer skeleton of the bedrock aquifers. It is possible to calculate the bulk modulus of compressibility from the values of barometric efficiency. Equation (9) can be written for this purpose as:

$$\alpha = \frac{(1 - BE) \cdot \theta \cdot \beta}{BE} \quad \ldots\ldots\ldots\ldots\ldots \quad (15)$$

Using the values for BE and θ from Table IV we find for the Ardkenneth aquifer:

$$\alpha_A = \frac{0.81 \times (0.2 \text{ to } 0.25) \times 3.3 \times 10^{-6}}{0.19} = 2.81 \times 10^{-6} \text{ sq. in/lb.}$$
$$\text{to } 3.51 \times 10^{-6} \text{ sq. in/lb.}$$

For the Beechy aquifer we find

$$\alpha_B = 1.88 \times 10^{-6} \text{ to } 2.35 \times 10^{-6} \text{ sq. in/lb.}$$

For the Belly River aquifer:

$$\alpha_{BR} = 1.03 \times 10^{-6} \text{ to } 1.29 \times 10^{-6} \text{ sq. in/lb.}$$

The averages of these values for α are shown in Table V, and will be used later in this report to calculate the amounts of aquifer compaction to be expected near Riverhurst and near the dam site as a result of reservoir flooding.

INFLUENCE OF A SURFACE-WATER RESERVOIR ON GROUNDWATER MOVEMENT

General

Every natural or artificial change in the stage of a surface-water body inevitably will have an effect on the movement of groundwater in the aquifers adjacent to that water body. A familiar effect of such a change in stage is bank-storage, occurring in river valleys at times of high water.

Table V

Average Aquifer Characteristics for Bedrock Aquifers in the Riverhurst Area

Characteristic	Ardkenneth	Beechy	Belly River
Thickness, ft.	60	30	40
Porosity, %	20-25	20-25	20-25
Permeability, in/hr	0.4	0.4	0.4
Coeff. of storage	1×10^{-4}	3.7×10^{-5}	3.3×10^{-5}
Discharge, cu ft./day per 100 feet	146.4	29.4	73.6
BE, %	19	26	39
LE, %	81	74	61
α, sq. in/lb.	3.2×10^{-6}	2.1×10^{-6}	1.2×10^{-6}
Chemistry of water			
Max. T.D.S., in p.p.m.	1,635	2,300	4,542
Ratio Cl/HCO_3	0.3 -2.2	2.3 -2.7	5.9 -23.8
Ratio Na + K/Cl	6.10-1.64	1.42-1.34	1.14-1.001

In each case the type and magnitude of the effect depend on the relation between the aquifers and the surface-water body, and on the magnitude of the original change in stage. The principal types of effect are those for watertable aquifers, confined aquifers in direct hydraulic connection with the surface-water body, and confined aquifers not in direct hydraulic connection with the surface-water body.

Various authors have treated the case of influence of a change in stage on the elevation of the water-table theoretically (Abramov et al., 1960; Abutaliev et al., 1962; Reed and Bedinger, 1961, 1962). Others have recorded changes in watertable elevation as a function of spring flood (Cady, 1941), or the filling of a reservoir (Trainer and Salvas, 1962). The case of a confined aquifer in direct hydraulic connection with a river was treated theoretically by Abramov et al. (1960), and Jacob (1950), and demonstrated on the basis of actual observations by Trainer and Salvas (1962). Following is a brief summary of these studies.

Watertable Case

Reed and Bedinger (1961) considered the shape and position of the watertable to be the sum of two components: (1) the boundary component, and (2) the accretion component. The boundary component is determined by the stream stage and the areal shape of the aquifer, the accretion component by the vertical gain or loss of the aquifer and by its areal shape. The boundary component may be obtained by electric-analog methods. The accretion component is then obtained by subtracting the boundary component from the known configuration of the watertable. A change of stream stage will result in a new boundary component that can again be determined by electric-analog method. The resultant new position of the watertable is derived by adding the new boundary component to the accretion component.

An alternative procedure was given by Reed and Bedinger in 1962. At many reservoir sites the change in stream stage is nearly linear with distance upstream from the dam site, and it extends from the dam to the upstream end of the pool. Farther upstream, as well as downstream from the dam, the change in average stage is considered to be zero.

The change in head (Δh) in a semi-infinite aquifer due to a change of head F(y) along the stream is given by:

$$\Delta h = \frac{1}{\pi} \int_{-\infty}^{+\infty} \frac{xF(z)dz}{x^2 + (z - y)^2} \quad \ldots\ldots\ldots\ldots (16)$$

where y = distance along the stream;

x = distance normal to the stream;

(x = 0, y = 0) = the location of the dam;

z = variable of integration.

Boundary conditions along the reservoir (x = 0) are:

$F(y) = 0, \; 0 > y > L,$ or the change in head along the channel upstream from the pool and downstream from the dam is zero;

and $F(y) = H - \frac{Hy}{L}, \; 0 < y < L,$

where H = change in stream stage at the dam;

L = length of the reservoir.

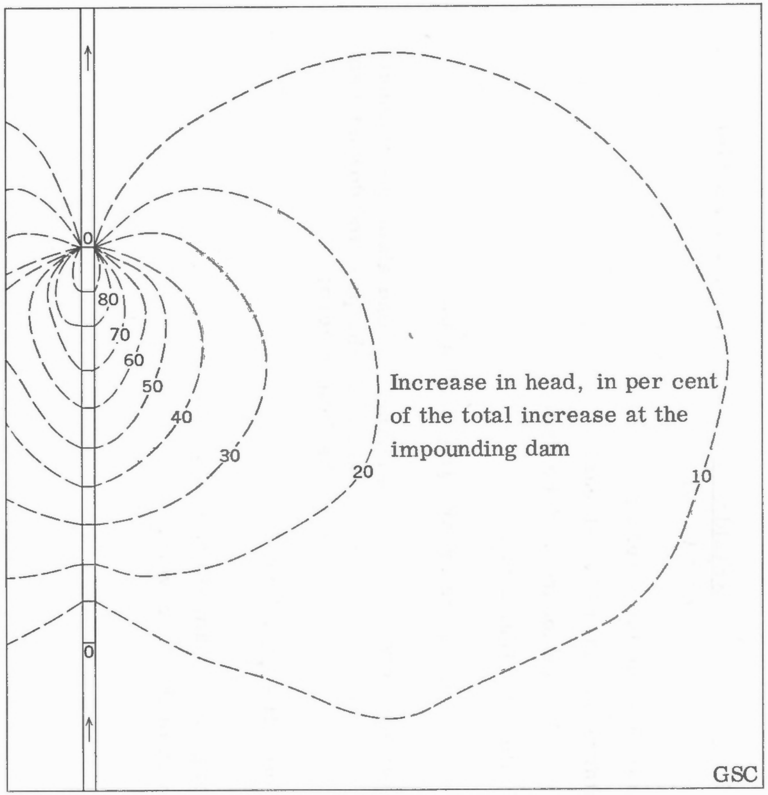
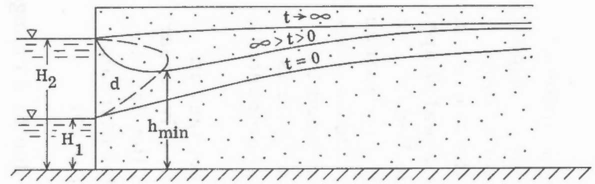


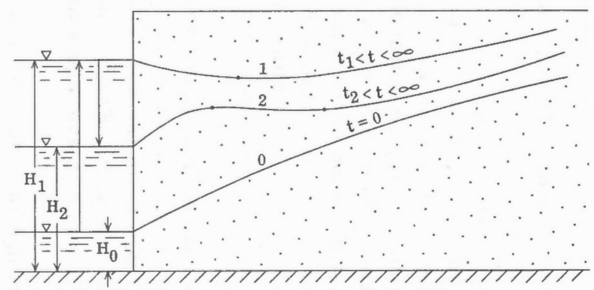
Figure 11. Influence of a storage reservoir on groundwater levels in an aquifer in hydraulic connection with the reservoir (after Reed and Bedinger, 1962).



h_{min} - Lowest point in the water-table, marking limit of the zone of 'reversed flow'.

d - Part of aquifer saturated by actual infiltration of water from the reservoir.

Figure 12. Positions of the water-table near a reservoir, at times t=0, $0 < t < \infty$, and $t \to \infty$ (after Abramov et al., 1960).



H_0 - Original level, at $t = 0$

H_1 - Maximum storage level, reached at $t = t_1$

H_2 - Level of partly drained reservoir, reached at $t = t_2$

Figure 13. Groundwater levels near a reservoir, in relation to fluctuations of the storage level (after Abramov et al.. 1960).

The solution of the integral given by Reed and Bedinger for these boundary conditions is shown graphically in Figure 11. It is worthwhile to note that some rise in watertable elevation occurs on both sides of the river, both upstream and downstream from the reservoir. Estimates of head changes, based on this procedure, will be in error if applied to the area near a meandering stream. Therefore Reed and Bedinger (1962) proposed use of an electric-analog model to estimate head changes near the stream, in conjunction with the integral solution applied to the remainder of the affected area.

Abutaliev et al. (1962) developed an electronic-computer program, based on the equation of Boussinesq that governs non-steady unidirectional flow in an aquifer:

$$\frac{dh}{dt} = \frac{k}{2\theta} \cdot \frac{\delta^2 h}{\delta x^2} \quad \text{. . . . . (17)}$$

with: $h = f(x)$ at $t = 0$;

$h = \Phi_1(t)$ at $x = 0$;

$h = \Phi_2(t)$ at $x = L$;

where h = groundwater level, dimension L;

k = filtration coefficient or hydraulic conductivity, dimension L/T;

θ = fillable porosity, expressed as a fraction;

t = time;

L = length of section, dimension L.

For a useful application of such a program detailed data on $\underline{k}$ and θ are needed.

An exhaustive treatment of the case of aquifers in hydraulic connection with the reservoir was given by Abramov et al. (1962). The main principles demonstrated by them are the following. All changes that occur in the groundwater regime as a result of a change in stage of a surface-water body obey the laws governing potential fields. The ultimate equilibrium position of the watertable (being an average position between seasonal extremes) depends on the amounts of precipitation, evaporation, and transpiration, as well as on the magnitude of the change in stage and the characteristics of the aquifers affected. If the average annual values for the first three factors remain constant then the ultimate effect will be a function of aquifer transmissibility and magnitude of change-in-stage.

Variations in permeability and saturated thickness of the aquifers modify the effect. In areas of lower transmissibility the lines of equal secondary head (or effect) tend to lie closer together than in areas of higher transmissibility, other conditions being the same. The percentage distribution of the effect is independent of the magnitude of the change in stage. Porosity or coefficient of storage of the aquifers affects the time required for the establishment of a new equilibrium, but not the spacial distribution of the influence. The time factor is further dependent on the rate of the change in stage. The rise of the watertable is limited by topographic elevation. If the watertable comes too close to the surface, further rise is prevented by an increase in evaporation and transpiration, and possibly by surface run-off.

The increase in the elevation of the watertable in the area adjacent to a surface reservoir is caused in part by infiltration of water from the reservoir, in a zone of 'reversed flow', and in part by obstruction of discharge. The part that is supplied by infiltration from the reservoir is indicated in Figure 12 by a broken line.

The point of minimum elevation of the watertable (h_{min}) at any time ($0<t<\infty$) marks the limit of the zone of reversed flow. At first h_{min} moves away from the edge of the reservoir; it approaches the reservoir again for $t \rightarrow \infty$.

When the level in a surface reservoir drops rapidly after a prolonged high stage, a groundwater ridge is left behind near the edge of the reservoir. This phenomenon is an important factor in the occurrence of landslides after a rapid drawdown in a surface reservoir. The theoretical position of the watertable a short time after the reservoir level dropped to H_2, is indicated by curve 2 in Figure 13. The original zone of reversed flow is cut off and water is flowing from the ridge in both directions.

These principles can be illustrated with the case of Flathead Lake, Montana (Cady, 1941; see Fig. 14). The situation on June 11 (high surface stage) demonstrates the presence of a zone of reversed flow. On August 7, when the level in the lake had fallen to near its original position, a groundwater ridge was found a short distance from the shore of the lake. On October 15 the watertable had returned to near its normal winter level.

In general, the relative magnitude of the effect of a surface reservoir on the watertable decreases in a direction perpendicular to the reservoir. The rate of decrease is smallest in the case of a semi-infinite aquifer, as demonstrated in Figure 15a. The area of influence is usually limited by the presence of hydraulic boundaries (drainage channels, impermeable formations) at various distances from the reservoir. This is illustrated in Figure 15b, for the case where no surface recharge to the aquifer takes place. Figures 15c and 15d demonstrate the effect when recharge ($w>0$) or discharge ($w<0$) affect the aquifer between the surface reservoir and the constant-head boundary. For the area of the South Saskatchewan Reservoir the situations of either Figure 15b or Figure 15c will be applicable.

Figure 15c further demonstrates that the groundwater divide in the recharge area will shift towards the reservoir, and that the elevation of the watertable at the divide will increase with increasing reservoir level, subject to the limitations imposed by topographic elevations.

Confined Case

For confined aquifers, whether they are in hydraulic connection with the reservoir or not, both the character of the influence of a surface reservoir, as well as the boundary conditions differ from those for the watertable case.

The influence will be a function of the permeability (k) and the storage coefficient (s) of the aquifer if a hydraulic connection exists between aquifer and surface water; and a function of the loading efficiency of the aquifer if no such hydraulic connection is present.

In the latter case the head increase under the reservoir can be calculated from the head of water in the reservoir, H, and the loading efficiency LE:

$$\Delta h = H \times LE \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (18)$$

The distribution of the pressure effect in the aquifer at some distance from the reservoir depends on the areal boundaries and the physical properties of the aquifer.

The maximum effect Δh_{max} ($= H_{max} \times LE$) occurs at the dam site; the minimum effect $\Delta h = 0$ at the tail end of the reservoir. The influence decreases with distance upstream from the dam, assuming that LE is constant for the whole aquifer. The dam does not constitute a boundary for the effect, which means that some effect may be found in the aquifer below the valley downstream from the dam. The effect also decreases with distance perpendicular to the reservoir, at a rate depending on the aquifer characteristics. If the aquifer outcrops in an adjacent surface-drainage channel, that channel will be a boundary of the character $\Delta h = 0$ for the loading effect.

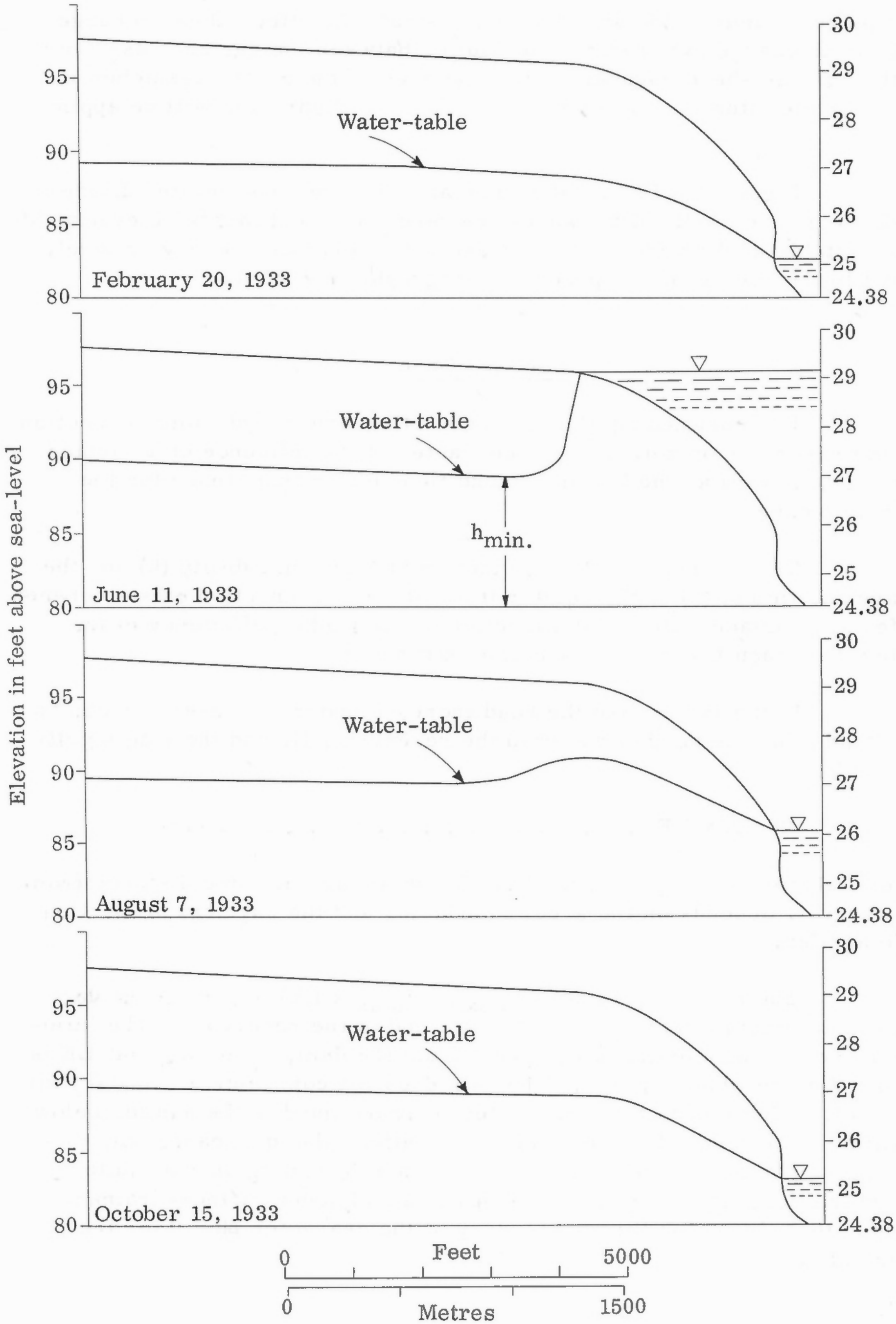
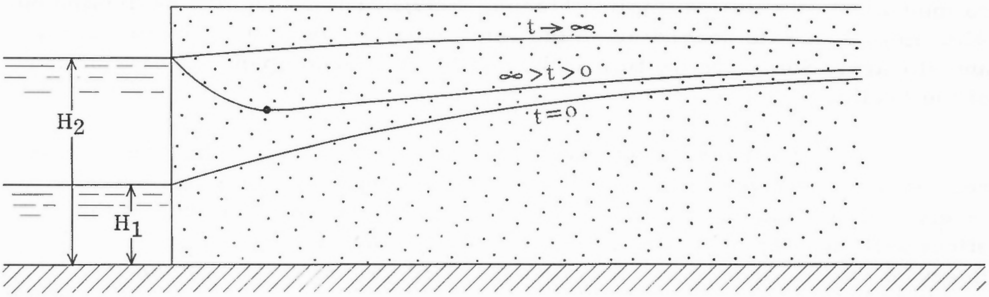
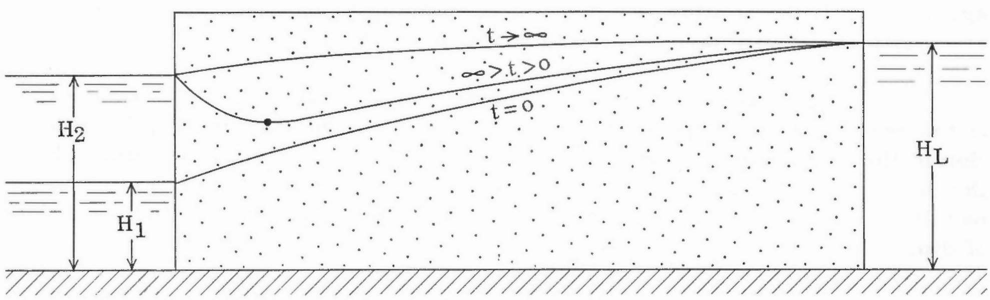


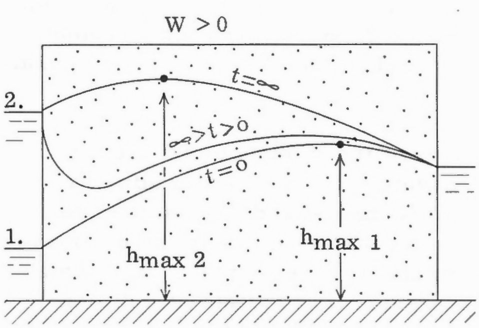
Figure 14. Variations in water-table elevation with stage, Flathead Lake, Montana (from Cady, 1941)



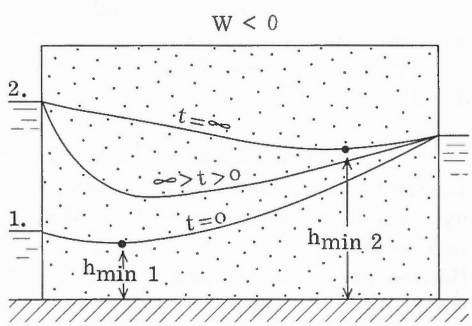
a. Constant recharge from large distance



b. Constant head at distance L. Surface recharge W = 0



c. Surface recharge W > 0



d. Surface recharge W < 0

GSC

Figure 15. Basic types of boundary conditions for groundwater movement in a free aquifer near a reservoir (after Abramov et al, 1960)

The loading effect should be practically instantaneous, because no movement of water is implied (Jacob, 1939). The effect will be dissipated with time, at a rate depending on the aquifer parameters of transmissibility and storage. Some compaction of the aquifer will accompany the dissipation of the loading effect.

If, however, a confined aquifer has some form of hydraulic connection with the river (reservoir), then the loading effect on piezometric levels will be replaced by a 'river effect'. The relative magnitude of the effect will then depend on the head-loss through the alluvial material or 'leaky' confining beds (which may be described as the 'river efficiency').

The same principle applies to all cases where confined aquifers outcrop in a river valley below future storage level. There the river efficiency will be 100 per cent, and the maximum effect at the outcrop is equal to the difference in elevation between the aquifer outcrop and the future storage level. If the aquifer is covered by slumping or by glacial drift the river efficiency will have a value smaller than 100 per cent.

Decrease or increase of the river effect in a direction parallel to the reservoir will depend on the behaviour of the aquifer outcrop in relation to the storage level. If the aquifer outcrop is horizontal the effect along the reservoir will have a constant value. If the aquifer has a certain dip parallel to the reservoir, then the effect will tend to increase in the direction of dip.

The magnitude of the effect decreases with distance perpendicular to the reservoir, following the principles described for the true confined case. The effect, however, will not be dissipated with time.

Groundwater divides in a confined aquifer in hydraulic connection with the reservoir will tend to shift towards the reservoir and the piezometric head at the new divide will be somewhat higher than it was at the original divide.

Trainer and Salvas (1962) described the influence of Lake St. Lawrence, St. Lawrence county, N.Y., on water in a bedrock aquifer in hydraulic connection with the lake, through unconsolidated deposits. The full reservoir rise of 80 feet produced a rise in water-levels in the unconsolidated deposits ranging from 3 to 32 feet in about three months. In bedrock wells the rise ranged from 20 feet near the reservoir to 5 feet at a distance of about 3 miles. The piezometric contours for the area indicated a zone of reversed flow near the reservoir. The original movement of groundwater was towards the river; after filling of the reservoir, water moved from the reservoir into bedrock towards Grass River, approximately 2 miles south of the reservoir. A rise in piezometric level was even registered in two wells beyond Grass River, demonstrating that the influence on the pressure in a confined aquifer is not limited by adjacent surface-drainage channels. In a topographic low 1.5 miles south of the reservoir three wells in bedrock started flowing as a result of filling of the reservoir (Trainer and Salvas, Fig. 14, p. 50). The aquifer types, their relation to the reservoir and the types of reservoir influence, as described above, are summarized in Table VI.

Table VI

Summary of the Various Types of Reservoir Influence.

1. Aquifer unconfined	Permanent effect due to infiltration of water from the reservoir, and obstruction of discharge from the aquifer. Limited by the presence of surface-drainage channels, and by topographic elevations.
2. Aquifer confined, but in hydraulic connection with the river.	Permanent effect due to movement of water between the reservoir and the aquifer. May be partly due to loading initially. Not limited by surface-drainage channels, unless aquifer outcrops in such channel. (River efficiency RE = 0 to 100 per cent.)
3. Aquifer confined, no hydraulic connection with the river.	Temporary effect due to loading of the aquifer. Not limited by surface-drainage channels, unless aquifer outcrops. Effect is dissipated with time. Compaction of the aquifer. (Loading efficiency LE = 0 - 100 per cent.)

THE SOUTH SASKATCHEWAN RIVER PROJECT

General Description

The South Saskatchewan River Dam, a rolled-earth fill under construction at Cutbank, 18 miles upstream from Outlook, Saskatchewan, will impound a reservoir 140 miles long, in the valley of South Saskatchewan River, with an arm extending into the valley of Aiktow Creek. The projected full-storage level for the reservoir is 1,827 feet above sea-level, with a maximum depth of water at the main dam of 187 feet. The two main purposes of the reservoir are supply of irrigation water and generation of power.

A second, smaller dam will be constructed at the head of the valley of Qu'Appelle River, approximately 12 miles southeast of Elbow, Saskatchewan. This dam is located near the divide between Aiktow Creek and Qu'Appelle River; it will control diversion of water from the South Saskatchewan Reservoir into the Qu'Appelle River system, supplying water to the cities of Moose Jaw and Regina. At full storage level the depth of water at the Qu'Appelle dam will be approximately 70 feet. Additional project statistics are given in Appendix IV.

Boundary Conditions Governing the Influence of the South Saskatchewan Reservoir on the Groundwater Regime

Referring to Table VI the following classification can be made for aquifers in the area of the South Saskatchewan Reservoir.

(1) Unconsolidated (glacial and alluvial) deposits form the watertable or unconfined aquifers of type 1.

(2) Other unconsolidated deposits (e.g. the gravel tapped in the Riverhurst town well) form confined aquifers of type 2, that will have hydraulic connection with the future reservoir.

(3) The Ardkenneth, Beechy, and Belly River sandstones are confined aquifers, in part with hydraulic connection to the reservoir (type 2), in part with only a loading efficiency (type 3).

Unconfined Aquifers

The future influence of the South Saskatchewan Reservoir on watertable elevations in the surrounding area will be subject to the following boundary conditions. The maximum effect (Δh_{max}) will occur at the dam site owing to the maximum rise in reservoir level H_{max} = 187 feet. The effect will decrease from Δh_{max} to $\Delta h = 0$ along the valley upstream from the dam, at a rate depending on the rise in elevation of the river channel. All permanent and semi-permanent surface-drainage channels including the river upstream from the reservoir and downstream from the dam, are boundaries of the type $\Delta h = 0$. These boundary conditions have been applied to a secondary flow-field model, described in a later section of this report.

Boundaries, caused by the inhomogeneous nature of the glacial and alluvial deposits, have been disregarded in this first approximation of the reservoir influence.

Bedrock Aquifers

Both the thickness and the hydraulic conductivity of the Upper Cretaceous sandstones are fairly constant over large parts of the reservoir area. The picture is, however, somewhat complicated by the dip of the aquifers, deduced from the available drill-hole and outcrop data.

Figure 16 demonstrates that each of the sandstones in turn dips from elevations near present river level, or even above full reservoir level, to elevations below the base of the bedrock valley. Actual outcrops of the aquifers are few, because of the extensive slumping that has occurred along the valley of South Saskatchewan River. Some of the outcrops found at present are part of slump blocks and have no longer any connection with the sandstone beds themselves. Glacial and alluvial deposits cover other potential outcrops, or 'subcrops'.

Even if the 'subcrops' of an aquifer are covered by glacial till or by shale (through slumping), hydraulic connection with the reservoir is still possible. Loss of circulation encountered in drill-holes located in landslide topography near Riverhurst indicated that open fractures must exist, at least in the slump blocks, both in till and shale (Scott, 1964, personal communication).

Hydraulic connection between the reservoir and the aquifers also exists where the aquifers are cut by the bedrock channel of the river, although the intervening fill of the bedrock valley will reduce the efficiency of the connection.

Only approximate indications can be given for the reaches of the South Saskatchewan Reservoir where any of the sandstones occur (a) between future storage level and present river level; (b) between present river level and the base of the bedrock valley; and (c) below the base of the bedrock valley (see Table VII).

The indications are based on the assumption of an approximate average dip of the sandstone beds of 10 - 12 feet per mile to the east-northeast in the area between Saskatchewan Landing and Elbow, and a very slight dip to the south between Elbow and Outlook.

Uncertainty is caused by local irregularities in the sandstone beds, especially in the Elbow area, as well as by lack of data on the depth of the bedrock valley. The future storage level and the approximate present river level at each of the available stratigraphic sections are indicated in Figure 16. The depth of the bedrock valley is indicated for the sections at Riverhurst and the dam site. A few miles upstream from Elbow the base of the bedrock valley lies approximately 1,485 feet above sea-level.

Table VII Relation Between Aquifer Elevations and the South Saskatchewan Reservoir.

Aquifer	Top of aquifer		
	A Between full storage level and present river level. (x)	B Between present river level and base of bedrock valley. (xx)	C Below base of bedrock valley.
Belly River sandstone	West of Saskatchewan Landing	Saskatchewan Landing to just east of Swift Current Creek	Downstream from Swift Current Creek
Beechy sandstone (2)	S. 7, T. 20, R. 13 to S. 32, T. 19, R. 11	S. 32, T. 19, R. 11 to S. 14, T. 20, R. 11	Downstream from S. 14, T. 20, R. 11
Beechy sandstone (4)	S. 30, T. 19, R. 11 to S. 17, T. 20, R. 10	S. 17, T. 20, R. 10 to S. 5, T. 21, R. 9	Downstream from S. 5, T. 21, R. 9
Ardkenneth sandstone	S. 23, T. 20, R. 10 to S. 3, T. 21, R. 8	S. 3, T. 21, R. 8 to near Elbow	Downstream from Elbow
Cruikshank member	S. 3, T. 23, R. 7 to dam site	Around Elbow	- - - - - - - -

[x] Lower parts of each aquifer will still be below full storage level for a few miles upstream from the reach indicated.

[xx] Lower parts of each aquifer will already be below present river level a few miles upstream from the reaches indicated.

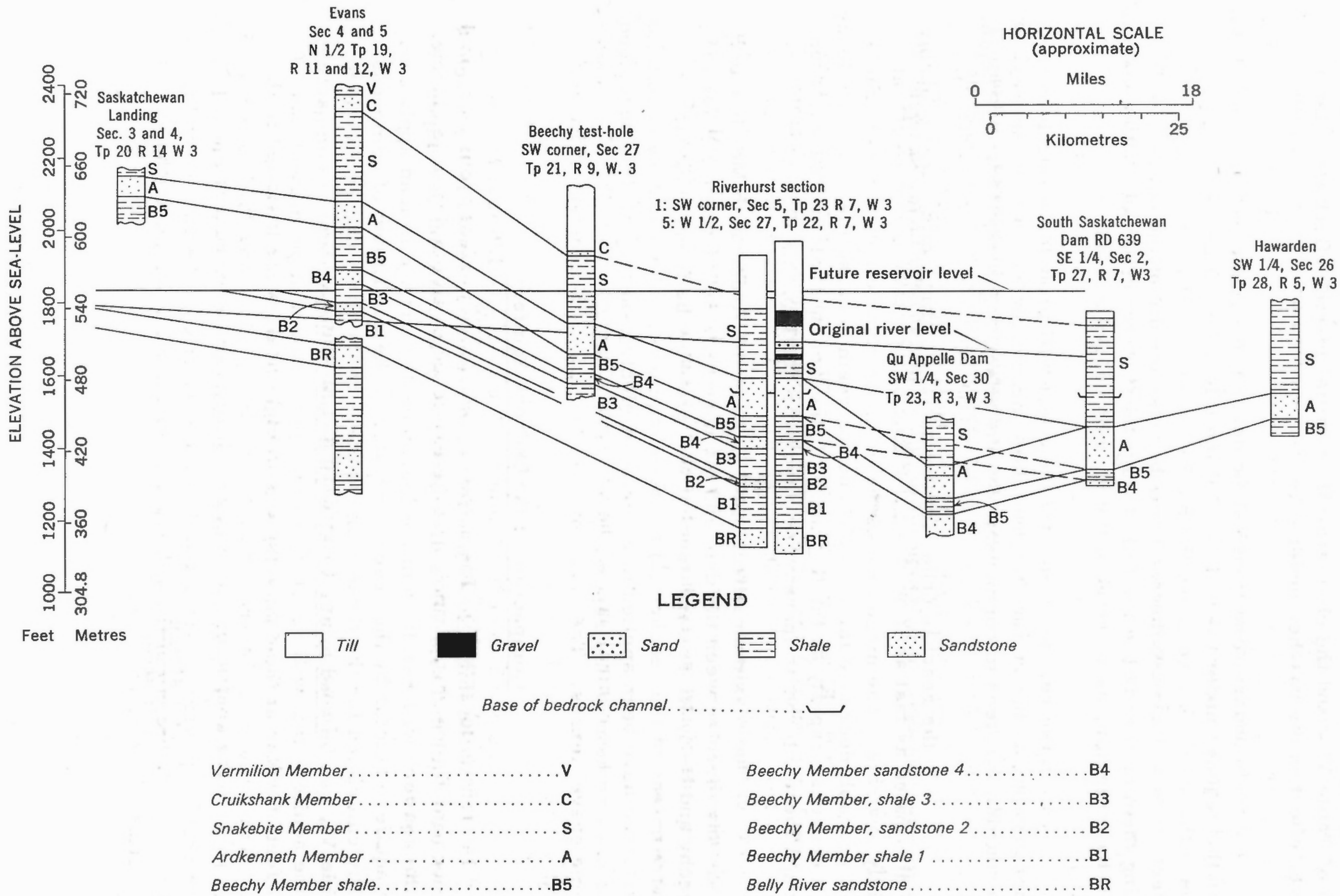


Figure 16. Stratigraphic correlation, and relation between Upper Cretaceous Aquifers and the South Saskatchewan Reservoir.

The influence of the reservoir on pressures in the bedrock aquifers will have the character of a river effect in the reaches under (a) and (b) of Table VII, and the character of an initial loading effect and a later river effect in the reaches under (c).

Boundary conditions can be described in general terms as follows. For the reaches under (a) in Table VII the effect $\Delta h = 0$ lies at the point where the aquifers rise above the future storage level in the valley. The effect tends to increase downstream, because the dip of the aquifers will bring them farther below the full storage level in that direction. The increase will be irregular, as a result of the varying degree of river efficiency.

In the reaches under (b) the effect will probably be fairly constant in value, as the increasing head-loss through an increasing thickness of overburden will tend to compensate for the effect of greater reservoir depth.

In the reaches under (c) the initial (loading) effect will probably be dissipated as fast as it occurs, if filling of the reservoir proceeds at a fairly low rate. The magnitude of the ultimate river effect in these reaches will probably decrease fairly rapidly downstream because the river efficiency will decrease rapidly as the thickness of intervening shale increases, even though there will be an increase in reservoir depth in this direction.

The maximum effect in the case of the Ardkenneth Member may occur anywhere between the dam and the upstream end of reach (c); for the Beechy and Belly River sandstones it will probably be found near the upstream end of the reaches (c) for these aquifers. The boundary conditions mentioned have been applied to a series of electric-analog models described in a later section of this report.

Compaction of the Bedrock Aquifers

As the initial loading effect on piezometric levels in the reaches shown under (c) in Table VII is dissipated, a certain amount of compaction of the aquifers will result from the (permanent) increase in load applied on the aquifer skeleton by the reservoir water. The coefficient of compressibility calculated for the three main aquifers in the foregoing section (see Table V), can be used to arrive at an estimate of the amount of compaction of the aquifers that will result from the application of a permanent load of 187 feet of water at the dam site, and 135 feet of water at Riverhurst.

The coefficient of compressibility can be expressed as

$$\alpha = \frac{\text{unit strain}}{\text{unit stress}} = \frac{\varepsilon}{s} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (19)$$

where unit strain can be written as

$$\epsilon = \frac{\Delta m}{m} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (20)$$

if m is the thickness of the aquifer and Δm the compaction, or reduction in thickness.

Thus combining equations (19) and (20) the amount of compaction can be derived from

$$\Delta m = m \times \epsilon = m \times \alpha \times \overline{s} \quad \ldots\ldots\ldots\ldots \quad (21)$$

The unit stress from the reservoir load for the Ardkenneth aquifer at Riverhurst, $\overline{s}_A$, equals 109 feet of water, or 47.3 lb./sq. in.; for the Beechy aquifer $\overline{s}_B$ is approximately 100 feet of water, or 43.2 lb./sq. in.; for the Belly River aquifer $\overline{s}_{BR}$ is about 82 feet of water, or 35.6 lb./sq. in.

Using these values for $\overline{s}$ and the values for m and α from Table V, we find for the amount of compaction of the Ardkenneth aquifer:

$$\Delta m_A = 60 \times 12 \times 3.2 \times 10^{-6} \times 47.3 = 0.109 \text{ inch.}$$

Similarly for the Beechy aquifer:

$$\Delta m_B = 30 \times 12 \times 2.1 \times 10^{-6} \times 43.2 = 0.0326 \text{ inch.}$$

and for the Belly River aquifer:

$$\Delta m_{BR} = 40 \times 12 \times 1.2 \times 10^{-6} \times 35.6 = 0.0205 \text{ inch.}$$

For the Ardkenneth equivalent at the dam site the compaction, based on an assumed aquifer thickness m = 30 feet, a bulk modulus of compression $\alpha = 2.5 \times 10^{-6}$, and a stress increase $\overline{s}$ equal to 57.6 lb./sq. in. (131 feet of water) is $\Delta m_{A(d)} = 0.0510$ inch. Values for $\overline{s}$ and Δm are listed in Table VIII.

The reduction in permeability and porosity resulting from compaction by the reservoir load is thus negligible.

Model Study

Assumptions, secondary flow field, infinite model

A model study was carried out to obtain a first approximation of the magnitude and distribution of the potential influence of the South Saskatchewan Reservoir on the groundwater regime. The models used were electric-analogs of the continuous-solid-conductor type, using Teledeltos paper with a resistivity of approximately 2,000 ohms per square.

The assumptions inherent in the use of this type of model are:

1. Groundwater flow is steady-state flow in two dimensions.
2. Changes in watertable elevation due to accretion are not a function of time.
3. The coefficient of transmissibility of the aquifer is constant, both in time and space.
4. Hydrologic boundaries are well defined.

For the type of model used the assumptions are fairly well satisfied by the bedrock aquifers under study. In the case of the effect on the watertable, however, any change in the position of the watertable changes the saturated thickness of the aquifer and thus the transmissibility. We may only disregard this effect if the thickness involved is small compared to the thickness of the aquifer. A further error is introduced by disregarding the variable character of the Pleistocene and recent deposits. On the other hand insufficient data are available to warrant the use of a more accurate (but more complicated) resistor-capacitor network that would represent the variations in transmissibility.

The models were set up as secondary-flow-field models. In such a model the changes in boundary conditions in the field (drawdown in a drainage channel; increase in reservoir level) form the boundary conditions for the model. The distribution of the secondary-potential field obtained with the model is then added to the original watertable elevations or piezometric levels in the case of a reservoir rise, or subtracted in the case of a drainage channel.

Figure 17A shows the potential distribution obtained with a simple Teledeltos paper model for the influence of a straight surface reservoir on the elevations of the adjacent watertable. The edges of the model paper act as impermeable boundaries; secondary flow is parallel to these boundaries, and the equipotential lines terminate at right angles to the edges. This is in marked contrast with the numerical solution given by Reed and Bedinger (1962), shown graphically in Figure 11.

In order to eliminate the influence of the arbitrary model-boundaries a conformal transformation used by de Jong (1962, see van Everdingen and Bhattacharyya, 1963, p. 17) was applied. A point P outside a circle of radius R, at a distance r from the centre of the circle can, through conformal transformation, be represented by a point P', inside the circle, at a distance r' from the centre, such that

$$r \times r' = R^2 \quad \ldots\ldots\ldots\ldots\ldots \quad (22)$$

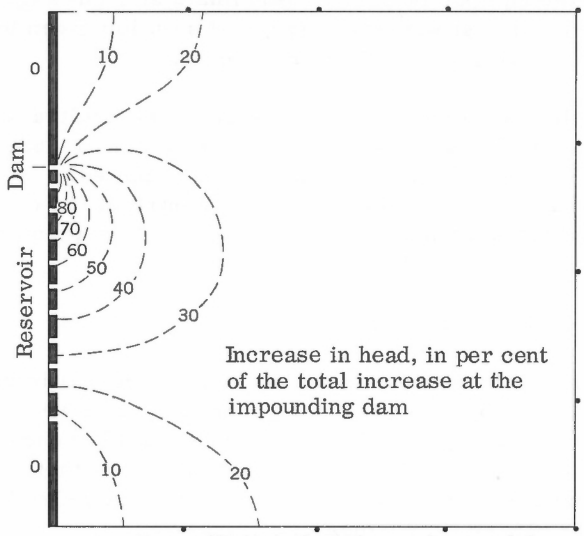
The transformation of the area outside the main model (a) is represented by the second model part (b) in Figure 17B. The two parts were interconnected at points along their edges, spaced approximately 2 1/2 inches apart in this example. A comparison of Figures 17A and 17B shows that this procedure compresses the potential field and at the same time largely eliminates the influence of the arbitrary (impermeable) boundaries.

Instrumentation and arrangement of models

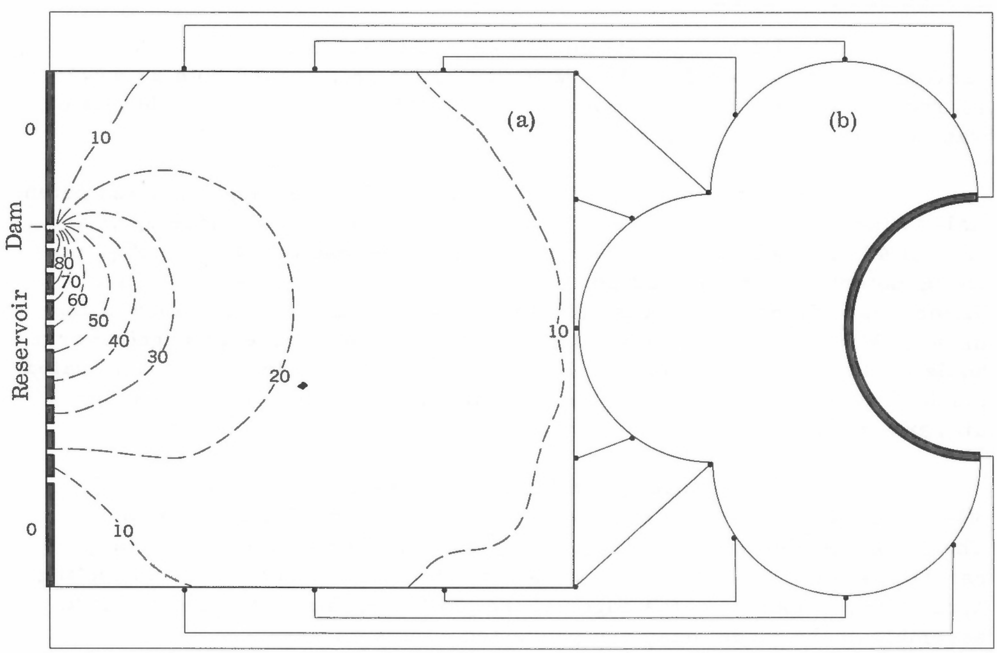
The following instruments were used for the models. A Servomex field plotter Type FP-92 (C in Figure 18), served both as power source and as measuring instrument. The probe used with the field plotter was an ordinary 2H lead pencil.

A potential divider (D in Figure 18), for the supply of fixed potentials to the various potential electrodes on the models, was made up of a bank of 40 selected 1/2-watt resistors of 2.7 ohms each (tolerance 5%), providing potential steps of 2 1/2 per cent each. The total resistance of the divider was 108 ohms, at least 10 times smaller than the resistance of the model. Wires from the potential divider to the model were arranged over a horizontal bar, suspended about 15 inches above the model. This eliminated much of the confusion of wires and facilitated easy access for measuring to all parts of the model.

The main model (A in Figure 18) was mounted on a sheet of 3/4-inch plywood of 19 by 26 inches, supported on four 8-inch long posts. The second model part (B in Figure 18) was attached to a piece of heavy cardboard below the platform that carried the main model. Interconnecting wires were draped over the edges of the platform; this arrangement made assembly of the model easy and prevented confusion.



A. From 'finite' electric-analog model



B. From 'infinite' electric-analog model

Figure 17. Influence of a storage reservoir on groundwater levels in an aquifer that is in hydraulic connection with the river

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Connections to both parts were made easier by leaving small strips of the paper (approximately 1/8 inch) protruding from the edges at the connecting points. These strips were painted with silver paint. The two model parts were fastened to platform and cardboard, respectively, by ordinary steel pins driven through the protruding strips. A small amount of silver paint was then applied to the base of the pins to ensure good contact between the pins and the paper. Wires were attached to the pins by miniature alligator clips.

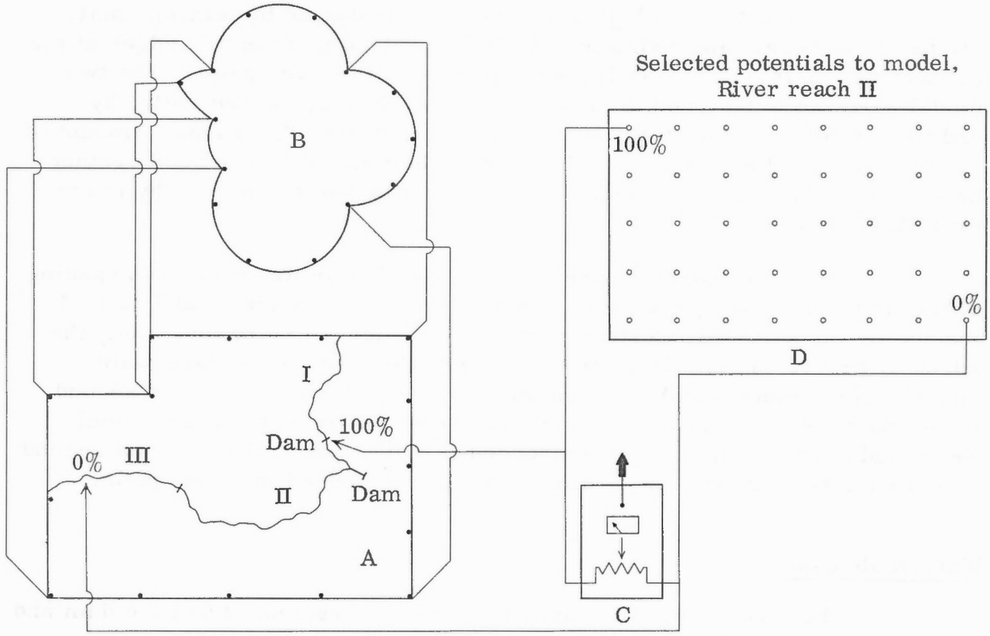
For the models of the South Saskatchewan Reservoir the spacing of the interconnecting points was 1 inch for most of the area and 1 1/2 to 2 inches for the narrower western part of the model (small dashes along the edges of Figures 19 and 20). In the watertable case the surface-water courses (zero electrodes) from the main model (C) continue on the second model part (D), also as zero electrodes. Electrodes on the main model were made of thin copper wire embedded in silver paint; those on the second model part were made from ordinary staples embedded in silver paint.

Watertable case

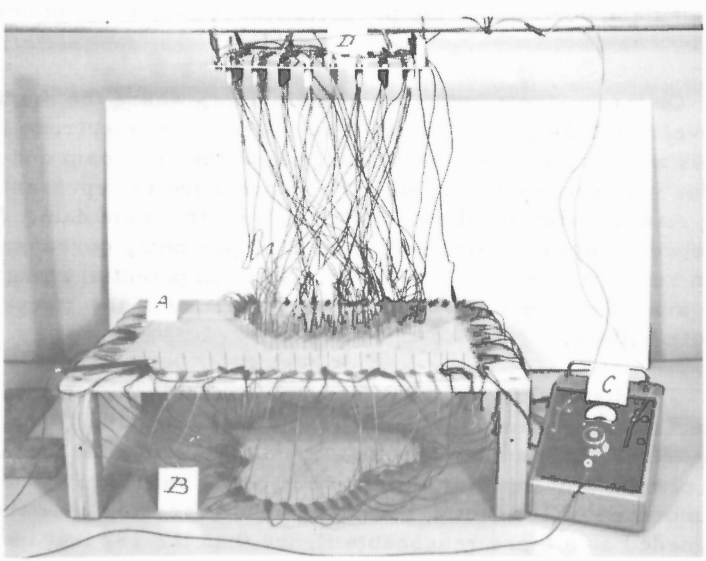
For the watertable case, the river downstream from the dam and upstream from the tail end of the reservoir is represented by a zero-per-cent potential electrode, because no change in water level elevation will take place there. The same applies for all other surface-water channels in the area. Dams are cut out of the paper, because they form impermeable boundaries.

On the upstream side of the main dam, where the maximum rise of water level will take place, a one-hundred per cent electrode is located. Between this and the zero-per-cent electrode at the upstream end a number of electrodes with decreasing potentials are arranged to represent the decreasing rise in water level with distance from the main dam. Steps in potential between adjoining electrodes are 2 1/2 per cent, corresponding to a decrease in reservoir head of 4.625 feet. Steps in potential along the Qu'Appelle arm of the reservoir are larger, because of the steeper slope of the reservoir bottom.

The distribution of the effect on watertable elevations, obtained with the electric-analog model, is illustrated in Figure 19. Each step of 10 per cent effect represents approximately 10 feet potential increase in watertable elevation at the time full equilibrium is reached, based on a maximum increase of 100 feet at the edge of the reservoir near the dam. This is regarded as a more reasonable figure than the 187 feet increase that will take place over the central channel at the dam site.



(a) Schematic circuit diagram



(b) Actual model

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Figure 18. Electric-analog model, South Saskatchewan Reservoir

The actual increases at any given point will probably be less than those indicated by Figure 19, because of variations in the transmissibility of the water-bearing deposits; increase in evapo-transpiration where the watertable comes near the surface; and insufficient elevation to accommodate the indicated rise in watertable. On the other hand the indicated effect may be exceeded in irrigation areas, due to seepage from irrigation canals and infiltration from irrigated fields (recharge $w > 0$). The time needed for the establishment of full equilibrium will probably be long, in view of the low permeability of much of the material involved.

Confined cases

For the confined aquifers in hydraulic connection with the reservoir (Ardkenneth Member, the sandstones in the Beechy Member, and the Belly River sandstone), separate models were run to evaluate the distribution of the reservoir influence on piezometric levels. Another model was set up to investigate the theoretical distribution of the loading effect in a confined aquifer without hydraulic connection to the reservoir. The latter model has little practical value, because the loading effect will probably be dissipated as fast as the load is applied. No model was made for the Cruikshank Member, because its hydraulic characteristics and its relation to river and reservoir levels are almost completely unknown.

In the models for the reservoir effect due to hydraulic connection, equipotential electrodes were applied along the reaches (a) and (b) (Table VII) where outcrops and 'subcrops' of the aquifer are assumed to lie between full storage level and the base of the bedrock valley. The magnitude of the electric potentials applied to these electrodes was based on the future depth of water over the aquifers, which implied the assumption of a constant river efficiency for both reaches. Zero-potential electrodes were applied along the upstream part of South Saskatchewan River where the aquifers lie above full storage level ($\Delta h = 0$). No direct influence was assumed for the reaches (c).

A conformal transformation of the area outside the main model was again used to avoid distortion of the potential field by the arbitrary boundaries of the model paper. Apart from the interconnecting wires between the two model parts, the only electrodes on the transformed part were those representing continuation of the aquifer outcrops (or 'subcrops') above full storage level.

The assumption of homogeneity, implied in the use of this type of electric-analog model, is probably better satisfied in the case of the bedrock aquifers than in the watertable case. Variations in transmissibility appear to be less sudden than in the glacial and alluvial deposits that form the watertable aquifers. On the other hand there is a trend of decreasing permeability and thickness of the sandstones from west or southwest towards east or northeast. Thus the lines of equal influence determined from the models, shown in Figure 20 A to D, presumably lie somewhat too close together in the western part of the area, and somewhat too far apart in the eastern part.

The models assume that there is no connection between the aquifers. Figure 20 represents the distribution of reservoir influence at the time when full equilibrium has been reached. A fair amount of time will be needed to establish such equilibrium, because of the low transmissibility of the aquifers involved, although nearly instantaneous response of piezometric levels is to be expected in the immediate vicinity of the reservoir. The actual increases in piezometric levels will be less than those indicated on Figure 20, because the efficiency of the hydraulic connection between aquifers and reservoir will be smaller than 100 per cent almost everywhere.

No attempt was made, at this stage in the investigation, to determine the probable time required for the establishment of a new equilibrium based on the presence of a full South Saskatchewan Reservoir.

In the first place the time factor depends on the <u>rate of filling of the reservoir</u>, which in turn is a function of:

(1) the discharge of the South Saskatchewan River entering the reservoir reach, unknown as far as the filling period is concerned;

(2) the geometry of the reservoir, i.e. the slope of the reservoir bottom, and the irregular shape and size of the valley cross-section; and

(3) the maximum storage level that can be safely maintained at any one time during the early stages, when construction of the dam is not yet completed.

In the second place the time factor depends on the <u>rate of response of the aquifer</u> (to a given change in stage), which in turn is a function of:

(1) the hydraulic conductivity of the aquifers;

(2) the coefficient of storage for the aquifers;

(3) the thickness of the aquifers; and

(4) the magnitude of the natural discharge through the aquifers towards the river valley (or recharge from the river to the aquifers), because this factor controls the relative quantity of water to be supplied from the reservoir for the increased groundwater storage under the new equilibrium conditions.

The potential field in a semi-infinite confined aquifer under non-equilibrium conditions, like those created by the South Saskatchewan Reservoir, is described by the differential equation:

$$\frac{\delta^2 h}{\delta x^2} + \frac{\delta^2 h}{\delta y^2} + \frac{\delta^2 h}{\delta z^2} = \frac{T}{S} \cdot \frac{dh}{dt} \quad \text{. . . . .} \quad (23)$$

If we select a reach of the reservoir over which a virtually constant change in stage may be expected, then we can restrict our attention to changes in piezometric head in a plane at right angles to the axis of the reservoir. In that case $\frac{\delta h}{\delta y}$ is constant for a constant x and z, and equation (23) becomes:

$$\frac{\delta^2 h}{\delta x^2} + \frac{\delta^2 h}{\delta z^2} = \frac{T}{S} \cdot \frac{dh}{dt} \quad \text{. . . . .} \quad (24)$$

We may further assume that the aquifer is horizontal and of restricted thickness m, and that $\frac{\delta h}{\delta z}$ is constant, within the aquifer, for x = constant. Equation (24) is then further simplified to:

$$\frac{\delta^2 h}{\delta x^2} = \frac{T}{S} \cdot \frac{dh}{dt} \quad \text{. . . . .} \quad (25)$$

In principle it would be possible to obtain a solution for (25) when the change in stage in the surface water has a simple relation to time (e.g. instant rise; sinusoidal increase), for this would give a simple expression for $\frac{dh}{dt}$ at x = 0 (see for example Jacob, 1950). It is felt, however, that it would be more rewarding not to introduce all the restrictions imposed by the simplifying assumptions, but instead to attempt a more generally valid solution of equation (23). A study is being made at present to determine the feasibility of such a general solution.

MANIFESTATIONS OF RESERVOIR INFLUENCE

Watertable

The predicted increase in watertable elevations may be beneficial in areas where the watertable at present is too far below the surface, by creating better moisture conditions and by reducing pumping lifts in watertable wells. The influence may be harmful, on the other hand, in areas near the reservoir where the watertable is already close to the surface under natural conditions. These areas may become intermittently or permanently water-logged, which would make them unsuitable as farmland;

soil salinity may increase through increased evaporation from a shallow watertable. One area that could be affected in this way is the NE-SW running depression southeast of Riverhurst. As the bedrock aquifers are the main object of this study, no observation wells were installed to determine actual changes in watertable elevation.

A certain amount of reservoir water will be 'lost' during the filling stage of reservoir operation, because non-saturated material in the zone of reversed flow is being saturated by infiltration from the reservoir. Once equilibrium has been reached the loss will stop, and discharge of groundwater into the reservoir will start again. The anticipated shifting of groundwater divides towards the reservoir, however, will reduce the amount of groundwater discharged into the reservoir reach of the river.

The area between Riverhurst and the river valley can serve to illustrate this point. Under natural conditions the watertable slopes from around elevation 1,940 feet above sea-level in Riverhurst to near elevation 1,690 at the river, a drop of 250 feet. Once the reservoir is filled the watertable at the edge of the reservoir will be at elevation 1,825, while at Riverhurst the watertable cannot go higher than elevation 1,959, the present ground elevation. The future head loss will thus be only 134 feet. The distance over which the drop in watertable occurs will be reduced by about 20 per cent. The gradient of the watertable between Riverhurst and open water in the South Saskatchewan Valley would thus be reduced by nearly 35 per cent. The corresponding reduction in discharge to the reservoir would not be quite as large as this, because the increased saturated thickness of the watertable aquifers creates a larger transmissibility.

After flooding of the reservoir area the losses by evapotranspiration from present vegetation in the valley will cease, at least until the time new vegetation has started along the new shore-line. The beneficial effect on the water budget of the area will largely be cancelled out by the increased evaporation that will result from the larger open-water surface of the reservoir and the higher elevation of the water surface.

Confined Aquifers in Drift

The piezometers in till and gravel in the Riverhurst area will give an opportunity to observe the influence of the reservoir on confined aquifers in drift. Piezometer 4, in gravel on the east side of the valley at elevation 1,791 feet above sea-level, is dry at present. Piezometer 5 and the new town-well (W5) at Riverhurst tap the same gravel, with static levels of 1,792 feet and 1,901 feet above sea-level, respectively (see Figures 3 and 6). As piezometer 4 is situated close to the top of the gravels, a certain rise in the water-level in the aquifer will presumably have to take place before water enters this piezometer. It is therefore possible that piezometer 5, approximately 2,600 feet farther up the slope of the valley, will register a rise in the piezometric level before any water enters piezometer 4.

Water samples for chemical analysis will be taken periodically from piezometers 4 and 5 and from the new town-well (W5), to endeavour determination of the extent of the zone of infiltration from the reservoir into this aquifer. If one of the piezometers lies within the zone of infiltration, the amount of total dissolved solids in the water should temporarily decrease; it should go back to near its original value by the time equilibrium is reached and the original flow-direction re-established.

The quantity of water discharged from this aquifer into the South Saskatchewan Valley will be reduced as a result of the head-increase in the reservoir. The original head-loss between the new town-well in Riverhurst (W5 in Fig. 3) and piezometer 4 is at least 110 feet(1,901 - 1,791). The head at the reservoir end of the aquifer will be raised at least 34 feet, to elevation 1,825 feet. The head at Riverhurst is expected to rise by about 85 per cent of that amount or 29 feet, to elevation 1,930 feet. The resulting head-loss between well W5 and piezometer 4 would thus be 105 feet, a reduction of 4.5 per cent. A corresponding reduction will take place in the amount of groundwater discharged from this aquifer to the South Saskatchewan Valley.

Bedrock Aquifers

The anticipated increase in piezometric head in the Ardkenneth sandstone may re-activate some artesian wells that have stopped flowing. Examples are well W9, which was drilled in 1929 and flowed at a rate of 2 gallons per minute, and well W10, which was drilled in 1925 and flowed initially at a rate of 1 gallon per minute (Maddox, 1932, p. 70). Static levels in these wells are 0.5 and 2 feet respectively, below ground level at present. The increase in piezometric head will reduce pumping lifts in other non-flowing wells in the aquifer.

No actual infiltration of reservoir water into the Ardkenneth Member is expected in the Riverhurst area. Such infiltration will only take place in the reaches (a) where aquifer 'subcrops' occur at elevations between present river level and future reservoir level. Periodic sampling of wells and piezometers in the Ardkenneth sandstone near Riverhurst, and chemical analysis of such samples should indicate the validity of this assumption.

The model study indicates a maximum ultimate rise in the piezometric level for the Ardkenneth Member at Riverhurst (piezometers A in nests 1 to 7 of 131 feet; for the Beechy Member (piezometers B in nests 1, 2, and 4 to 7) of 45.8 feet; and for the Belly River (piezometers C in nests 1 to 7) of 22.2 feet (see also Table VIII).

The piezometric minima, in feet above sea-level, found in the Riverhurst section would thus be changed as follows:

	Original heads*	Future heads*
River	1,690	1,825
Ardkenneth sandstone	1,697.0	1,828.0
Beechy sandstone	1,729.6	1,775.4
Belly River sandstone	1,779.4	1,801.6

*Feet above sea-level.

Upward movement of groundwater would thus continue to take place between the Belly River and Beechy sandstones, and from the Ardkenneth sandstone into the surface reservoir. At the same time the upward flow from the Beechy sandstone would be reversed into downward movement from the Ardkenneth sandstone. The gradient between the Belly River and Beechy sandstones could be reduced by 47 per cent; from the Ardkenneth sandstone into the reservoir by 57 per cent; and the original upward gradient between the Beechy and Ardkenneth sandstones would be replaced by a downward gradient, with a magnitude approximately 1.6 times as large as the original one (see Table VIII).

In addition, the downstream gradients (parallel to the river) within the two lower sandstones under the reservoir will increase to varying degrees as demonstrated by the model results (see Fig. 20, B to D). The original slight downstream gradient in the Ardkenneth sandstone will practically cease to exist in the Riverhurst area or it may be reversed.

The expected changes in the groundwater regime in the Riverhurst area can be summarized as follows: a decrease in the gradients from divide to reservoir will bring smaller amounts of groundwater to the reservoir area than before; reversal of the gradient between the Beechy and Ardkenneth sandstones will not only stop all contribution of groundwater from the Belly River and Beechy aquifers to the surface flow, but it will actually detract water from the Ardkenneth into the Beechy aquifer; increased gradients in the two lower aquifers, and especially in the Beechy sandstone, will carry the water in these two aquifers downstream as 'under-flow' in the bedrock.

Measurements of water levels in all piezometers and in the above-mentioned wells near Riverhurst will be continued at least till the full storage level in the reservoir has been reached.

Table VIII

Changes in Groundwater Regime in the Riverhurst Section, Expected as a Result of Flooding of the South Saskatchewan Reservoir.

	Ardkenneth sandstone	Beechy sandstone	Belly River sandstone
Increase in unit stress on aquifer(1):			
$\bar{s}$, in feet	109	100	82
$\bar{s}$, in lb./sq. in.	47.3	43.2	35.6
Compaction:			
Δm, in inch	0.109	0.033	0.020
Increase in total head:			
Δh, in feet	131	45.8	22.2
Ratio of new and old upward gradients:			
$\frac{I'}{I}$	0.43	-1.61	0.53
Reduction in discharge:	Bedrock aquifers	Gravels	Watertable aquifers
ΔQ, in per cent of original discharge Q	57	4 - 5	30 - 35

Effects of Sedimentation in the Reservoir

Because of the low velocity of flow in the reservoir the waters of South Saskatchewan River will deposit most of their load of suspended solids on entering the reservoir. The coarser fractions will be dropped at the upstream end, while finer material is taken farther downstream before being deposited. In the early filling stage this will be close to the dam site.

The sediment deposits will increase the load on the confined aquifers by varying amounts. The effect of the increased load on piezometric levels will presumably be dissipated as fast as it occurs. The final effect will be some further compaction of the aquifers below the reservoir.

Clay and silt deposits will reduce the storage capacity of the reservoir and at the same time they may reduce the possibility of leakage, both from and into the reservoir. Reduction of leakage from the reservoir would be potentially beneficial. It is, however, of little consequence in the case of the South Saskatchewan Reservoir, because groundwater gradients and flow will be directed towards the reservoir in most areas, once equilibrium has been established. Direct loss from the reservoir thus will occur only during the filling stage, while the zone of reversed flow in the water-table aquifers is being saturated by reservoir water; very little reduction of losses can be expected during that period, because sedimentation will only just have started.

Increased resistance to discharge of groundwater into the reservoir, as a result of sedimentation, may enable build-up of pressure in the adjacent groundwater. At times of drawdown in the reservoir, landslides along the shore-line would occur more easily under these conditions.

A further effect of sedimentation in the reservoir is the greater potential eroding capacity of the silt-free water discharged at the dam. The resulting scouring in the downstream channel, combined with the high (increased) piezometric heads in the underlying artesian aquifer may lead to increased upward movement of groundwater into this part of the river channel, and consequently to a lowering of the piezometric head in the aquifer. Piezometric measurements at the dam and farther downstream will provide information on this aspect of the influence of the South Saskatchewan Reservoir on the groundwater regime.

REFERENCES

Abramov, S.K., Bindeman, N.N., Bochever, F.M., and Verigin, N.N.
1960: Vliianie vodokhranilisheh na gidrogeologicheskie usloviia prilegaioeshchikh territorii; (Influence of reservoirs on hydrogeological conditions of the adjacent areas); Gostroyizdat, Moscow, 1960.

Abutaliev, F.B., Umarov, U., and Artykova, N.
1962: Calculating the prognosis of the level changes of groundwater, using electronic computers; Soviet Hydrology, 1962, No. 5, pp. 553-557.

Acton, D.F., Clayton J.S., Ellis, J.G., Christiansen, E.A., and Kupsch, W.O.
1960: Physiographic subdivisions of Saskatchewan, map scale 1 inch = 24 miles; Sask. Res. Council, Sask. Soil Survey, Geol. Div.

Cady, R.C.
1941: Effect upon groundwater levels of proposed surface-water storage in Flathead Lake, Montana; U.S. Geol. Survey, Water Supply Paper 849-B, pp. 59-81.

Christiansen, E.A.
1959: Glacial geology of the Swift Current area, Saskatchewan; Sask. Dept. Min. Resources, Rept. 32, 62 p.

Evans, J.K.
1961: Stratigraphy of the Cretaceous Bearpaw Formation in the South Saskatchewan River valley; Master's thesis, U. Sask., 106 p.

van Everdingen, R.O.
1965: Water-sampling equipment; in Report on Activities, office and laboratory; Geol. Surv. Can., Paper 65-2, pp. 28-31.

van Everdingen, R.O., and Bhattacharyya, B.K.
1963: Data for groundwater model studies; Geol. Surv. Can., Paper 63-12, 31 p.

Fraser, F.J., McLearn, F.H., Russell, L.S., Warren, P.S., and Wickenden, R.T.D.
1935: Geology of Southern Saskatchewan; Geol. Surv. Can., Mem. 176, 137 p.

Gignoux, M., and Barbier, R.
1955: Géologie des Barrages et des Aménagements Hydrauliques; Masson et Cie., Paris, 343 p.

Hvorslev, M.J.
1951: Time lag and soil permeability in groundwater observations; Waterways Experiment Station, Corps of Engineers, U.S. Army, Vicksburg, Miss., Bull. No. 36, 50 p.

Jacob, C.E.
1939: Fluctuations in artesian pressure produced by passing railroad trains as shown in a well on Long Island, N.Y.; Trans. Am. Geoph. Union, vol. 20, pp. 666-674.

1950: Flow of groundwater; in Engineering Hydraulics, H. Rouse, ed.; John Wiley and Sons, New York, pp. 321-386.

Kazman, R.G.
1964: New problems in hydrology; J. Hydrology, vol. 2, 1964, pp. 92-100.

Maddox, D.C.
1932: The Darmody-Riverhurst artesian water area, southern Saskatchewan; Geol. Surv. Can., Summary Report 1931-B, pp. 58-71.

1933: The artesian water areas of the west half of Rush Lake and east half of Elbow quadrangles, southern Saskatchewan; Geol. Surv. Can., Summary Report 1932-B, pp. 75-89.

Prairie Farm Rehabilitation Administration
1963: Summary of information on Belly River aquifer; P.F.R.A. Construction Headquarters, Cutbank, Sask., unpublished report.

Meyboom, P.
(in press) Groundwater studies in the Assiniboine River drainage basin. Part I. The evaluation of a flow system; Geol. Surv. Can., Bull. 139.

Reed, J.E., and Bedinger, M.S.
1961: Projecting the effect of changed stream stages on the water table; J. Geoph. Research, vol. 66, No. 8, pp. 2423-2427.

1962: Estimating the effects of stream impoundment on groundwater levels; U.S. Geol. Surv., Prof. Paper 450-B, pp. 88-89.

Scott, J.S.
1962: Surficial geology of the Elbow map-area, Saskatchewan; Geol. Surv. Can., Paper 61-15, 10 p.

Trainer, F.W. and Salvas, E.H.
1962: Groundwater resources of the Massena-Waddington area, St. Lawrence county, New York - with emphasis on the effect of Lake St. Lawrence on groundwater; New York Water Resources Commission, Bull. G.W. -47, 227 p.

Water Rights Division, Sask. Dept. of Agriculture
1959-1962: Records of water wells reported during 1959, 1960, 1961 and 1962.

Appendix I. Stratigraphy of the Riverhurst section.
(Elevations in feet above sea-level)

Ground		1930		1869		1882		1704		1699		1859		1967
Surficial deposits	Sand	1930	Sand	1869	Brown till	1882	Sand	1704	Sand	1699	Till	1859	Till	1967
	Till	1926	Till	1865	Blue till	1846	Till	1698	Till	1693	Gravel	1807	Gravel	1777
							Gravel	1681	Gravel	1603	Till	1736	Till	1735
							Till	1673			Gravel	1714	Sand	1687
							Gravel	1615			Till	1707	Till	1677
							Till	1597					Gravel	1660
													Till	1644
Bedrock[1]		1784		1749		1786		1584		1551		1658		1634
Ardkenneth, sandstone		1590		1578		1573		1584		1551		1595		1593
Beechy, shale (5)		1491		1475		1467		1516		1515		1495		1484
Beechy, sandstone (4)		1427		1411		1405		1451		1451		1430		1422
Beechy, shale (3)		1398		1385		1377		1416		1415		1395		1384
Beechy, sandstone (2)		1312		1303		1301		1337		1335		1319		1312
Beechy, shale (1)		1295		1285		1283		1320		1319		1298		1296
Belly River, sandstone		1178		1175		1178		1216		1202		1185		1189
Total depth		1122		1121		1142		1184		1159		1119		1107
	Location 1		Location 2		Location 3		Location 7		Location 6		Location 4		Location 5	

[1]Top of bedrock: may be shale of the Snakebite Member, or sandstone of the Ardkenneth Member.

Appendix II. Well data.

Piezometer or well number	Elevation of collar in ft.	Total depth, in feet	Formation	Elevation of top of screen, in ft.	Elevation of water-level, in feet	Fluctuations during 1964, in ft.
Piezometer 1	1931.57	105	Till	1860.07	1909.3	-
Piezometer 1A	1931.44	365	Ardkenneth sdst., top	1585.14	1698.1	0.6
Piezometer 1B	1931.88	570	Beechy sdst., (4)	1403.08	1746.4	0.3
Piezometer 1C	1930.95	808	Belly River sdst.	1150.50	1866.1	0.7
Piezometer 2	1869.89	105	Till	1785.49	1851.4	-
Piezometer 2A	1870.39	315	Ardkenneth sdst., top	1571.59	1697.0	0.4
Piezometer $2A_1$	1870.15	400	Ardkenneth sdst., base	1485.65	1707.7	-
Piezometer 2B	1870.25	524	Beechy sdst. (4)	1407.70	1744.6	0.7
Piezometer 2C	1871.36	748	Belly River sandstone	1167.86	1841.8	0.4
Piezometer 3A	1883.23	330	Ardkenneth sdst., top	1563.73	1698.2	0.3
Piezometer 3C	1883.01	740	Belly River sandstone	1173.71	1867.0	0.7
Piezometer 7	1705.70	105	Till	1609.30	1693.5	-
Piezometer 7A	1706.39 1)	195	Ardkenneth sdst., base	1528.98	1723.1	-
Piezometer 7B	1706.42 1)	285	Beechy sdst. (4)	1437.83	1729.6	-
Piezometer 7C	1706.68 1)	530	Belly River sdst.	1210.97	1779.4	-
Piezometer 6	1699.94	120	Gravel/sand	1592.49	1688.4 min. 1696.9 max.	8.5
Piezometer 6A	1701.47 1)	195	Ardkenneth sdst., base	1525.56	1705.0	-
Piezometer 6B	1701.05 1)	285	Beechy sdst. (4)	1436.67	1734.2	-
Piezometer 6C	1701.88 1)	560	Belly River sandstone	1196.85	1809.6	-
Well # 1	1701.20	470	Beechy or Belly River sdst.	-	1705	-
Well # 2	1709.22	527	Belly River sandstone	-	1710	-
Well # 3	1695.00	1112	Belly River sandstone ?	-	1705	-
# 4, spring	1788.70 2)	-	Gravel/till contact	-	1788.7	-
Piezometer 4	1860.66	75	Gravel	1794.41	1792.1 3)	-
Piezometer 4A	1861.00	300	Ardkenneth sdst., top	1577.00	1835.1	0.4
Piezometer $4A_1$	1860.05	370	Ardkenneth sdst., base	1503.55	1835.0	-
Piezometer 4B	1860.38	485	Beechy sdst. (4)	1425.88	1746.5	1.0
Piezometer 4C	1859.70	740	Belly River sandstone	1172.70	1823.7	0.5
Piezometer 5	1968.80	225	Gravel	1751.62	1791.6	1.1
Piezometer 5A	1969.04	410	Ardkenneth sdst., top	1577.04	1915.4	0.3
Piezometer 5B	1968.65	560	Beechy sdst. (4)	1414.15	1761.8	-
Piezometer 5C	1968.46	860	Belly River sandstone	1176.96	1835.4	0.9
Well # 5	1958	141	Gravel	1830	1902	-
Well # 6	1953	386	Ardkenneth sdst., top	1567	1926	-
Well # 7	1945	6	Silty clay	1939	1944	-
Well # 8	1969	364	Ardkenneth sdst., top	1605	1955	-
Well # 9	1958	348	Ardkenneth sdst., top	1610	1958 4)	-
Well # 10	1963	352	Ardkenneth sdst., top	1611	1961 4)	-

1) Top of fittings, collar elevation is about 5 inches lower.

2) Ground elevation.

3) Dry piezometer.

4) Elevation of water-levels in 1931: W9-1959; W10-1965 (Maddox, 1932).

Water-level in South Saskatchewan River fluctuated between 1967' (spring-flood crest) and 1688' (low water in August 1964).
Screens installed are 3 feet long, 2 inches inside diameter, No. 10 slot, Johnson, except in 4A (5 feet long) and 4B (No. 12 slots).

Appendix III. Chemical analyses of groundwater in the Riverhurst area.

Type and No. of source	Total solids, p.p.m.	Conductivity, micromhos.	Ca^{++} milliequiv.	Mg^{++} meq.	$Na^+ + K^+$ meq.	Cl^- meq.	$SO_4^=$ meq.	HCO_3^- meq.	Formation	Mg/Ca	Na/Ca + Mg	Cl/SO_4	Cl/HCO_3	Na + K/Cl
Piezometer 1	Contaminated	with cement.	-	-	-	-	-	-	Sandy till	-	-	-	-	-
Piezometer 1A	1078	2981	4.870	0.125	7.265 + 5.472	7.786	0.739	9.384	Ardkenneth, top	0.026	2.55	10.5	0.83	1.64
Piezometer 1B	2299	4142*	0.319	0.600	38.91 + 0.115	28.20	0.206	11.680	Beechy, 4	1.88	42.5	137.0	2.42	1.38
Piezometer 1C	4065	7164	1.088	0.990	67.83 + 0.182	63.71	0.314	6.194	Belly River	0.91	32.7	203.0	10.29	1.07
Piezometer 2	1105	1640	0.010	6.673	9.875 + 0.340	0.666	13.450	3.180	Till/gravel	-	1.53	0.049	0.21	15.33
Piezometer 2A	593	1076	0.090	0.010	8.701 + 0.217	2.598	2.373	4.138	Ardkenneth, top	0.111	89.2	1.09	0.63	3.43
Piezometer $2A_1$	917	1719	0.150	0.090	14.964 + 0.217	5.473	2.015	2.491	Ardkenneth, base	0.600	58.4	2.72	2.20	2.77
Piezometer 2B	2268	4033	0.938	0.582	37.845 + 0.120	28.44	0.541	10.740	Beechy, 4	0.621	25.0	52.5	2.65	1.34
Piezometer 2C	4211	7604	0.080	1.050	71.34 + 0.222	66.58	1.353	3.911	Belly River	13.1	63.4	49.2	17.03	1.08
Piezometer 3A	1322	2300	0.379	0.154	23.19 + 0.125	11.618	0.229	11.489	Ardkenneth, top	0.406	43.7	50.7	1.01	2.01
Piezometer 3C	3662	6682	2.869	1.127	58.725 + 0.384	57.81	0.333	4.950	Belly River	0.392	14.8	173.9	11.68	1.02
Piezometer 6	2065	2925	1.387	2.183	14.138 + 0.220	0.671	29.825	7.949	Gravel/sand	1.58	4.02	0.023	0.084	21.38
Piezometer 6A	1541	2701	0.060	0.420	26.318 + 0.079	15.064	0.129	11.948	Ardkenneth, base	7.0	55.0	116.8	1.26	1.75
Piezometer 6B	2247	3350	0.185	0.538	38.019 + 0.102	27.618	0.187	11.653	Beechy, 4	2.80	52.7	147.9	2.37	1.38
Piezometer 6C	4339	7859	2.156	1.061	71.775 + 0.176	67.76	0.125	6.408	Belly River	0.494	22.4	542.0	10.58	1.06
Piezometer 7	397	720	0.723	0.100	4.959 + 0.251	0.316	4.705	1.057	Till	0.138	6.34	0.067	0.29	16.51
Piezometer 7A	Contaminated	with cement.	-	-	-	-	-	-	Ardkenneth, base	-	-	-	-	-
Piezometer 7B	2281	4078	0.389	0.554	39.150 + 0.100	27.843	0.129	11.522	Beechy, 4	1.42	41.6	216.0	2.42	1.38
Piezometer 7C	4542	7478	1.866	1.111	75.680 + 0.199	72.192	0.416	5.655	Belly River	0.595	25.5	173.3	12.78	1.05
Well W 1	3871	6863	0.474	0.949	64.38 + 0.171	56.570	0.916	9.655	Belly River ?	2.01	45.3	61.8	5.86	1.14
Well W 2	4465	7942	1.460	1.070	73.95 + 0.179	69.227	0.937	6.174	Belly River	0.733	29.4	73.9	11.21	1.07
Well W 3	4928	8326	0.229	2.917	81.345 + 0.182	78.311	0.666	5.720	Belly River ?	12.7	25.9	117.6	13.69	1.04
Spring W 4	1763	2311	6.901	10.935	9.740 + 0.220	0.443	21.42	6.200	Gravel/till contact	1.59	0.559	0.021	0.071	23.0
Piezometer 4	Dry	-	-	-	-	-	-	-	Gravel	-	-	-	-	-
Piezometer 4A	1635	2615	0.080	0.605	25.448 + 0.110	6.234	10.681	9.516	Ardkenneth, top	7.57	38.2	0.548	0.624	4.1
Piezometer $4A_1$	Contaminated	with cement.	-	-	-	-	-	-	Ardkenneth, base	-	-	-	-	-
Piezometer 4B	2118	3865	0.299	0.780	35.496 + 0.153	25.160	0.916	10.927	Beechy, 4	2.61	32.0	27.4	2.30	1.42
Piezometer 4C	3661	6572	1.028	1.250	60.248 + 0.176	60.285	0.281	2.639	Belly River	1.22	26.5	214.3	23.82	1.001
Piezometer 5	1942	2602	9.182	11.357	11.571 + 0.228	1.568	17.655	13.702	Gravel	1.24	0.575	0.089	0.114	7.53
Piezometer 5A	1397	2394	1.841	0.325	22.620 + 0.151	9.710	0.323	15.160	Ardkenneth, top	0.177	10.5	30.0	0.641	2.34
Piezometer 5B	Riverwater	-	-	-	-	-	-	-	Beechy, 4	-	-	-	-	-
Piezometer 5C	2500	4617	1.143	0.411	41.108 + 0.153	38.070	0.333	4.769	Belly River	0.36	26.6	114.2	7.98	1.08
Well W 5	2380	3101	8.000	8.460	20.66 + 0.256	1.185	25.19	11.657	Gravel	1.06	1.27	0.047	0.102	17.67
Well W 6	1622	2525	0.414	0.243	26.883 + 0.097	4.427	8.078	14.859	Ardkenneth, top	0.588	41.0	0.548	0.298	6.09
Dugout W 7	1141	1533	7.510	6.500	3.893 + 0.164	0.350	13.53	4.401	Dugout in silty clay	0.866	0.29	0.026	0.079	11.60
Well W 8	No sample	-	-	-	-	-	-	-	Ardkenneth, top	-	-	-	-	-
Well W 9	1323	2190	0.254	0.144	23.490 + 0.087	6.176	0.874	16.521	Ardkenneth, top	0.567	59.2	7.06	0.37	3.82
Well W 10	1388	2208	0.334	0.164	24.795 + 0.095	7.360	0.062	17.341	Ardkenneth, top	0.491	50.2	118.8	0.42	3.38

Appendix IV. Project Statistics, South Saskatchewan Dam and Reservoir.

South Saskatchewan River Dam:

Location: 18 miles upstream from Outlook, Saskatchewan.

Height	210 feet
Length, overall	16,700 feet
Length, main fill	8,000 feet
Width at base	2,600 feet
Width at top	60 feet

Spillway:

Length of crest	528 feet
Discharge capacity	265,000 c.f.s.

Qu'Appelle Dam:

Location: 12 miles southeast of Elbow, Saskatchewan.

Height	90 feet
Length	9,000 feet
Width at base	700 feet
Width at top	70 feet

Reservoir:

Area	109,600 acres (5.2% now cultivated)
Total storage	8,000,000 acre-feet
Usable storage	2,750,000 acre-feet
Length	140 miles
Depth of water, main dam	185 feet
Depth of water, Qu'Appelle dam	70 feet

Drainage basin above dam site	48,800 sq. miles
Irrigation area (proposed)	500,000 acres
Power production, ave. ann. output	475,000,000 kwh.