Lake Bonneville: Geology and Hydrology of the Weber Delta District, Including Ogden, Utah

GEOLOGICAL SURVEY PROFESSIONAL PAPER 518

Prepared cooperatively by the U.S. Geological Survey and the U.S. Bureau of Reclamation with the cooperation of the Utah State Engineer

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By J. H. FETH, D. A. BARKER, L. G. MOORE, R. J. BROWN, and C. E. VEIRS

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PREFACE

During much of Pleistocene time, and probably earlier, northern Utah was occupied by lakes of large extent. The best known and last widespread lake in this area was Lake Bonneville. At maximum extent, Lake Bonneville was approximately as large as Lake Michigan, about 20,000 square miles, and as much as 1,000 feet deep. The relics of Pleistocene Lake Bonneville are modern Utah Lake, Great Salt Lake, and Sevier Lake.

In 1890 the U.S. Geological Survey published G. K. Gilbert's classic study of Lake Bonneville, which is still the only study of the lake that includes its entire basin. In 1946 the Geological Survey began a restudy of the geology of the Bonneville Basin to evaluate in greater detail the geologic history and the resources of the region (Hunt and others, 1953; Bissell, 1963; Williams, 1963). This report is concerned primarily with the Weber Delta district, an area containing the Weber Delta, the largest delta formed in glacial Lake Bonneville.

Today the Weber Delta district is constituted of broad plains and terraces, extending from the shore of Great Salt Lake to the base of the Wasatch Range, and is occupied by one-sixth of Utah's one million people. The Weber River still carries some sediment to the lake, but its present significance to the economy of the region is as a source of water for irrigation and for municipal and industrial use. The Weber Delta district has a semiarid climate, with average annual precipitation insufficient for crops, and the further handicap that only one-third of the annual total falls during the growing season. The limit of human occupancy of the district is, therefore, set by the extent to which the surface and subsurface water resources can be managed to yield perennial supplies.

The characteristic flow pattern of the Weber River and its principal tributaries includes a freshet in the spring from melting snows in the mountains, a rapid diminution to a minimum by late summer, and runoff near this minimum level throughout the winter and until the next freshet. In addition to these seasonal fluctuations there are marked variations from year to year, so that the maximum annual runoff of record may be 5–10 times the minimum. The water of Weber River was first used by new settlers for irrigation in 1848, and rights to all the normal summer flow of the river and its perennial tributaries had been established before 1896. Later, reservoirs were developed for assurance of water supply throughout the irrigation season. Three major reservoirs — Echo, East Canyon, and Pine View — have been in operation more than a quarter of a century, chiefly to provide irrigation water to the Weber Delta district; but as of 1950, the combined storage capacity of these reservoirs was less than a quarter of the average annual runoff of the Weber and Ogden Rivers.

The Weber Basin Project of the U.S. Bureau of Reclamation, authorized in 1949, provides for comprehensive development of the water of the Weber River drainage basin to yield ultimately an average of 278,000 acre-feet of water annually, of which 166,000 acre-feet is for irrigation of about 133,000 acres of land, 52,000 acre-feet for municipal and industrial use in the Weber Delta district, and 60,000 acre-feet for migratory waterfowl refuges. The project includes enlargement of the Pine View and East Canyon dams and reservoirs and construction of the Wanship and Lost Creek dams, thus increasing the mountain reservoir storage to more than double the capacity prior to 1950. Additional storage will be provided by Willard dam in Willard Bay, formerly an arm of Great Salt Lake. The project also includes construction of wells and drains in the integrated development and management of the basin's water resources. Conjunctive use of subsurface reservoirs with surface reservoirs will be essential to ultimate full development of the water resources, because the total surface storage, even with Willard Reservoir, will still be less than the average annual production of the river system.

Thousands of wells are in the Weber Delta district, many of them more than 50 years old, and most of them flowing wells of small diameter and small yield. The total discharge from these wells — about 25,000 acre-feet per year, of which one-third comes from about 60 pumped wells of large capacity — has been small in comparison with the quantities diverted from the Weber and Ogden Rivers; but this water is important in municipal and rural domestic supply, stock watering, industrial supply, and irrigation of small tracts. The wells are distributed widely but irregularly over the district, reflecting in part the conditions of occurrence of usable ground water.

An evaluation of the ground-water resources of the Weber Delta district at present would show the occurrence of ground water, not under original conditions, but under conditions modified by discharge from wells, by application of surface water for irrigation, and by artificial facilities for drainage of land and disposal of water. Further modifications can be expected as additional water of the Weber Basin project is used in the area. Thus, the source, movement, storage, and discharge of ground water will be modified by man's operations; and they can be modified to maximum benefit and minimum detriment to his welfare. But this requires an adequate understanding of the hydrology — a greater understanding than we now have, and one that will require continuing observation and interpretation of the effects of development and use of the water throughout the project area.

The sediments of the Weber Delta constitute the framework through which ground water moves, and they are thus a controlling factor in the natural storage and circulation and also in the effects of man's activities. The geology of the Weber Delta — texture, sorting, bedding, and structure, which affect the permeability of the sediments; soluble materials which may degrade the water quality; other features which influence the infiltration, percolation, and discharge of ground water — is thus a subject of major and continuing importance in making optimum use of the ground-water resource.

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[Plates in pocket]

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By J. H. FETH, D. A. BARKER, L. G. MOORE
R. J. BROWN, and C. E. VEIRS

ABSTRACT

A cooperative investigation to determine the geology of the Weber Delta district, with emphasis on the occurrence and chemical quality of ground water, was made by the U.S. Geological Survey and the U.S. Bureau of Reclamation with the later assistance of the Utah State Engineer in the final preparation of the report. The Weber Delta district covers an area of almost 400 square miles between the Wasatch Range and the east shore of Great Salt Lake in north-central Utah. The district, which is about 30 miles long and 3–20 miles wide, is dominated by the Wasatch Range on the east. West of the mountains is a generally narrow foothill area, from which flatlands, interrupted by a few low sand ridges, slope gently westward to the shore of Great Salt Lake. Breaching the foothills and the flatlands near the center of the district is the Weber Delta, which is the largest of the deltas built in the Pleistocene Epoch by Lake Bonneville on an open plain. The Weber Delta, the smaller delta of the Ogden River to the north, and the alluvial fans of several small streams, coalesce to form a belt of plateaulike highlands from 2 to 7 miles wide and about 10 miles long from north to south. Ten miles north of the city of Ogden the Pleasant View salient projects westward from the front of the Wasatch Range, and about 15 miles west of the mountain front, Little Mountain rises 450 feet above the surface of the nearly level plain.

The climate of the Weber Delta district is temperate and semiarid. The mean annual temperature is about 52°F, and the annual precipitation ranges from about 12 inches near the western part of the district to about 20 inches adjacent to the base of the mountains. The precipitation on the mountains, in the headwaters of the Weber and Ogden Rivers, however, is as much as 50 inches per year.

The Wasatch Range and Little Mountain consist of consolidated rocks of Precambrian and Cambrian age. The deposits exposed in the rest of the district are unconsolidated and weakly consolidated rocks of the Lake Bonneville Group of Pleistocene age or younger deposits of Recent age.

The Lake Bonneville Group in the Weber Delta district consists of the Alpine, Bonneville(?), and Provo Formations. Sand and gravel of the Alpine Formation are exposed principally in areas very close to the mountain front, but the most distinctive lithology of the Alpine in the district is a cliff-forming slabby clay that has a thickness of at least 80 feet. Deposits of sand and gravel at altitudes ranging from 5,100 to more than 5,200 feet above sea level are considered closely equivalent to strata mapped as the Bonneville Formation in northern Utah Valley in central Utah. In the Weber Delta district, however, no clear disconformity was found at the base of the sand and gravel units, and therefore these high-level sand and gravel deposits are called Bonneville(?) and Alpine Formations undifferentiated. They are characteristically only 20–30 feet thick. Sand and gravel of the Provo Formation, characteristically 10–30 feet thick, cover broad areas of the Weber Delta benchland and small areas of the Ogden Delta; locally, deposits of gravel or sand of the Provo are less extensive.

Sediments of Recent age are at the surface in much of the Weber Delta district. Extensive lacustrine or flood-plain deposits are at altitudes between 4,200 and 4,300 feet; the channels of the modern rivers are characterized by variable thicknesses of gravel; patches of gravel extending far westward reflect the presence of old channels of the Weber River or other major streams; locally, extensive deposits of colluvium are conspicuous along the Wasatch front; and clay deposited by Great Salt Lake underlies the western boundary of the district. The Wasatch fault, which is part of a fault zone of great regional extent, is the largest geologic structure in the Weber Delta district. It is a normal fault, downthrown to the west, and dips on the fault surface range from about 20° to as much as 70° to the west. Probably the fault is not a single break but rather a zone of movement a mile or more in width.

Geophysical evidence suggests that the bedrock surface slopes very steeply just south of the Pleasant View salient, as though along a major normal fault. Indirect evidence suggests that this fault may extend a considerable distance. Another fault zone east of Little Mountain probably trends north-south, paralleling the Wasatch fault. A gravity survey shows that the bedrock between the Wasatch Range and Little Mountain has the general configuration of an elongate trough or somewhat canoe-shaped sink, the deepest part of which is about 5 miles west of the Wasatch fault scarp. The gravity anomalies imply a maximum thickness of 6,000 to possibly 9,000 feet of unconsolidated rock in the trough.

The valley fill is an intricately interfingering mass of lenticular or wedge-shaped strata of gravel, sand, silt, and clay. Strata deeper than about 1,000 feet below the land surface have been explored by only a few wells. Profiles prepared from subsurface data permitted tentative correlations of a few fairly continuous north-trending zones; the writers infer that many of the beds were deposited by lake

currents paralleling the shoreline of Lake Bonneville. The valley fill forms the ground-water reservoir, and local lithology has a marked influence on the quantity and quality of water yielded by wells.

A water budget shows that about 950,000 acre-feet of water enters and leaves the Weber Delta district annually. The larger sources of inflow are the Ogden and Weber Rivers which, respectively, contribute 160,000 and 360,000 acre-feet of water annually, and precipitation on areas below 5,000 feet which contributes an estimated 350,000 acre-feet of water annually. About 330,000 acre-feet of water leaves the district annually in the Weber River; about 80,000 acre-feet leaves the district annually in other surface channels; and about 520,000 acre-feet leaves the district annually by evapotranspiration. Unaccounted for is about 20,000 acre-feet, which may be direct leakage into Great Salt Lake.

The Weber Delta district has been divided into the Weber Delta, Ogden-Plain City, North Ogden, West Warren, Little Mountain, and Kaysville-Farmington subdistricts. The boundaries of the subdistricts are based principally on the quality of the water yielded by the aquifers in the subdistricts.

The Weber Delta subdistrict has a greater present and potential development of ground water than any of the other subdistricts. The Delta and Sunset artesian aquifers yield most of the ground water in the subdistrict. The Delta aquifer, which is probably 50–150 feet thick and whose top is 500–700 feet below the land surface, is highly permeable and supplies water to many of the pumped wells of large yield. The Sunset aquifer, which is probably 50–250 feet thick and whose top is generally 250–400 feet below the land surface, is less permeable and yields smaller quantities of water to wells. The water from both aquifers is of good chemical quality, although hard. In areas near Roy and Syracuse, shallow artesian aquifers 50–150 feet below the land surface yield water that is more mineralized than the water from the underlying Delta and Sunset aquifers; whereas in an area near Layton, water from wells is less mineralized than water from the Delta and Sunset aquifers.

The Ogden-Plain City subdistrict is underlain by predominantly fine-grained materials, but large yields can be obtained from wells in parts of the subdistrict. The chemical quality of water varies both laterally and vertically, but because of a high dissolved-solids and sodium content, the water is commonly unsuitable for irrigation.

Wells obtain relatively small yields from the artesian aquifer in the North Ogden subdistrict, but the water rises to the highest altitude known in the Weber Delta district. Recharge is from the mountain front. The water is of excellent chemical quality, and it can be used for most purposes without treatment.

The West Warren and Little Mountain subdistricts are underlain predominantly by the fine-grained materials and yields of wells are small. The water in the West Warren subdistrict is suitable for domestic use; but because it has a high sodium bicarbonate content, it cannot be used readily for irrigation. Water in the Little Mountain subdistrict contains considerable sodium chloride and is unsatisfactory for most uses.

Aquifers of the Kaysville-Farmington subdistrict are separated from the aquifers of the Weber Delta subdistrict to the north by a bedrock high. Wells in the Kaysville-Farmington subdistrict near the Wasatch Range generally have small yields, but the water is of good chemical quality. Westward from the mountains the sodium bicarbonate content of the water increases by ion exchange, and the water becomes less suitable for irrigation.

The original source of all water that recharges the ground-water reservoir in the Weber Delta district is precipitation that falls on the drainage basin. The estimated recharge to the aquifers of the district is about 70,000 acre-feet per year, and the principal recharge area consists of the channel of the Weber River and a belt of sand and gravel ranging in width from a few to a few thousand feet just west of the mountain front. The direct sources of recharge are the Weber and Ogden Rivers, mountain-front streams, infiltration of precipitation, irrigation seepage, canal losses, and subsurface flow from the mountain front. The latter, amounting to about 30,000 acre-feet per year, is the largest source of recharge. Artificial-recharge experiments, during which about 2,170 acre-feet of water infiltrated through a 3¼-acre gravel pit during a 7-week period, indicated that artificial recharge on a large scale may be feasible.

The total quantity of water in storage in the 200 cubic miles of unconsolidated sediments that underlie the Weber Delta district (not including the Kaysville-Farmington subdistrict and the northwestern part of the Ogden-Plain City subdistrict), assuming an average porosity of about 25 percent, is estimated to be almost 170 million acre-feet. However, much of this water is of poor chemical quality or is in fine-grained sediments, which do not yield water readily to wells. The maximum known depth of fresh water is 1,300 feet below the land surface. The quantity of water that could be withdrawn in the Weber Delta subdistrict by lowering water levels a maximum of 150 feet, but still not dewatering the artesian aquifers, was calculated by 2 methods to be 80,000 or 100,000 acre-feet. The additional quantity of water that could be withdrawn in the subdistrict by dewatering the upper 50 feet of the artesian aquifer was calculated by 2 methods to be 300,000 or 600,000 acre-feet. The amount of water that could be withdrawn from the remainder of the Weber Delta district by dewatering the upper 50 feet of the artesian aquifers was calculated to be about 700,000 acre-feet. Long-term trends of water levels, from records that go back as far as 1935, indicate that the principal effects of pumping are local and that there has been little change in storage from 1935 to 1961.

Ground water in the aquifers of the Weber Delta district in general moves westward from the Wasatch Range toward Great Salt Lake. Calculations based on the hydraulic gradient and the permeability of materials in the Weber Delta subdistrict between the surface and 1,300 feet indicate that about 40,000 acre-feet of water flows through the district annually. Some of this water is discharged by wells, but about 20,000 acre-feet may continue westward to discharge into the lake.

The discharge of ground water from pumped and flowing wells in the Weber Delta district in 1954 was about 25,000 acre-feet. Discharge from springs during the same period probably was on the order of a few thousand acre-feet.

Twenty aquifer tests were made in the Weber Delta district, principally using the larger pumped wells that tap the Delta aquifer. Coefficients of transmissibility obtained from these tests range from 2,000 to 300,000 gallons per day per foot for the entire district and from 25,000 to 190,000 gallons per day per foot for the Delta aquifer. The coefficient of storage for the Delta aquifer as determined from 3 tests averaged 7.9×10^{-4}. The tests in the Weber Delta subdistrict indicate that the aquifers to depths of about 700 feet have relatively large coefficients of transmissibility. The few tests made in other subdistricts indicate that the aquifers in the North Ogden subdistrict have a much lower coefficient of transmissibility; the aquifers in the Ogden-Plain City subdistrict have a relatively large average coefficient of transmissibility; and the aquifers in the Kaysville-Farmington subdistrict have a considerable range in transmissibility.

The chemical quality of ground and surface water in the Weber Delta district is known from analyses of more than 500 samples. The distribution of the main chemical types of ground water and mixtures of chemical types is shown on a map of the district. The district contains three main chemical types of ground water—calcium magnesium bicarbonate, sodium chloride, and sodium bicarbonate. The first two types are considered to be original types, whereas the sodium bicarbonate type was probably derived by the action of ion exchange on the calcium magnesium bicarbonate type water. The sodium concentration tends to increase from the mountains westward toward the Great Salt Lake.

The water of Utah Hot Springs and Hooper Hot Springs has a high content of radioactive constituents. Analyses of water from wells and springs in the vicinity of the Pleasant View salient showed a small increase in the average radon concentration of water from wells near the southern margin of the salient and in the vicinity of projections of fault traces into the area covered by unconsolidated sediments. This suggests that the radon is derived from water rising along faults. The increase of radon, however, could also result from the precipitation of radium at favorable sites governed by changes in permeability of the aquifers, rather than from highly radioactive waters rising along faults.

Studies of evaporation and evapotranspiration in 1954 and 1955 indicate that about 520,000 acre-feet of water is discharged annually from the nearly 400 square miles in the district between the 5,000-foot level and the 1952 shoreline of Great Salt Lake.

The district was divided into seven areas based on the principal type of vegetation in each area. The areas, the principal type of vegetation in each area, the acreage of each area, and the amount of water in acre-feet evaporated or transpired annually in each area are as follows: Area 1, cultivated crops depending on irrigation, 74,000, and 170,000; area 2, saltgrass pasture, 54,600 and 162,000; area 3, cattails, rushes, and reeds, 11,500 and 59,000; area 4, dry-land crops, grasses, and shrubs that depend on precipitation, 32,800, and 45,000; area 5, no vegetation (salt-crust barrens), 60,000, and 40,000; area 6, no vegetation (open fresh water in drains, canals, and streams), 5,800 and 24,000; area 7, vegetation diverse (scattered municipal and industrial areas), 16,499, and 22,000.

Future development of the water resources of the Weber Delta district will include increased use of surface water; may include the beneficiation of presently unused water, such as sewage, industrial waste, and saline water; and should include the use of the ground-water body as a reservoir. Withdrawal of ground water should be increased to lower the artesian pressure and reduce wastage, and continuing studies should be made of changes in water levels and artesian pressures, changes in discharge, and changes in chemical quality.

INTRODUCTION

PURPOSE AND SCOPE OF THE STUDY

As a part of the Weber Basin Project, the U.S. Bureau of Reclamation sponsored a comprehensive study of the ground-water resources of a 400-square-mile area that includes the Weber Delta and some adjacent lands. The study was made from February 1953 to July 1956, prior to the completion of any of the major elements of the Weber Basin Project. The Utah State Engineer contributed to the final preparation of the report as part of the regular State cooperative program with the U.S. Geological Survey.

Preparation of the report was the overall responsibility of J. H. Feth, U.S. Geological Survey. Extensive and critical contributions to various sections were made by the other authors, all of the U.S. Bureau of Reclamation, as follows: (1) Ground water, D. A. Barker and L. G. Moore, (2) chemical quality, C. E. Veirs and D. A. Barker, and (3) evaporation and evapotranspiration, R. J. Brown. Individual contributions of others are recognized in the acknowledgments.

The comprehensive investigation was undertaken to determine (1) the geology of the area with emphasis on the occurrence of ground water; (2) the recharge, use, and discharge of ground water; (3) the chemical quality of ground water; and (4) the amount of ground water available for development.

Various methods of investigation were used: (1) mapping surface geology, especially unconsolidated rocks, and studying subsurface geology using drillers' logs, well cuttings, and geophysical data; (2) defining the recharge areas; (3) studying the hydrologic properties of the aquifers; (4) making an inventory of flowing wells and large-yield pumped wells; (5) investigating springs, and surface drains that carry water out of the area; (6) studying evaporation and transpiration; and (7) determining the chemical quality of ground and surface water.

The investigation was concerned almost entirely with an area underlain by unconsolidated material. Consolidated rocks, such as those composing the adjacent Wasatch Range, were studied only where such data were needed to understand the ground-water conditions.

This report discusses the status of ground-water occurrence at the time of the investigation. Certainly this status will change as development proceeds and water use by the Weber Basin Project

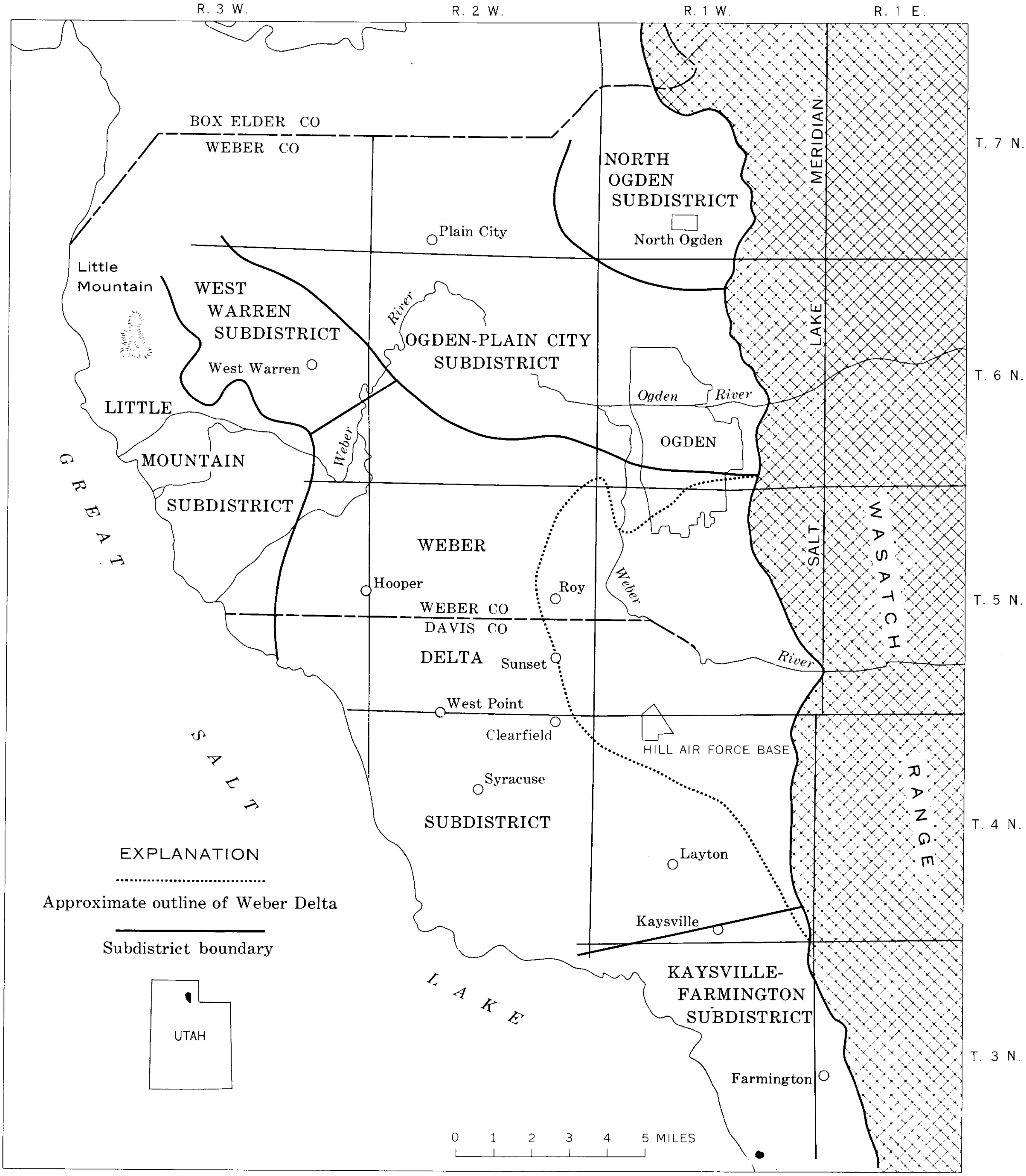


FIGURE 1.—Index map showing the Weber Delta district, Utah, and ground-water subdistricts.

increases as expected; this report, therefore, will be of value in defining the conditions prior to project operations.

The features that are related to the geology of the Weber Delta district—the recharge areas of the ground-water reservoir and the thickness, depth, and areal extent of the aquifers, for instance—are permanent and subject to negligible change. But our information concerning them is incomplete, and conclusions drawn now may require considerable revision as more data become available. Thus, the present evaluations of various aspects of the ground-water resources might best be classified as working hypotheses—to be accepted until more information is available.

LOCATION AND DEFINITION OF THE PROJECT AREA

The Weber Delta is the largest delta built into Lake Bonneville on an open plain (Gilbert, 1890, p. 164) and consists of material brought in by the Weber River. This delta and adjacent areas, comprising a total area of almost 400 square miles, constitute the Weber Delta district (fig. 1). The district is between the west face of the Wasatch Range and the east shore of Great Salt Lake and is 30 miles long from north to south and from 3 to 20 miles wide. The Weber Delta district was named after the Weber Delta of Gilbert by Thomas and Nelson, who included the district in a larger hydrologic unit which they identified as the East Shore area. According to Thomas and Nelson (1948, p. 63):

> The East Shore ground-water area is bordered on the north by the Lower Bear River Valley and on the south by the City Creek spur of the Wasatch Range, beyond which lies the Jordan Valley, in which Salt Lake City is situated. The East Shore area is a well-defined ground-water unit * * *.
>
> For the purpose of describing the ground-water conditions, the East Shore area may conveniently be divided into three districts: the Bountiful district in Davis County, including that part of the East Shore area lying south of Farmington Bay; the Weber Delta in Davis, Weber, and Box Elder Counties, extending from Farmington Bay to Bear River Bay of Great Salt Lake; and the Brigham district of Box Elder County, extending north from Bear River Bay to the lower Bear River Valley.

Thomas and Nelson indirectly defined the southern boundary of the Weber Delta district when they set the northern boundary of the Bountiful district "at the north edge of Township 2 North, Salt Lake Base and Meridian" (1948, p. 64). They did not precisely define the northern boundary of the Weber Delta district; therefore, in this report it is set as the north edge of T. 7 N. The Weber Delta district thus includes the area in Tps. 3–7 N. that is between Great Salt Lake and the Wasatch front.

The Weber Delta district has been divided into six subdistricts. The Weber Delta subdistrict is the largest part of the Weber Delta district and the part in which ground water has been most developed. The boundaries of the Weber Delta subdistrict and of the other five subdistricts—North Ogden, Ogden-Plain City, West Warren, Little Mountain, and Kaysville-Farmington—are shown at small scale in figure 1 and at a larger scale in figure 10.

PREVIOUS INVESTIGATIONS

Great Salt Lake and its basin are mentioned in the accounts of various trappers and explorers who visited the area during the period 1800–70. Brief discussions of the geography and geology of the area appear in reports of the U.S. Geographic and Geologic Surveys published during the 1870's. In 1890 the U.S. Geological Survey published Monograph 1, by G. K. Gilbert, entitled "Lake Bonneville," which included the first comprehensive survey of the geology of the surficial deposits of the Great Salt Lake Basin. Gilbert set up a chronology of Lake Bonneville and described in considerable detail the lake-formed features in the basin. Gilbert's work has furnished the framework on which all subsequent investigations of the basin have been based, at least in part. Gilbert (1928) presented his conclusions regarding Basin-Range structures, based largely on his work along the west front of the Wasatch Range.

The geology of the Wasatch Range has been studied by various investigators, notably by A. J. Eardley who published several papers culminating in 1944 in an overall discussion of the north-central Wasatch Range (Eardley, 1944). A summary of the geologic environment of the East Shore area is included in a statement by Blackwelder (1948) on the important geologic features of the Great Basin.

Ground-water conditions in the vicinity of Ogden were studied by Dennis and McDonald (1944), and additional work in this area was done by Dennis and Nelson (1945). Dennis (1952) studied recharge in the East Shore area.

Work done in adjacent and comparable areas provided information that was useful during this study. Thomas and Nelson (1948) described the geology and occurrence of ground water in the Bountiful district of the East Shore area. The sediments of Pleistocene Lake Bonneville in areas near Salt Lake City were described briefly by Jones and Marsell (1952). The geology of northern Utah Valley was discussed by Hunt, Varnes, and Thomas (1953) and by Bissell (1952). Ground water in part of the East Shore area was studied by W. K. Hamblin (written commun. 1954), and Williams (1952) described the geology of Cache Valley, Utah, and the ancient outlet of Lake Bonneville at Red Rock Pass, Idaho. The relation of fossil soils to Lake Bonneville was considered by Hunt and Sokoloff (1950) and Gvosdetsky and Hawkes (1953). A study of evaporation from Great Salt Lake and the influence of ground water inflow in maintaining the lake level was prepared by Peck (1954). Eardley (1955) edited a guidebook dealing with Tertiary and Quaternary geology of the eastern Bonneville Basin.

ACKNOWLEDGMENTS

The study was preceded by about 3 months of geologic mapping during the summer of 1951 by P. E. Dennis, of the U.S. Geological Survey. Valuable assistance and suggestions were obtained from many individuals during this study. A. S. Rogers, of the Geological Survey, made a study of radon content in waters from part of the area, and D. R. Mabey, also of the Geological Survey, prepared a preliminary gravity-contour map showing the configuration of the bedrock surface of the area. Fossil assemblages were identified and their ecologic significance discussed by I. G. Sohn, D. W. Taylor, G. E. Lewis, and M. J. Hough, of the Geological Survey; by C. B. Schultz, T. M. Stout, and L. G. Tanner, of the Upper Cenozoic Research Group; by J. P. E. Morrison, of the Smithsonian Institute; and by E. J. Roscoe, of the University of Utah.

V. D. Jensen, P. S. Moore, and G. M. Ross, engineers, U.S. Bureau of Reclamation, each worked full time on the study during various periods; Moore assisted in mapping and all participated in the hydrologic studies. A. G. Hyde, Regional Laboratory, Bureau of Reclamation, assisted in the chemical analysis of water samples and in the assembly and interpretation of chemical data. Personnel of the U. S. Weather Bureau in Salt Lake City were cooperative in furnishing information and equipment and in the discussion of problems, especially those related to evaporation. A precipitation map (fig. 2) was prepared especially for this study by the Weather Bureau. Noland Nelson, Refuge Manager, Utah State Fish and Game Commission, provided a site for a weather station at the Ogden Bay Bird Refuge and serviced the station daily. The Utah State Engineer made available logs of more than 2,000 water wells and provided additional information and assistance. H. D. Goode and J. S. Gates assisted in preparing the report for publication.

Members of the geology departments of Utah's universities shared their knowledge of local geologic features and discussed problems associated with the deposits of Lake Bonneville. Valuable assistance was received from Professors A. J. Eardley, W. L. Stokes, R. E. Marsell, and D. J. Jones, of the University of Utah; J. Stewart Williams, of Utah State University; and H. J. Bissell, of Brigham Young University. Dr. Jones was especially helpful in sharing his knowledge of ostracode faunas.

Thanks are due to the many residents of the East Shore area who gave permission to install water-stage recorders on privately owned wells or to make periodic measurements of water levels. Appreciation is also expressed to the municipal officials and personnel of Federal installations who have contributed useful information and cooperated in other respects. Well drillers were generous in providing information, and in several instances they collected drill cuttings for examination.

PHYSICAL GEOGRAPHY

The eastern boundary of the Weber Delta district is the western front of the Wasatch Range, whose peaks rise 4,000–5,000 feet above the plain east of the Great Salt Lake. The Wasatch front is a topographic expression of the Wasatch fault zone, a geologic feature of regional magnitude that reflects its structural origin by its linearity and the steepness of its slopes.

The Weber Delta district consists of two topographic units. The eastern unit is a foothill area of varied topography developed on Lake Bonneville deposits. Locally, the lake deposits form a hill-and-valley topography whose linear elements are at right angles to the mountain front. This type of topography is found where closely spaced mountain-front streams have dissected the lake deposits. Elsewhere, the lake deposits form broad terraces, virtually coextensive with the tops of ancient deltas, such as the Weber Delta. In some areas the foothill zone consists principally of two or three fairly broad terraces, the widest of which is at an altitude of 4,800 feet. In other areas the various levels of Lake Bonneville formed many terraces, so that in profile, looking northward parallel to the mountain front, the terraces resemble a flight of giant steps, with some steps wider and (or) higher than others.

The western and largest topographic unit of the Weber Delta district is a plain of little surface relief. This plain probably was formed partly by deposition on the floor of Lake Bonneville during the waning stages of the lake and partly by deposition by the Weber River as it meandered over the plain. The plain ranges in width from 2 or 3 miles near Farmington to about 14 miles north of Ogden. Most of the farmland of the region is on the plain. North of Ogden, where the plain is widest, its western limit is marked by Little Mountain, a ridge of bedrock that projects a few hundred feet above the surface of the lowlands and is about 3 miles long, north to south, and as much as 1 mile wide.

Over most of the area studied, the historic shoreline of Great Salt Lake is marked by a scarplet ranging from less than a foot to perhaps as much as 5 feet in height. This historic high-water mark, at an altitude of about 4,200–4,210 feet, has been taken as the western margin of the project area.

The Pleasant View salient interrupts the nearly linear Wasatch front about 10 miles north of Ogden (fig. 10). The salient is an outcrop of consolidated rock that rises about 1,000 feet higher than the adjacent plain to the north and south and extends about 4 miles west of the range front to the south and about 1 mile beyond the range front to the north. This salient is one of a number of similar structural elements that project from the Wasatch front along its entire length, but the only one of prominence within the Weber Delta district.

The lake-built features of the Weber Delta district and adjacent areas differ from those of other areas in the Bonneville Basin in that they do not include any of the massive spits and bars described by Gilbert (1890, p. 90–170). In his discussion of shore features, embankments, bars, spits, terraces, and deltas, Gilbert (p. 163–164) discussed the area of the Weber Delta district only in connection with the deltas of the Ogden and Weber Rivers. He commented that the delta of the Ogden River "is exceptional to the general rule in that it is somewhat below the Provo horizon," and stated, referring to the Weber Delta, that "It is the largest of all the deltas of the ancient lake built upon an open plain, but, owing to the lightness of its material, the details of its form are imperfectly preserved. * * * The principal terrace is at the Provo level, and upon this there stands a hill more than 200 feet high, which may possibly be the remnant of a more ancient and more lofty delta, but is probably a dune accumulated during the Provo epoch." Gilbert's assumption that the hill is an older higher delta is probably correct. Excavation of a similar hill north of the river during a phase of the Weber Basin Project showed a remarkable sequence of superposed ripple marks, which are probably the result of long-continuing deposition by southward-moving bottom currents in the ancient lake. Although dune building has obviously been effective in helping to cause the digitate shape of the higher hills and ridges on the delta, it appears to have been a secondary agent.

In some parts of the Weber Delta district, the higher shorelines of Lake Bonneville remain as wave-cut notches on the front of the Wasatch Range. In other places, however, these markings are not now visible, either because they were not well formed or because erosion and mass wasting has obscured them. North of Ogden and to the north of the district the shorelines can be recognized only in scattered localities, because they probably have been largely obliterated by mass wastage. North of Ogden damaging mudflows have emerged from some of the canyons in historic time, and at many places the mountain front has great heaps of talus at its base from the rapid breakdown of the clifflike face of the range.

ECONOMIC GEOGRAPHY

The Weber Delta district and adjacent areas along the western front of the Wasatch Range southward as far as Provo are the most densely populated parts of the State. According to the 1960 census, the population of Utah was about 900,000; that of Ogden, Salt Lake City, and Provo totaled about 300,000, of which the population of Ogden comprised 70,000. Industrial activity in the State largely centers in the area extending from Ogden to Provo, and many military installations constructed in the project area during World War II are still active and increase the business activity and population of the region.

The Weber Delta district has a large farm population that produces beef, dairy products, and domestic fowl. Since the earliest days of transcontinental railways, Ogden has been an important railroad center. The district also supports a flourishing food-processing industry which includes flour mills, packing houses, and especially plants where fruit and truck-garden produce are canned or frozen.

Clay deposited by Lake Bonneville furnishes raw

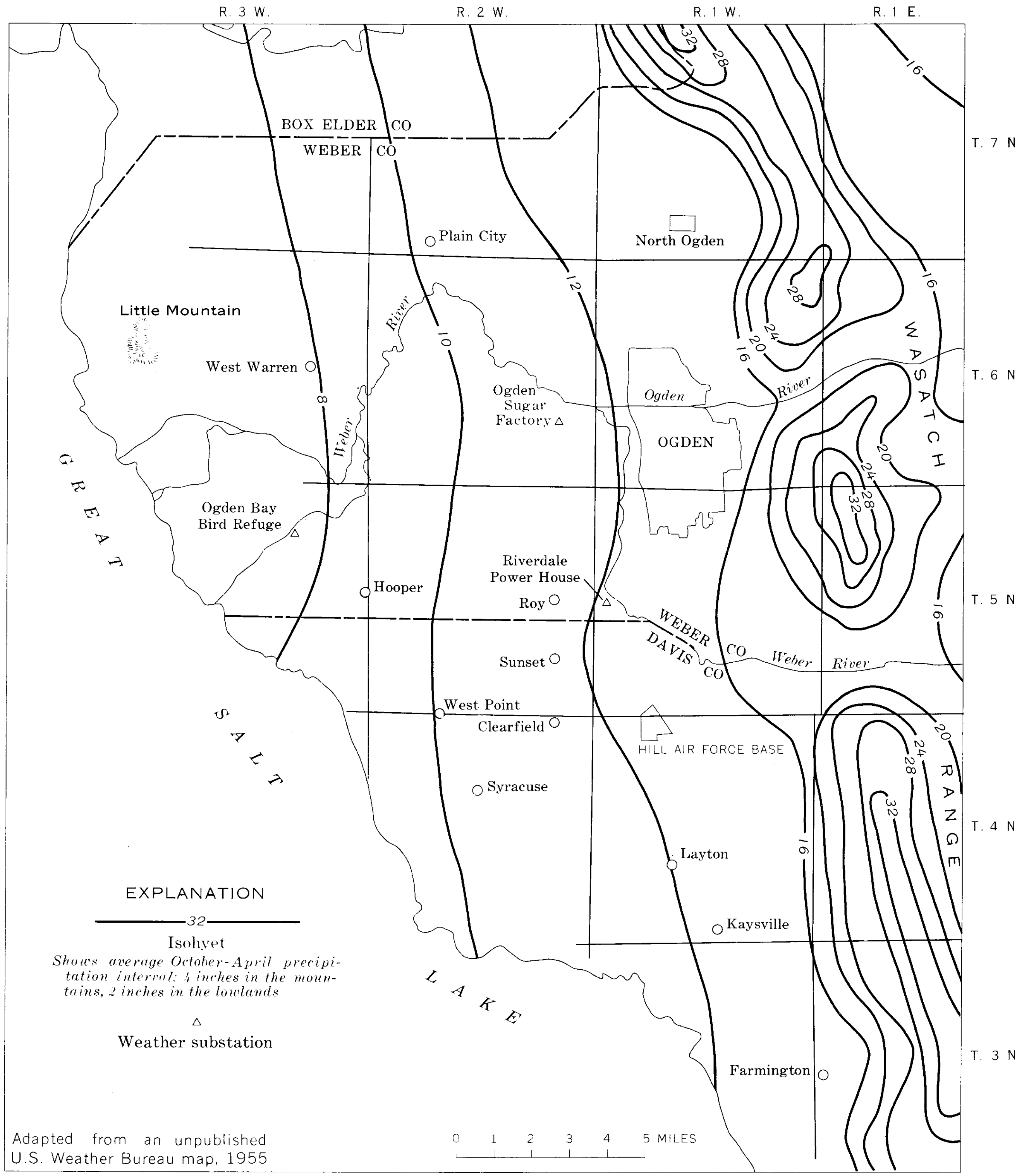


Figure 2.—Map of the Weber Delta district showing average October-April precipitation during the period 1915–55.

materials for a brick and tile industry that is adequate to supply local needs, and the coarser deposits of the lake provide sand and gravel for an active construction industry. Furthermore, the farmland itself largely was formed from sand, silt, and clay deposited in Lake Bonneville. Unconsolidated lacustrine and fluvial deposits form the aquifers and confining layers in the artesian system that furnishes much of the water supply for the region. Many homes below an altitude of 4,300 feet—the approximate upper limit of artesian flow—have small-diameter flowing wells in their yards from which water is obtained for domestic use. The nature and behavior of the artesian basin are subjects which are discussed extensively in this report.

CLIMATE

The climate of the Weber Delta district is temperate and semiarid. The mean annual temperature is about 52°F, with recorded extremes of 24° below zero and 106° above zero. Temperatures below zero are common during a cold winter, although periods of severely low temperatures are not prolonged because the mountains ward off most of the intensely cold air masses that move out of Canada into the United States. The frost-free growing season ordinarily includes the 5 months from May through September.

Winds are usually light to moderate, normally ranging from 7 to 10 miles per hour, although strong damaging winds occur occasionally. Near the mountains, air warmed by compression blows from the canyons and helps to prevent late-spring frosts. The percentage of hours of sunshine during the day ranges from 65 to 80, and the relative humidity is low, commonly dropping below 30 percent during midsummer days. The windiness, high percentage of hours of sunshine, high temperatures, and low atmospheric humidities in the summer tend to promote high rates of evaporation from water and moist land surfaces and high rates of transpiration from plants.

Precipitation in the western part of the Weber Delta district averages about 12 inches annually and increases to the east, averaging about 20 inches per year near the base of the Wasatch Range. Precipitation in the area as a whole averages about 16 inches annually. Most of this precipitation falls during the October-April period (fig. 2), so that irrigation is required to produce most crops.

Data from several weather substations (fig. 2) were used during the study. A summary of mean monthly temperatures and precipitation at Ogden Sugar Factory and at Salt Lake City Airport, which is about 12 miles south of the Weber Delta district, is given in table 1. Data from Riverdale Power House and Farmington were used to adjust the long-term normals to the period for which the water budget of the district was calculated. Data from Ogden Bay Bird Refuge were used in the studies of evapotranspiration.

TABLE 1.—*Mean monthly temperatures and precipitation at Ogden Sugar Factory and Salt Lake City Airport*

[Data from U.S. Weather Bureau]

Month	Mean Temperature		Mean Precipitation	
	Ogden Sugar Factory, 1929 to 1955 (°F)	Salt Lake Airport, 1928 to 1955 (°F)	Ogden Sugar Factory, 1925 to 1955 (inches)	Salt Lake Airport, 1928 to 1955 (inches)
January	25.2	26.5	1.64	1.20
February	32.1	33.4	1.68	1.23
March	40.3	41.1	1.79	1.66
April	50.0	50.1	2.23	1.76
May	58.4	58.9	1.74	1.56
June	66.2	67.1	1.31	.91
July	75.6	76.6	.60	.61
August	73.2	74.4	.75	.97
September	63.2	64.2	1.17	.74
October	52.3	52.9	1.75	1.34
November	38.8	39.3	1.67	1.42
December	30.1	31.5	1.83	1.34
Annual	50.5	51.3	18.16	14.74

WELL-NUMBERING SYSTEM USED IN UTAH

The well numbers used in this report indicate the well location by land subdivision according to a numbering system that was devised cooperatively by the Utah State Engineer and the U.S. Geological Survey about 1935. The system is illustrated in figure 3. The complete well number comprises letters and numbers that designate consecutively the quadrant and township (shown together in parentheses by a capital letter designating the quadrant in relation to the base point of the Salt Lake base and meridian, and numbers designating the township and range); the number of the section; the quarter section (designated by a letter); the quarter of the quarter section; the quarter of the quarter-quarter section; and, finally, the particular well within the 10-acre tract (designated by a number). By this system the letters A, B, C, and D designate, respectively, the northeast, northwest, southwest, and southeast quadrants of the standard base and meridian system of the Bureau of Land Management, and the letters a, b, c, and d designate the northeast, northwest, southwest, and southeast quarters of the section, of the quarter section, and of the quarter-quarter section.

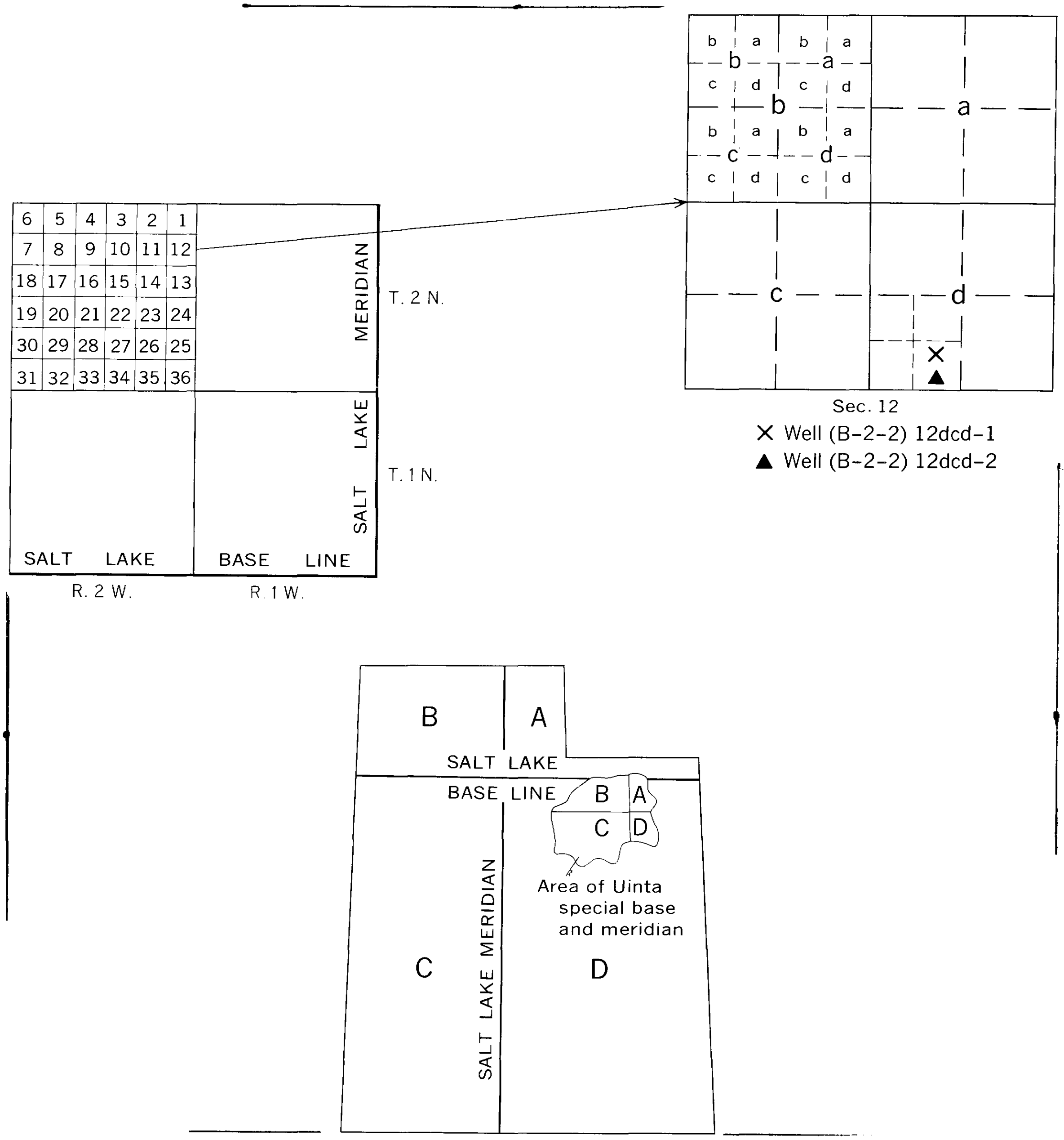


FIGURE 3.—Well-numbering system used in Utah.

Thus, the number (B-2-2)12dcd-2 designates well 2 in the SE¼SW¼SE¼ sec. 12, T. 2 N., R. 2 W., the letter B showing that the township is north of the Salt Lake base line and the range is west of the Salt Lake meridian; and the number (D-3-2)34 bca-1 designates well 1 in the NE¼SW¼NW¼ sec. 34, T. 3 S., R. 2 E., in the southeast quadrant of the standard base and meridian system.

GEOLOGY

Geology is the major factor controlling the occurrence and movement of ground water in the Weber Delta district. The ground-water reservoir consists of unconsolidated to poorly consolidated sediments that have been deposited in a large structurally-controlled basin of consolidated rocks. The maximum thickness of the unconsolidated rocks is perhaps as much as 9,000 feet. The consolidated rocks form the eastern, western, and lower boundaries of the ground-water basin. The unconsolidated sediments in the basin contain the ground water presently developed and available for development, and they include many strata of low permeability that confine water in more permeable beds, causing artesian conditions in much of the area.

The lithology of the various deposits largely determines the areas of recharge and of natural discharge of ground water. Lithology also determines the yield of the aquifers and the depth to which development of ground water is presently feasible, and it is an important determinant of the chemical quality of water in the district.

METHODS OF STUDY

The rocks in the Weber Delta district were divided into three principal groups—consolidated rocks of pre-Tertiary age, unconsolidated and poorly consolidated rocks of Tertiary age that comprise part of the basin fill but do not crop out in the district, and the deposits of the Lake Bonneville Group of Pleistocene age and younger deposits.

Eardley (1944) and Eardley and Hatch (1940) have reported on the pre-Tertiary rocks. In the present investigation, these rocks were mapped on the Pleasant View salient and on Little Mountain, but they were only examined where they form the eastern boundary of the ground-water basin.

Mapping of the Lake Bonneville Group in the Weber Delta district was started by P. E. Dennis, of the U.S. Geological Survey, during a 3-month reconnaissance of the area in 1951. All exposures of the Lake Bonneville Group in the district were mapped on airphotos during the period 1953–56. Soil-survey maps were used to supplement direct observations of lithology and mapping of formation contacts. These maps were available for most areas in which strata of the Lake Bonneville Group crop out and all areas in which younger sediments crop out. The soil surveys were based on data from hand-auger holes of various depths, commonly at least 5 feet deep. These auger holes were in concentrations ranging from one to many dozens per square mile. During this investigation, hand augering was done in areas which had not been included in earlier surveys, or in which the soil-survey information appeared to be inadequate. The geologic map, therefore, shows materials that are exposed at the surface and that extend to depths of about 5 feet.

Horizontal contacts between lithotypes in the unconsolidated rocks are seldom sharp; sand, for example, commonly grades into silt on one side and interfingers with gravel in another direction. The contacts shown on the geologic map (pl. 1) are, therefore, gradational, and not so sharp as they appear on the map. The stratigraphic sequence is tentative because no definitive criteria are available by which to identify the formations of the Lake Bonneville Group.

The subsurface geology of the area was studied from hundreds of drillers' logs and available drill cuttings and by constructing a three-dimensional model of the subsurface based on data from 300 of the deeper wells for which complete and accurate logs were available.

Data from two geophysical studies made in the area during the project were used in making subsurface interpretations. The U.S. Bureau of Reclamation, assisted by the Geophysics Branch of the U.S. Geological Survey, made a series of shallow-reflection seismic profiles in the area; D. R. Mabey, of the Geological Survey, made a generalized gravity survey of most of the area. Results of these surveys are presented in the section titled "Subsurface geologic studies."

BOUNDARIES OF THE GROUND-WATER BASIN

The northern and southern boundaries of the Weber Delta district have been previously defined. The consolidated rocks of the Wasatch Range form the eastern boundary of the ground-water basin, but the eastern boundary of the area that supplies water that can recharge the ground-water reservoir of the Weber Delta district is at the drainage divide of the Wasatch Range. In fact, the eastern edge of the area supplying water for recharge could be considered to be the eastern edge of the Weber River basin in the Unita Mountains, as the Weber River is a source of recharge.

The western boundary of the Weber Delta district is the historic high shoreline of Great Salt Lake, about 4,200–4,210 feet above mean sea level. The basin fill, however, extends west of the shoreline, and water in the aquifers underlying the district moves westward past the line. The western boundary of the ground-water basin also could be considered to be at the western edge of the trough of basin fill where a hard-rock ridge extends along a north-south line that includes the exposures of consolidated rock at Little Mountain in T. 6 N., Rs. 3 and 4 W.

The floor of the basin, which is formed by consolidated rock, has somewhat the configuration of a canoe having its keel oriented north-south and rising toward the surface near the Pleasant View salient on the north and near Farmington on the south. The thickness of fill in the trough has not been fully explored by drilling. Geophysical data suggest that the thickness reaches a maximum of

6,000–9,000 feet over the "keel" of the trough and that it ranges elsewhere from a featheredge adjacent to the mountains to about 2,500 feet over the bedrock ridges that are thought to enclose the basin at the north, south, and west.

As defined in this report, then, the ground-water basin of the Weber Delta district is a trough about 25 miles long, north to south, and as much as 15 miles wide north of Ogden.

SURFACE GEOLOGY

Consolidated rocks of pre-Tertiary age are exposed in the Wasatch Range, on Little Mountain, and on the Pleasant View salient; unconsolidated deposits of Pleistocene and Recent age are exposed in the rest of the Weber Delta district. Rocks of Tertiary age are not exposed in the district, but they are presumed to occur in the subsurface of the basin between the basement rocks of pre-Tertiary age and the Quaternary deposits. The distribution of the consolidated rocks and the Lake Bonneville Group and younger deposits is shown on the geologic map (pl. 1).

STRATIGRAPHY AND WATER-BEARING PROPERTIES OF THE ROCKS

ROCKS OF PRE-QUATERNARY AGE

Rocks of Precambrian and Cambrian age are the only rocks of pre-Quaternary age exposed in the mapped area. The Precambrian and Cambrian strata that crop out in the area are given in the generalized stratigraphic column (table 2) after Eardley (1944).

TABLE 2.—*Generalized stratigraphic column of the consolidated rocks that crop out in and near the Weber Delta district, Utah*

[Modified from Eardley, 1944, p. 826–827]

	Feet
Unconformity.	
1. Limestone and dolomite of Middle and Late(?) Cambrian age: Dominantly limestone with interbedded shale and dolomite. The limestone is mostly dark gray, commonly has wormy markings, and is locally pisolitic or oolitic or both. The unit comformably overlies the Ophir Shale	1,375±
2. Ophir Shale of Early and Middle Cambrian age: Shale, brown to olive-green, with a micaceous sheen, and large wormy markings on the bedding surfaces. Contains numerous arkosic and quartzitic layers ¼–1 in. thick. Conformably overlies the Tintic Quartzite	200
3. Tintic Quartzite of Early and Middle Cambrian age: Massive quartzite, pink and gray, with some buff, red, and purple beds. Contains numerous conglomeratic layers. The sand-sized particles are 99 percent quartz, and the pebbles are dominantly of quartz or quartzite. Conformably overlies Precambrian rocks in some places, but disconformably in others	500–700
Local disconformity.	
4. Phyllites, tillites, and quartzites of late Precambrian age: Upper 7,000 ft is dominantly purplish or rusty-weathering quartzites; lower 3,000 ft is arkosites, phyllites, and tillites interbedded with quartzites. The lower part of the section is exposed on Little Mountain, but not in the Wasatch front except locally in overthrust plates	10,000+
Angular unconformity.	
5. Farmington Canyon Complex of Eardley (1944) of Precambrian age: Metasedimentary and metavolcanic(?) rocks, generally showing remnant stratification or banding, now consisting of quartzite, schist, arkosite, and injection gneiss. Described in more detail by Bell (1952)	10,000+

PRECAMBRIAN ROCKS

The oldest rocks that crop out in the area are a thick series of Precambrian metamorphic rocks which are exposed in the Wasatch Range just east of the Wasatch fault zone. These rocks are particularly conspicuous south of the Weber River. This group of rocks was named the Farmington Canyon Complex by Eardley (1944) and described in detail by Bell (1952). The metamorphic rocks constitute a major part of the eastern boundary of the ground-water basin, and they probably contain and conduct large volumes of water which recharge the aquifers of the Weber Delta district. These circumstances are discussed in the section on "Recharge" (p. 41).

Rocks of younger Precambrian age are exposed on Little Mountain in T. 6 N., Rs. 3 and 4 W. (pl. 1). A tillite makes up the larger part of this isolated mass of rock; the rest is phyllite. These rocks are part of a much thicker late Precambrian sequence that is exposed at various places in the Wasatch Range and elsewhere in north-central Utah (Eardley and Hatch, 1940). They have no known significance in the occurrence of ground water in the area, unless they are present in the buried ridge extending southward from Little Mountain which may be the western boundary of the ground-water basin.

PALEOZOIC ROCKS

Much of the northern part of the eastern boundary of the Weber Delta district consists of rocks of Cambrian age, mostly quartzite and limestone or, locally, shale or dolomite. This sequence has been described by Eardley (1944). In addition, quartzite and limestone of Cambrian age make up the mass of the Pleasant View salient.

The oldest rock of Cambrian age is the Tintic Quartzite, which forms much of the mountain front. Except where shattered, the Tintic Quartzite is nearly impermeable. The Cambrian limestone, on the other hand, tends to be cavernous, especially where the rock has been dissolved along faults or other fractures. Local residents reported that, early in 1944, excavation in limestone on the Pleasant View salient exposed the mouth of a small cavern which extended an unknown distance into the rock. A stream of excess irrigation water, having a volume of several cubic feet per second, reportedly was diverted into the excavation for several days. During this time the entire stream was conducted underground by the cavernous limestone, and water did not reappear downslope from the excavation. The cavern, therefore, was large or had an outlet into permeable material.

Near Willard, just north of the Weber Delta district, ground water probably occurs in a limestone, thought to be of Cambrian age, that makes up much of the crest of the Wasatch front. About 4,300 acre-feet of water is discharged annually by wells near Willard in an area of about 5 square miles. In addition, a narrow strip of unconsolidated deposits between the Wasatch front and Willard Bay yields ground water prolifically, and, at times in the spring, ground water discharges as a sheetflood across saltgrass pastures near the shore of Willard Bay. This ground-water discharge together with the discharge of the wells in the Willard area, however, do not constitute all the available ground water in the Willard area. Since Willard Bay contains fresh water, and surface inflow is probably negligible, a considerable amount of fresh ground water seeps into the bay. The Cambrian limestone, where present, therefore, undoubtedly is recharged with water from snowmelt and transmits it to the unconsolidated aquifers in the Willard area and probably also in the Weber Delta district.

OTHER PRE-QUATERNARY ROCKS

Rocks of Paleozoic, Mesozoic, and Tertiary ages crop out in broad areas east of the Wasatch front. These rocks, however, are not exposed in the Weber Delta district; the nearest outcrops are several miles east of the Wasatch front in canyons such as those of the Ogden and Weber Rivers. Although rocks of Paleozoic and Mesozoic age may be part of the bedrock surface of the trough, no evidence of this exists.

Drill cuttings from Hickey oil-test 2, (B-3-1) 36ddd, near Farmington, indicate that, at least locally, strata of the Salt Lake Formation of Pliocene age lie below unconsolidated valley fill. Cuttings from 1,900–2,000 feet below the land surface in the oil test lithologically resemble rock from outcrops of the Salt Lake Formation in valleys tributary to the Great Salt Lake basin. At depths below 2,000 feet, however, the oil test penetrated sand and gravel similar to material from shallower depths, and the cuttings presumed to be of the Salt Lake Formation may have been erroneously identified or were from cobbles and boulders of Salt Lake Formation in a gravel deposit.

In summary, rocks of ages between Cambrian and Pleistocene may occur in the subsurface of the project area, but their presence has not been confirmed.

The age of some rocks shown on the geologic map (pl. 1) is inferred from scanty information. These rocks crop out in foothill zones adjacent to the Wasatch Range and are mostly poorly consolidated mudflow deposits that appear to be older than most, or all, of the Lake Bonneville Group. Because their exact stratigraphic position is unknown, these rocks have been mapped as a unit. The mudflow deposits are unsorted and contain an abundance of fine material; therefore, they have low permeability and probably contain little ground water. Various drillers' logs of wells commonly report "gravel and clay" or "boulders and clay," which probably is older mudflow material buried at depths of several hundreds of feet in the valley fill. Thus, mudflow material may have been deposited at many times during the history of the basin. Mudflow deposition apparently took place under semiarid climatic conditions during periodic violent storms. During such storms, large masses of weathered rock material in the Wasatch Range became saturated and then flowed into the adjacent basin.

QUATERNARY DEPOSITS

Hunt (Hunt and others, 1953, p. 17–24) coined the name "the Lake Bonneville group" for the strata of Wisconsin age deposited in Lake Bonneville in northern Utah Valley. Hunt's mapping in Utah Valley confirmed the Lake Bonneville chronology established by Gilbert (1890), and the present study is based on this chronology.

Sediments of the Lake Bonneville Group, in chronological order, younger to older

Gilbert, 1890	Hunt, 1953
Stansbury and other post-Provo lake deposits.	Utah Lake is at or above the Stansbury level, and Stansbury deposits, therefore, have not been recognized; post-Provo deposits are scattered and thin.

Sediments of the Lake Bonneville Group, in chronological order, younger to older—Continued

	Unconformity
Provo-stage deposits.	Provo formation.
	Unconformity
Bonneville-stage deposits.	Bonneville formation.
	Unconformity?
Intermediate-stage deposits.	Alpine formation.
	Unconformity
Pre-Lake Bonneville deposits.	Pre-Lake Bonneville deposits.

PROBLEMS IN SEPARATING AND IDENTIFYING FORMATIONS OF LAKE BONNEVILLE GROUP

A simplified discussion of Gilbert's (1890) chronology of Lake Bonneville will aid in the understanding of some of the problems.

The first stage of Lake Bonneville was the Intermediate stage, during which the Alpine Formation (named by Hunt in Hunt, and others 1953, p. 17) was deposited. The lake apparently stood at about 5,100 feet for a long time, depositing gravel and sand as beaches, deltas, spits, and other shore and near-shore deposits, and laying down silt and clay in deeper water throughout most of the basin. But it must not be assumed that deposits were laid down over the whole area covered by water, for in many places, waves and currents in the lake eroded vast areas that were covered by older deposits. Not only did the littoral and offshore currents plane off large volumes of preexisting alluvial or lake deposits, but in many other areas these currents kept deposition at a minimum. Thus, when the Alpine lake withdrew, perhaps to complete desiccation, the Bonneville basin was covered by thick deposits of the Alpine Formation in some areas; but in other areas, older deposits were exposed or were covered by a few inches to a few feet of Alpine deposits.

When the basin filled again in Bonneville time, the water rose above the Alpine shoreline and overflowed through an outlet in Red Rock Pass at the north end of Cache Valley in southeastern Idaho. The Bonneville lake was short lived and its principal deposits are shore and near-shore gravel and sand near the Bonneville level of about 5,200 feet.

When the Bonneville lake overflowed, its level dropped quickly, and in 25 years or less (Gilbert, 1890, p. 177) the lake dropped to the Provo level, where the river outlet reached a bedrock barrier at about 4,800 feet. How long the lake remained at the Provo level is unknown, but below 4,800 feet are extensive shore, near-shore, and deep-water deposits that blanket much of the area. Like the Alpine deposits, the Provo deposits were laid down in discontinuous beds that in places cover the older Alpine Formation and in other places are absent.

At a few places in the Lake Bonneville basin, notably Stansbury Island, Gilbert (1890, p. 134–135, 186) recognized a conspicuous shoreline 300–350 feet lower than the Provo level of 4,800 feet. To explain this shoreline, he postulated a post-Provo rise in water level to a level he designated as Stansbury. Gilbert offered no reason for a still-stand at the Stansbury level.

Gilbert's correlation of wave-cut benches, beaches, bars, spits, and other massive deposits with lake stages was based principally on topographic position or altitude. Deposits at or just below the Bonneville shoreline, at about 5,200 feet in the Weber Delta district, were presumed to be associated with the Bonneville stage of the lake. Deposits at about 5,100 feet were recognized as being older than the deposits at the Bonneville level and were correlated with the Intermediate stage of the lake, so named because of its position intermediate between the Bonneville shoreline and the lower Provo shoreline at about 4,800 feet. Thick and extensive "embankment" (Gilbert's term) deposits below but near the Provo shoreline were correlated with the Provo stage of the lake.

After each of the lakes receded, its discontinuous deposits were partly removed by subaerial erosion, were covered in some places by subaerial deposits, or were reworked by the wind, mass wastage, or by soil-forming processes. In places subjected to subaerial erosion after the Provo lake receded, the deposit exposed might be Provo Formation, a post-Alpine subaerial deposit, Alpine Formation, or any one of the pre-Alpine unconsolidated or consolidated rocks. Thus, identifying a deposit by its altitude obviously is not a completely reliable method.

Hunt's separation of the deposits above the Stansbury level in northern Utah Valley was based on "superposition of beds, lateral tracing of contracts between formations, observations of lateral and vertical changes in lithology" (Hunt and others, 1953, p. 4). Hunt's discussion of the mapped units and his map indicate that the Alpine and Provo Formations have shore and near-shore facies of gravel and sand that grade lakeward into silt and clay, whereas the Bonneville Formation was "recognized only as a thin and discontinuous beach deposit along the high shoreline and in a spit at the Point of the Mountain" (Hunt and others, 1953, p. 20), where the deposit is about 300 feet thick. Jones and Marsell (1955, p. 94–96) have reinterpreted the 300-foot-thick deposit as a compound spit related to the Alpine Formation rather than to the Bonneville Formation.

To date, no one has reported any physical criteria by which the several formations composing the Lake Bonneville Group can be distinguished from each other. In contrast to other areas in the country, where Pleistocene formations are sometimes identified by differing degrees of chemical breakdown of pebbles in gravels composing parts of the formations, there appears to be no difference in degree of weathering of the pebbles from the several formations in the Lake Bonneville Group. It is probably a safe generality to state that the Alpine Formation is predominantly finer grained than any of the others, but Hunt describes a gravel member within the Alpine Formation, and gravel and sand that appear to belong to the Alpine Formation are also found in the Weber Delta district. Similarly, silt-clay phases of the Provo Formation have been observed in various parts of the Bonneville Basin, including the Weber Delta district. In consequence, the textural criterion is not uniformly applicable as a device for separating one formation from another.

Fossil criteria by which to separate one formation from the other are extremely scarce. One species of ostracode appears to be confined to the Provo Formation; but unfortunately, it is not found everywhere in sediments of the Provo Formation. Further discussion of the fossil record appears later in the section on "Paleontology" (p. 31).

Various attempts (Morrison, 1952a, b; Richmond and others, 1952) have been made to use Pleistocene soil horizons as markers within sequences of lacustrine strata. Although this method was not used in the Weber Delta district, it appears to be a promising approach to the zonation of the Lake Bonneville Group.

The environments of deposition during Pleistocene time in the East Shore area were different from those of many other parts of the Lake Bonneville basin. The area faces the widest part of the ancient lake and thus was subject to maximum wave activity at each stage of Lake Bonneville. Shore features developed on unconsolidated materials were subject to rapid and extensive reworking to a degree perhaps not encountered anywhere else in the basin. The consolidated rock of the Wasatch Range is almost completely covered by sediments from the present valley floor to the Bonneville shoreline; therefore, if wave-cut notches were formed in the consolidated rock at altitudes lower than that of the Bonneville shoreline, the notches are now masked by unconsolidated material. The result of these conditions is that many shore features prominently developed in other parts

TABLE 3.—*Pebble-count analyses of gravel in the Provo and Alpine Formations of the Lake Bonneville Group*

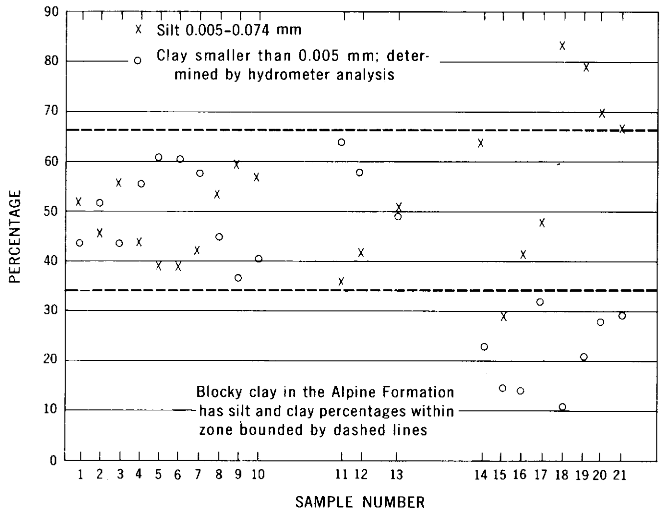
Location and number of pebbles	Name	Number of pebbles									
		Rounded						Angular			
		Percent total	Spheroid	Disk	Elongate disk	Cylinder	Irregular	Cuboid	Slab	Blade	Irregular
Provo Formation											
(B-5-1) 22dd: 213 pebbles from gravel pit at crest of hill, north side of Weber Canyon.	Quartzite	82	34	35	24	43	27	5	4	3	------
	Chert	3	1	1	------	2	1	------	------	------	1
	Quartz breccia	1	------	------	------	------	1	------	------	1	------
	Quartz	5	1	1	------	2	3	1	1	1	------
	Volcanic rock	1	------	------	1	------	1	------	1	------	------
	Gneiss	8	1	1	------	4	3	2	1	5	------
(B-5-1) 22dc: 110 pebbles from gravel pit on rim of Uintah Bench about 0.2 mile west of location named above.	Quartzite	87	22	18	11	20	15	5	4	------	2
	Chert	2	2	------	------	------	------	------	------	------	------
	Limestone	3	2	------	1	------	------	------	------	------	------
	Quartz	3	------	1	------	------	------	2	------	------	------
	Volcanic rock	1	------	------	------	1	------	------	------	------	------
	Gneiss	4	------	2	------	------	------	------	1	1	------
Alpine Formation											
(B-5-1) 20: 118 pebbles from marly conglomerate on flank of Uintah Bench about 200 ft above Weber River level.	Quartzite	69	24	16	10	16	9	2	2	1	1
	Chert	4	------	------	------	1	2	2	------	------	------
	Limestone	2	1	------	------	------	1	------	------	------	------
	Quartz	6	1	1	1	1	2	------	------	------	1
	Gneiss	19	1	2	1	2	3	9	2	2	1
(B-5-1) 20: 112 pebbles from poorly consolidated gravel 150 yd east of above sample and presumably stratigraphically equivalent.	Quartzite	80	18	21	9	21	13	2	3	1	------
	Chert	7	------	------	------	2	2	1	3	------	------
	Limestone	2	1	1	------	------	------	------	------	------	1
	Quartz	3	------	1	2	1	------	------	------	------	------
	Gneiss	8	------	1	2	1	1	1	2	1	------

of the Lake Bonneville basin cannot be recognized in the East Shore area.

In the Weber Delta district, neither prominent shorelines nor deposits were recognized that might be assigned to the Stansbury. Comparison of the geologic map of the district (pl. 1) with a topographic map indicates that the interval 4,450–4,500 feet is underlain in most places by coarse—gravel and sand, or sand—facies of the Alpine or Provo Formations; locally, the interval is underlain by finger grained material of Recent age. The Alpine and Provo Formation facies extend above and below the contours that enclose the Stansbury interval. Under these circumstances recognition of Stansbury deposits would be unlikely. If deposits were formed by a Stansbury-stage lake in the Weber Delta district, they remain unrecognized and are included on the geologic map in the coarse-grained facies of the Alpine and Provo Formations. In places where the Stansbury shoreline might be expected to be conspicuous, such as the western margin of the Weber Delta, there is a succession of more than ten shorelines, most below the Stansbury level. Of this locality, W. K. Hamblin (written commun., 1954, p. 16) said, "there is virtually no indication of any shoreline at this (Stansbury) elevation as the delta has an almost uniform grade from its top to more than 100 feet below the elevation of the Stansbury shore."

During the investigation of the Weber Delta district an attempt was made to distinguish gravel in what is inferred to be part of the Alpine Formation from gravel in a nearby exposure of the Provo Formation. The results of four pebble counts, two each from the Provo and Alpine Formations, were inconclusive (table 3). Additional gravel studies might possibly disclose statistical differences that would permit identification of the formations. For example, the presence (in the two Provo samples) or absence (from the two Alpine samples) of volcanic rock might be a significant lithologic difference.

Attempts were also made to use mechanical analyses of finer grained sediments to distinguish the Provo from the Alpine Formation. The results of 21 mechanical analyses (fig. 4) suggest that the fine-grained facies of the Alpine Formation contains more clay than the fine-grained facies of the Provo. This conclusion is not always applicable, however, because the Provo Formation may include material reworked from the Alpine. Presence of the ostracode *Cytherissa* cf *C. lacustris* (Sars) (see p. 31) in strata containing proportions of silt and clay typical of the Alpine suggests that these deposits are Alpine material reworked and deposited as part of the Provo Formation.



Sample — *Alpine Formation*[1]

1. (B–7–1)19bc, canal cut.

(B–5–1)21c, west wall of canyon: — *Feet*

2. Above base of exposure — 20–25
3. Do — 15–20
4. Do — 10–15
5. Do — 5–10
6. Do — 2–5
7. Do — Base—2

(B–5–1)19cd:

8. Cut bank at road level.
9. 10 feet higher.
10. (B–5–1)6c, base of clay bank below Ogden Airport.

Reworked Alpine Formation

(B–6–1)34bcc, pit east side of Harrison Blvd., Ogden:

11. 6 feet above floor of pit.
12. At floor level.
13. (B–7–2)14dc, blocky red clay stratum in gravel pit.

Provo Formation

14. (B–5–1)21c, top of bank 30 ft above base of section.

(B–5–1)18d:

15. Cut bank at level of farm road. — *Feet*
16. Below road — 25
17. Do — 50
18. Do — 60
19. Do — 70
20. Do — 80
21. (B–7–1)19cc, roadcut near Pleasant View.

[1] Blocky clay in the Alpine Formation has silt and clay percentages within zone bounded by dashed lines.

FIGURE 4.—Diagram showing percentages of fine-grained material in samples from the Alpine and Provo Formations and from reworked Alpine deposits. U.S. Bureau of Reclamation Laboratory, Ogden, Utah.

LAKE BONNEVILLE GROUP

Alpine Formation

The oldest formation of the Lake Bonneville Group is the Alpine Formation named by Hunt (Hunt and others, 1953, p. 17) for outcrops in northern Utah Valley near the town of Alpine. Three characteristic lithofacies of this formation, (1) gravel, (2) sand, and (3) clay, silt, and fine sand, were recognized in the Weber Delta district and are shown on the geologic map (pl. 1). The most distinctive lithology of the Alpine Formation

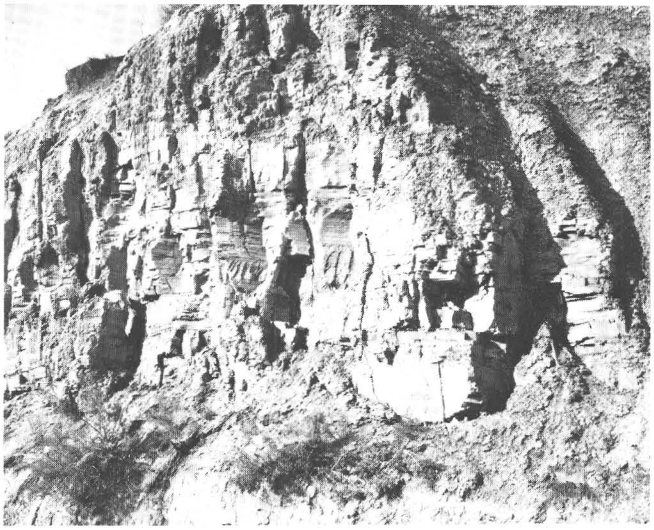


FIGURE 5.—Cliff-forming clay of the Alpine Formation, sec. 21, T. 5 N., R. 1 W., in a canyon cut into the Weber Delta. About 35 feet of strata is shown in the photograph.

in the district is a slabby salmon-pink to reddish-brown well-consolidated clay that is particularly well displayed on the Weber Delta in the first several miles downstream from the mouth of the canyon of the Weber River. This unit, which is at least 80 feet thick in some places, is a prominent cliff-forming member (fig. 5) on the north side of the present river valley cut into the Weber Delta. Less-well-consolidated strata, largely sand, silt, and clay, also assigned to the Alpine Formation, underlie much of the district, but they are most commonly exposed only just west of the foothills bordering the Wasatch fault zone.

North of the Weber River, U.S. Highway 89 climbs from the level of the Weber River to the Uintah Bench, about 300 feet higher. The roadcut exposes an almost unbroken sequence of medium-grained sand beds with a few thin intercalated clay-silt layers. The topmost 15–20 feet of the section is gravel, here interpreted as part of the Provo Formation, and the sand and clay composing most of the section probably are part of the Alpine Formation. The sequence is given in the following measured section:

Measured section of the Alpine and Provo Formations

[Secs. 22 and 23, T. 5 N., R. 1 W., in a conspicuous roadcut on the north side of U.S. Highway 89. Section measured by P. E. Dennis (unpub. data, 1951); field checked and modified by J. H. Feth in 1954. Color of fine-grained unit is buff to reddish tan when not otherwise stated]

	Feet
Present land surface.	
Provo Formation:	
1. Soil, gray	0.5
2. Clay, silty, brown; concentrations of calcareous material near the base	4
3. Gravel	10
Total thickness of the Provo Formation	14.5
Disconformity.	
Alpine Formation:	
4. Mostly silt with fine sand, all thinly laminated	40
5. Sand, clayey, with interbedded iron-stained sand; water seeps out above this zone	3
6. Clay with some interbedded silt and sand	4
7. Sand, fine, reddish with brown silty bedding surfaces; some interbedded silt and clay	30
8. Clay, thinly laminated, shaly, plastic when wet	1
9. Sand, fine to medium	2
10. Sand, well-cemented, pink	.5
11. Sand, fine to medium; three intercalated clay beds less than 1 in. thick	15
12. Silt	1
13. Sand, fine	2
14. Clay; shaly when dry, plastic when wet	.1
15. Sand, fine	3
16. Clay; light gray at base, brown at top; iron-stained	.5
17. Sand, fine, silty	2
18. Silt; shaly partings; cream-colored	.2
19. Sand, fine	6
20. Sand, clayey	.3
21. Sand, fine	2
22. Clay, light-brown, shaly; plastic when wet	.2
23. Sand, mostly fine; some clay in a few beds	8
24. Silt and very fine sand	.5
25. Sand, mostly fine	1
26. Silt and fine sand, clayey; water issues above this unit	.5
27. Sand, fine to medium, light-brown to buff	12
Base of the Alpine Formation concealed in deposits of windblown sand.	
Total measured thickness of the Alpine Formation	135

West of the roadcut described above, the Alpine Formation is exposed in gullies and canyons incised into the Uintah Bench. In this area the Alpine grades rapidly westward from sand to a sequence of salmon-pink well-consolidated slabby silts and clays. Toward the toe of the delta this sequence of sediments changes first to a section of somewhat coarser thin-bedded (1–3 in. beds) silt, rather poorly consolidated and intercalated with sand and thin lenses of gravel, and then, near the toe of the delta in the vicinity of Riverdale, to a sand. The thin-bedded poorly consolidated silt intercalated with sand contains the fossil *Cytherissa* cf. *C. lacustris* (Sars), which is here considered characteristic of the Provo Formation (p. 31). The silt and sand probably were deposited during Provo time as a sand bar against the toe of an older delta. During the final phase of Provo time, a deposit of gravel, not exceeding 20 feet in thickness, was deposited across the entire delta area.

An exposure in a canyon incised into the Uintah Bench in sec. 21, T. 5 N., R. 1 W., illustrates another difficulty in correlating formations using the criterion of altitude alone. In that canyon, salmon-pink well-consolidated silt and clay, which by all evidence are part of the Alpine Formation, have been folded and dragged along a high-angle fault that strikes approximately northeast along the axis of the canyon. The total displacement on the fault is about 175 feet; the east side is downthrown relative to the west side. This fault is further described on page 22. A displacement of this magnitude could bring shoreline deposits of, for example, the Alpine Formation below the Alpine shoreline and result in such strata being mistakenly designated as Provo. The section on the west wall of the canyon in sec. 21 is described below. This section is pictured in figure 5, and mechanical analyses of samples from it are included in the data of figure 4.

Measured section of the Alpine and Provo(?) Formations

[SE¼ sec. 21, T. 5 N., R. 1 W., on the northwest wall of a canyon cut into the Uintah Bench north of the Weber River. Field relations indicate that the canyon is cut along a northeast-trending fault; the southeast block is downthrown about 175 ft relative to the northwest block. The section described has not been found on the southeast wall of the canyon. The base of the prominent marl unit was used to correlate the part of the section at the first location with that at the second location. Measured by J. H. Feth and P. S. Moore]

	Feet
Present land surface.	
Provo(?) Formation:	
1. Conglomerate, gray overall; consists of metamorphic rocks, orthoquartzite, quartz, limestone, sandstone, and chert in a heavily calcareous silty matrix; discoidal snails abundant, other snails present	10
Angular(?) unconformity.	
Alpine Formation:	
2. Clay, well-consolidated; similar to unit 3 but crumpled and contorted, bedding nearly indistinguishable	12–15
3. Clay, pinkish-tan, very well sorted, well-consolidated, calcareous cement; forms prominent cliffs; bedding planes flat and sharply-defined, causing slabby weathering; beds generally 1–6 in. thick; brick-red interbedded laminae, ¼–1 in. thick; smooth-shelled ostracodes (*Candona sp.*) common in some beds, other ostracodes sparse; a few plant-stem imprints, none identifiable	32
4. Clay, well-consolidated, red, with interbedded reddish-tan sand and silt; mud curls at top of unit suggest deposition under playalike conditions	3
5. Marl, light- and dark-gray laminae with some black (organic) and green (clay) laminae; mostly papery weathering but some light-gray beds weather to white dust; numerous snails; ostracodes, mostly smooth-shelled; fish spines; many unidentifiable plant imprints; seeds common in some laminae	13
The following part of the section was measured in a trench dug through slope wash about 50 yd south of the location above. The marl (unit 5) is at both localities.	
Detailed description of a 1-ft zone in unit 5. The top of the detailed section is 2.00 ft above the base of the marl.	
a. Marl, gray papery; dark- and light-gray streaks subparallel to bedding	0.18
b. Marl, dense, dark-gray, organic	.07
c. Marl, like *a*	.20
d. Marl, like *b*	.01
e. Marl, like *a*	.14
f. Clay, olive-green, hair-thick laminae; irregular rusty stains	.10
g. Marl, like *a*	.20
h. Clay, like *f*	.10
Base of detailed section is 1.00 ft above base of unit 5.	
Base of marl, unit 5.	
6. Gravel, reddish-brown overall; calcareous cement; well-sorted; 6 in. bed of sand about halfway up from base, marked by a band of limonite staining	12
7. Clay, dark-reddish-brown, finely laminated; 2–3 in. layer of pebbles at the base; a sandy stringer in the upper foot, ¼ in. thick; limonite staining in the upper 1½ in.	5
8. Sand, tan and gray; tan sand is fine, gray is coarse; ripple marks with an amplitude of about 1 in. in some beds; base of unit is flat	4
9. Pebbles and sand, alternating	3
10. Clay; basal 1/ft rusty brown, rest of unit red; plastic when wet	4.5
11. Sand, tan, medium, well-sorted; sparse laminae of red silt and clay, ¼–¾ in. thick; base buried in more than 4 ft of slopewash, assumed to be at level of small stream draining the canyon	13
Total thickness of the Alpine Formation	101.5–104.5

Sand and gravel of the Alpine Formation are exposed principally in areas close to the mountain front, and some of the water in the streams that drain the west front of the Wasatch Range moves into these unconsolidated sand and gravel deposits and enters the ground-water reservoir. In some areas, such as in sec. 23, T. 5 N., R. 1 W., along U.S. Highway 89, local bodies of perched ground water in the sand and gravel of the Alpine Formation discharge at the faces of canyon walls or roadcuts. The water moves downward to the upper surface of a clay unit of the Alpine Formation and then moves laterally to a point of discharge. The clay in the Alpine characteristically has a low permeability and greatly retards passage of water.

On the Weber Delta just north of the Weber River (the Uintah Bench) a few narrow ridges and an isolated hill, which rise about 75 feet above the general land surface, have been mapped as clay (pl. 1). These ridges and the hill consist of fine-grained salmon-pink rather well-consolidated sand

and silt and, in part, of clay of similar color and degree of consolidation. The ostracodes in these beds are characteristic of silt and clay of the Alpine Formation; these strata are, therefore, correlated with the silt-clay phases of the Alpine.

Bonneville(?) Formation

A series of sand and gravel deposits at altitudes ranging from 5,100 to more than 5,200 feet immediately adjacent to the consolidated rock of the Wasatch Range may be closely equivalent to strata mapped in northern Utah Valley (Hunt and others, 1953, pl. 1) as the Bonneville Formation. These outcrops are characteristically elongated north-south, parallel to the Wasatch front, and are thin, commonly on the order of a few feet to 20 or 30 feet in thickness. In the Weber Delta district no clear unconformity or disconformity has been found at the base of these sand and gravel units and therefore the Bonneville(?) cannot be differentiated from the Alpine. Some of these high-level sand and gravel deposits are shown on the geologic map (pl. 1) as sand and gravel of the Bonneville(?) and Alpine Formations undifferentiated. As these deposits are commonly rather well sorted and are characteristically uncemented, they are exceptionally receptive to recharge. Their small areas of outcrop and their disconnected nature, however, restrict their significance in the total ground-water picture of the district.

Provo Formation

Three lithofacies—gravel, gravel and sand, and sand—are recognized in the Provo Formation, the youngest of the Lake Bonneville Group to be recognized in this study. Adjacent to the mountains, a considerable area is underlain by material mapped as gravel and sand of the Provo Formation, and this material accepts recharge that eventually moves to the ground-water reservoir. This gravel and sand, as well as sand of the Provo Formation, also covers broad areas on benchlands at about 4,800 feet, typical of which are the Uintah Bench and the bench south of the Weber River on which Hill Air Force Base is located. In local areas adjacent to the mountains and on the benchlands, gravel of the Provo Formation has been mapped as a separate unit. On the benchlands, strata of the Provo are characteristically about 10–30 feet thick. At the Provo stage the lake planed the older, higher, deltaic materials deposited during the Alpine stage to a level bench at about 4,800 feet. The gravel and sand of the Provo Formation were deposited mostly as beach and shore features, probably during recession of lake from the Provo stage. Sand of the Provo Formation caps terraces below 4,800 feet and is commonly 10–20 feet thick, although locally it is 50–100 feet thick.

The coarse material of the Provo Formation absorbs water that falls on or runs across its surface, such as precipitation or irrigation on the small areas of farmland and much broader areas of lawns and gardens on the benchland of the Weber Delta district. Such recharge percolates downward through the Provo Formation until it reaches the finer materials in the underlying Alpine Formation, and then it moves laterally. Locally, then, areas covered by Provo deposits are recharge areas for bodies of perched ground water on the benchlands, and a relatively shallow artesian aquifer south of the Weber River and west of the town of Roy is probably recharged through these deposits. Some water moving through the Provo deposits may also reach deeper aquifers.

RECENT DEPOSITS

Sediments of Recent age are at the surface in much of the Weber Delta district. The thickness of the Recent deposits is not known accurately, but it is probably in the order of a few to 40 feet. No fossils are known by which these deposits can be distinguished from lithologically similar sediments in the Provo or Alpine Formations. Lacustrine or flood-plain deposits of Recent age occupy extensive areas at altitudes between 4,200 and 4,300 feet; consequently, these deposits blanket the surface in areas of artesian discharge.

In areas mapped as hardpan (pl. 1), silt and sand have been loosely to tightly cemented, mostly by lime. The resulting cemented sand is locally so hard that it is difficult to break with a sledge hammer. Such cemented layers range in thickness from less than 1 foot to as much as 5 feet and characteristically occur as elongated strips. Preliminary tests made in connection with the drainage program of the Weber Basin Project show that despite their cemented character, many of the hardpan deposits are still quite permeable.

Recent sand occupies various areas in the lowlands, but perhaps the most prominent deposits are two elongated ridges that extend generally northeast-southwest, west of the city of Ogden, in Tps. 5 and 6 N., R. 2 W. The tops of these ridges are a few feet to about 10 feet above the lowlands on either side and are here interpreted as bars formed when lake water stood only a few feet above the present land surface. As the sand ridges are highly permeable, irrigation ditches leak profusely where they cross the ridges, thus adding to waterlogging of adjacent clay lowlands. In a few places small bodies of perched water are in the sand ridges. The soil on the ridges is generally a sandy loam, suitable, when irrigated, for raising most crops common to the area. The adjacent lowlands in many places are water-soaked and encrusted with various amounts of salts, locally with sodium carbonate ("black alkali") or with sodium chloride. Prosperous farms are on the sand ridges, whereas the lowlands are either barren or support saltgrass pasture, pickleweed (*Allenrolfea occidentalis*), or other highly salt-tolerant plants of no economic value. Some of these lowlands probably could be reclaimed by drainage and leaching.

Areas underlain by clay, mostly in the low-lying western part of the Weber Delta district, will have to be drained before they are suitable for agriculture; reclamation of these areas is vital to the success of the Weber Basin Project. In some places, however, the clay is rather dense and is saturated with sodium chloride. If the water table is at or very near the land surface in such places, the sodium chloride-saturated clay has become impregnated with sodium carbonate. Land-classification data show that locally the alkali impregnation and saturation with other salts has destroyed the soil structure and the land is considered unreclaimable. In other areas the land probably can be reclaimed and used for agriculture by draining it and by applying excess irrigation water, preferably of a calcium magnesium bicarbonate type.

Local areas are occupied by Recent gravel which apparently marks former channels of the Weber River or other major streams that crossed the area. Inasmuch as the gravel is thin and is underlain by finer materials, it has no effect on the occurrence of ground water.

Near the mountains, the youngest sediments exposed are characteristically coarse. In river channels the most recent deposits consist of boulders, cobbles, gravel, and coarse sand, which are highly receptive to recharge. Elsewhere, however, the deposits consist of mud rock flows, the material of which ranges in size from silt and clay to blocks the size of small houses. Thus, although the coarse fraction predominates, in some places there is enough fine interstitial material to reduce greatly the permeability of the mud rock flows.

The western boundary of the Weber Delta district is underlain by clay deposited by Great Salt Lake. The clay extends from the 1956 shoreline at about 4,197 feet to the base of the lowest scarplet, at about 4,200–4,210 feet, which marks the limit of the wave erosion of the modern lake. This modern clay is estimated (Eardley and Gvosdetsky, 1960) to be less than 10 feet thick, and it is thinnest at the upper (eastern) margin of the deposit. The clay is characteristically dark gray, green, or black and has a fetid odor and a relatively high organic content derived largely from material washed into Great Salt Lake or brine shrimp (*Artemia*) remains. The clay, at least in the top 4 feet explored in this investigation, is thoroughly impregnated with salts, principally sodium chloride. The low rate of evaporation from the salt-encrusted barrens underlain by the clay, discussed later in the section "Evaporation and evapotranspiration studies," shows that the rate of upward leakage of artesian water through the clay is very slow. The clay is exposed at the surface in a rather narrow strip along the western boundary of the district (pl. 1). It extends many miles westward under the present basin of Great Salt Lake, however, and probably is a seal which separates the brine of Great Salt Lake from the water in the artesian aquifers under the lake. The extent of the fresh-water aquifers under the lake is not known; therefore, the role of the clay in determining this extent cannot be evaluated.

STRUCTURE

FOLDS

The few folds in the Pleistocene deposits in the Weber Delta district are small. The largest fold observed is related to drag on a normal fault in the SE¼ sec. 21, T. 5 N., R. 1 W., in a canyon in the Uintah Bench. There, in the immediate vicinity of a normal fault (discussed below), clays interpreted as of Alpine age have been dragged 10–20 feet through an arc of about 45°.

Most of the other folds observed have amplitudes only of inches. They represent deformation during compaction of the sediments or minor adjustments to stresses, such as small slippages. A sandy sequence exposed at several places in T. 6 N. displays folds that in a few places have amplitudes of 1–2 feet. At this location the intricate nature of the folding, the presence of graded bedding, and other evidence lead to the conclusion that this sequence and a few others in the area, are turbidity current deposits (Feth, 1955, p. 48–49).

MAJOR FAULTS

The largest geologic structures in the area are faults of regional magnitude. The Wasatch Range is separated from the valleys at its western base by a great fault (Gilbert, 1928, p. 11) that extends for some 150 miles, locally marking the eastern border of the Basin and Range physiographic province and also the eastern boundary of Meinzer's (1923a, pl. 31) southwestern bolson ground-water province. It is a normal fault, downthrown to the west, and the fault surface dips to the west from about 20° to as much as 70° and averages about 33° (Gilbert, 1928, p. 22).

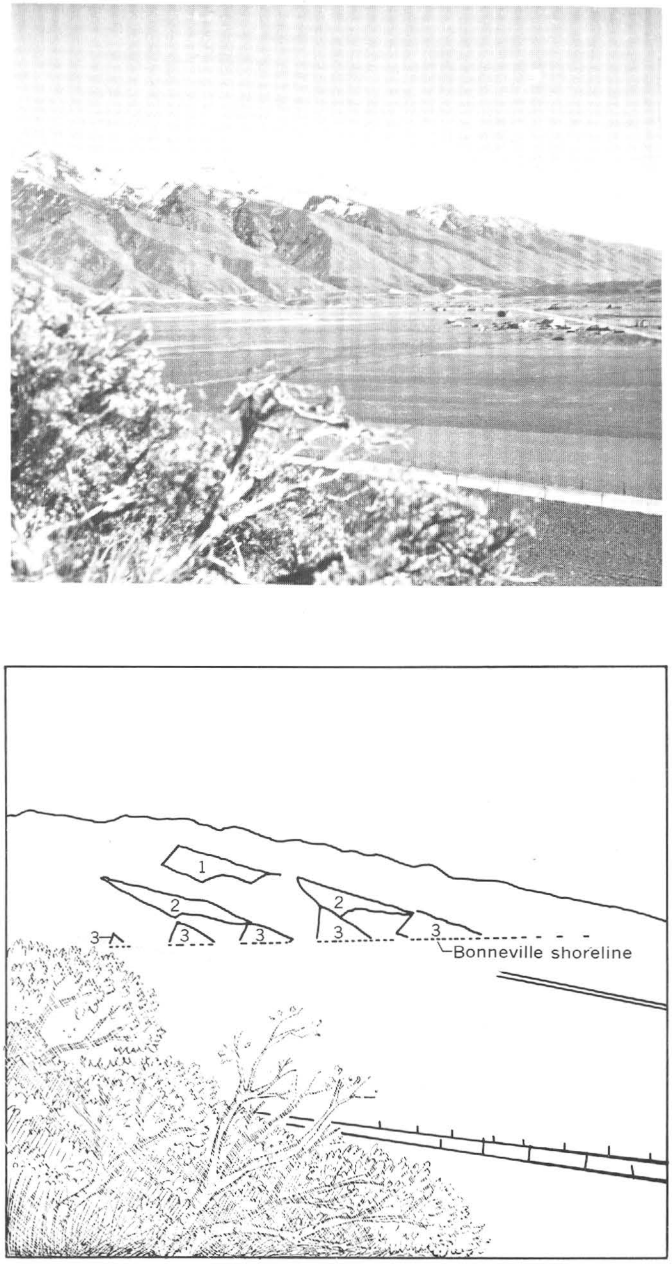


FIGURE 6.—Photograph of multiple fault facets on the west front of the Wasatch Range near the mouth of Weber Canyon. Upper, View southeastward across the flood plain of the Weber River. Lower, Sketch from the photograph above showing interpretation of the facets. (1) oldest facet; (2) facet of intermediate age; (3) youngest facet.

Total relief from movement along the Wasatch fault is not known. It may exceed 10,000 feet adjacent to the Weber Delta district, however, as some peaks of the frontal range near the fault zone are more than 9,000 feet above sea level and geophysical data indicate that near the fault, bedrock is on the order of 2,000 to possibly as much as 5,000 feet below sea level.

Under certain conditions of light, multiple fault facets may be seen along the Wasatch fault and are best seen immediately south of Weber Canyon. There (fig. 6) the impression is that the youngest and most marked triangular facets of the Wasatch fault are themselves on an earlier larger fault facet, dissected by erosion into two spurs. The older "facet" is at a flatter angle than are the most recent facets. It is also possible to visualize a still older "facet," higher on the range and at a still flatter angle, whose downward projection may include four of the recent facets and the two facets of intermediate age. These relations are shown in figure 6.

If all the facets were formed by faults, then there is evidence of at least three periods of major uplift along the Wasatch fault. The Wasatch Range also would appear to have been successively tilted eastward, causing the fault facets of each period of movement to lie at a flatter angle than those of the following period. The highest semiplane surfaces on the Wasatch front may be remnants of even older facets, but they have been interpreted (Eardley, 1944, p. 877) as an ancient erosion surface graded to the ancestral Weber River. It is also possible that the surfaces here interpreted as older facets represent erosion surfaces. The fact that the Bonneville shoreline crosses the lowest (youngest) facets about half way from their bases suggests that they are not facets cut by waves, a possibility suggested by Eardley (1944, p. 888) for the origin of some facets.

The Wasatch fault probably is not a single break, but rather it is a zone of shattering, movement, and slippage a mile or more in width. Locally, this zone has considerable influence on the occurrence of ground water. In certain areas, the frontal-fault zone apparently serves as a channelway along which warm mineralized water rises from considerable depth, such as at El Monte Spring at the mouth of Ogden Canyon and at Utah Hot Springs at the west end of the Pleasant View salient.

Topographic and geophysical evidence suggests that an east-trending fault of regional magnitude may pass through the Weber Delta district at about the southern boundary of the exposures of Cambrian rocks on the Pleasant View salient (pl. 1). Topography and gravity studies (D. R. Mabey, written commun., Mar. 22, 1956) indicate that the bedrock surface dips very steeply just south of the Pleasant View salient, as though downthrown along a major normal fault.

In addition, a fault, downthrown to the south with a displacement on the order of several thousand feet, cuts Paleozoic rocks near the south end of Promontory Point, about 10 miles west of the west boundary of the district (Richard Olson, oral commun., 1956). This fault zone can be projected by eye, according to Olson, eastward along the southern boundary of the Pleasant View salient and up North Ogden Canyon. However, additional evidence will be required to confirm the presence of this structure.

A major north-south fault may trend just east of Little Mountain (pl. 1). Little Mountain consists of Precambrian tillite and phyllite (Eardley and Hatch, 1940, p. 807) and is more than 10 miles west of the nearest point in the Wasatch Range where rocks of such age are exposed. Many wells in the area between Little Mountain and the Wasatch front penetrate 500–750 feet of unconsolidated sand, silt, and clay, and the Bureau of Reclamation test well 4A, (B–6–3)15dad–1, was drilled 1,210 feet without penetrating bedrock. Further south, the Bureau's test well 5B, (B–5–2)16dcd–2, was drilled 3,007 feet without penetrating bedrock. Geophysical data imply that as much as 6,000–9,000 feet of unconsolidated material is in the trough. Westward, the next exposure of phyllite is at Promontory Point, which is separated from Little Mountain by a large arm of Great Salt Lake. Little Mountain, therefore, is either a horst, a peak on the west edge of a block downthrown along the Wasatch fault at its eastern margin and tilted to the east, or a klippe remaining after erosion of a sheet overthrust from the west. However, the great thickness of valley fill suggests that there has been vertical displacement between Little Mountain and the Wasatch front. Little Mountain is probably a horst because seismic data indicate a fault at its east flank.

Data on quality of water also suggest a fault on the east flank of Little Mountain. Many seeps that produce sodium chloride water fall on several northwest-trending lines between Little Mountain and Hooper Hot Springs to the southeast (fig. 12). The spring water is similar in composition, although less mineralized, than the saline water rising along the Wasatch fault zone. The water from Hooper Hot Springs, in particular, probably rises along a fault because of its high temperature, high salinity, and relatively high boron content (1.2–4.7 ppm (parts per million)).

MINOR FAULTS

In the SE¼ sec. 21, T. 5 N., R. 1 W., a northeast-southwest trending canyon is cut into the Uintah Bench. The canyon is less than a quarter of a mile long, but a shallow trough marked by swampy ground extends for more than a mile northeastward from the head of the canyon. The northwest wall of the canyon (fig. 5) displays a section of hard slabby clay considered characteristic of the fine-grained facies of the Alpine Formation. Below the clay is 13 feet of white and gray marl. These beds have not been recognized on the southeast wall of the canyon. At the upper end of the canyon, the clay is folded through an arc of about 45° and dragged downward 10–20 feet on the southeast. About a quarter of a mile to the east and at an altitude about 175 feet lower, a farm road cut into the Uintah Bench exposes strata equivalent in lithology and fossil content to the slabby Alpine clay that is exposed in the canyon in sec. 21. The canyon, therefore, probably is located along a high-angle fault, downthrown about 175 feet to the southeast. A projection of the trend of the canyon southwestward across the Weber River valley to the benchland south of the river is marked by a notch and gully. The fault, therefore, may continue for 4 or 5 miles.

North of the mouth of Ogden Canyon in sec. 22, T. 6 N., R. 1 W., a small fault parallel with, and presumably related to, the Wasatch fault displaces sediments of the Alpine Formation. The fault is probably downthrown to the west, but the magnitude of displacement is not known.

SUBSURFACE GEOLOGIC STUDIES

Strata of the Lake Bonneville Group are within a 1,200-foot topographic interval from the Bonneville shoreline at an altitude of 5,200 feet to about 200 feet below the present surface of Great Salt Lake, or at an altitude of about 4,000 feet. The maximum thickness of the Lake Bonneville Group is not accurately known, but it is probably 200–350 feet.

Geophysical information implies, however, that the unconsolidated fill is at least 6,000 feet thick in the deepest part of the trough underlying the Weber Delta district. Thus, the Lake Bonneville

Group represents only a relatively short part of the history of the Bonneville Basin. The geophysical data suggest, however, that the entire thickness consists of materials similar to the lake-deposited sediments of the Lake Bonneville Group.

The deposits of the Weber Delta, to depths of at least 800 feet, consist predominantly of sand and gravel extending fanlike from the mouth of Weber Canyon (pl. 5) over an area of about 140 square miles. Much of this material is below the base of the Lake Bonneville deposits, thus indicating that conditions near the Weber Delta during pre-Lake Bonneville Pleistocene time were not significantly different from conditions during Lake Bonneville time.

During times of glaciation in the Pleistocene Epoch much material was eroded in the mountains by the glaciers, and runoff carried this material into the valley and deposited it in lakes. During interglaciations the climate was probably similar to the present semiarid climate, and most of the material moved into the basin was transported by floods caused by summer storms or spring runoff. During parts of Pleistocene time, probably principally during interglaciations, loess was probably blown into the area, deposited on the mountain slopes, and later eroded and deposited in the basin, overlapping the sands and gravels of earlier times (H. D. Goode, oral commun., Aug. 1963).

The coarse material originally eroded by glaciers cannot be distinguished from other fragments in drilling samples; so the glacial sequence cannot be determined by studying the valley fill. Glaciation occurred several times in the Wasatch Range during Pleistocene time, however, and the material originally eroded by glaciers may make up a significant part of the deposits in the Weber Delta district. Periodic uplift of the Wasatch Range probably occurred during much of Tertiary and Quaternary time; therefore, the range has long been a source of coarse material.

These general conclusions do not apply at any specific point in the district because variations in environment in the basin resulted in widely different types of sediments at different places. Because the ground water in the district occurs principally in the unconsolidated deposits, however, much effort was spent in determining the thickness and distribution of these deposits. Information was obtained from well logs and from test-hole, gravity, and seismic data. These data are discussed in the following sections.

Since 1935, water-well drillers have been required to file logs with the Utah State Engineer; hence, a large body of well-log information is available for the Weber Delta district. Using the logs of 300 wells, a peg model was made which illustrated the gravel, sand, silt, and clay beds in the subsurface of the district. These well data and data obtained from other well logs were used to prepare maps showing the distribution of coarse and fine materials in two depth zones (pls. 2, 3). Although the accuracy of the drillers' logs varies, the logs provide much useful information which can be used to determine the generalized distribution of materials in the subsurface.

During the period 1952–56, drill cuttings were obtained from six test wells drilled by the Bureau of Reclamation and from several privately owned wells.

Two geophysical studies were made during the project; one was a gravity survey made by D. R. Mabey, of the U.S. Geological Survey, and the other was a shallow-reflection seismic survey made cooperatively by the Geological Survey and the Bureau of Reclamation.

PEG MODEL AND DRILLERS' LOGS

The peg model made from 300 drillers' logs showed clearly that no series of beds can be traced over long distances in the Weber Delta district. Rather, the valley fill consists of an intricately interfingering mass of lenticular or wedge-shaped strata of gravel, sand, silt, and clay. Little is known about strata deeper than about 1,000 feet below the land surface because only four holes are known to have been drilled to greater depths in the district. North-south cross sections show a few fairly continuous zones, but along east-west cross sections the absence of continuous beds is striking. Apparently many of the sand, silt, and clay beds were distributed by lake currents in bands paralleling the shoreline of Lake Bonneville and thus are fairly continuous from north to south. Perhaps it is more difficult to recognize individual units that extend from east to west because the texture of any unit probably becomes finer from the mountains toward the lake. Gravel lenses may be more continuous from east to west than from north to south, however, because the large fragments would be less readily spread by lake currents and more likely to remain as originally deposited, in deltas or alluvial fans laid down by the mountain streams. Among the largest of the known groups of gravel lenses are two continuous zones that extend westward from the mouth of Weber Canyon. These gravel zones are important as sources of water and

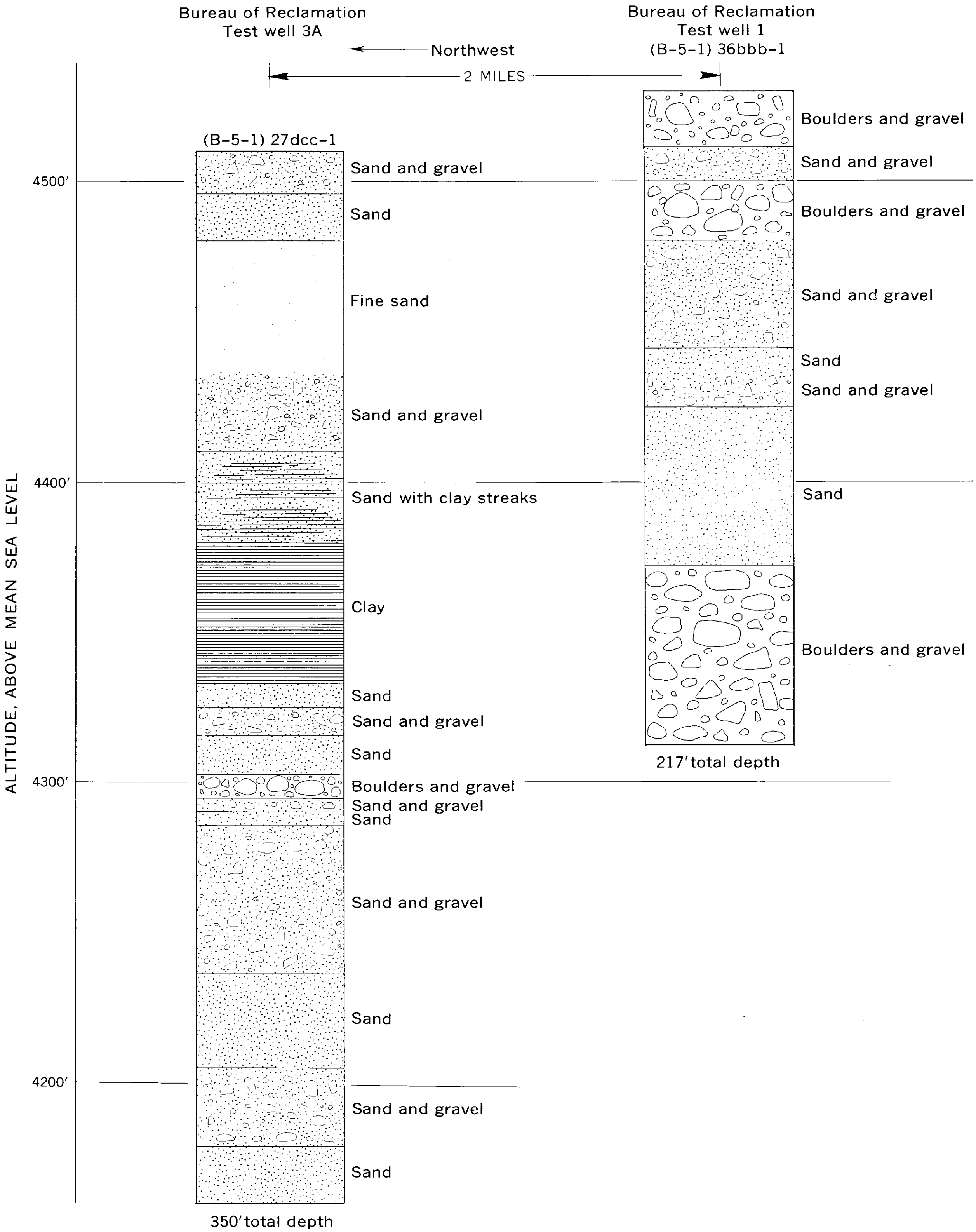


FIGURE 7.—Logs of two test wells on the Weber River flood plain.

are here named the Delta and the Sunset aquifers (pls. 5, 6).

The difficulty encountered in tracing the lenticular beds in the Weber Delta district is illustrated by the logs of two wells near Woods Cross. Although Woods Cross is about 4 miles south of the district, deposits there are similar to those in the district. The two wells are 500 and 600 feet deep and are less than half a mile apart. The cuttings collected from the 500-foot well consisted largely of gravel and sand with only a few layers of clay; whereas the 600-foot well penetrated a section dominated by fine sand, silt, and clay. Beds cannot be correlated from one well to the other, even over so short a distance.

The logs of two test wells drilled for the Bureau of Reclamation on the flood plain of the Weber River (fig. 7) show that in this area the material is mostly coarse grained, much of it gravel, from the land surface to a depth of at least 350 feet. Logs of wells drilled for Hill Air Force Base and the Naval Supply Depot at Clearfield show that in those areas similar sections of gravel are considerably deeper below the land surface. The difference in the altitude of the land surface, however, may account for the difference in depth, and the gravel beds actually may be continuous from the river flood plain to the Clearfield area. Such gravel could be part of an alluvial fan formed off the mouth of Weber Canyon during some period when the lake level was low. Because the fine materials overlying the gravel are thought to be part of the Alpine Formation, the hypothetical alluvial fan would be of early Alpine or pre-Alpine age. The Delta aquifer is part of this inferred pre-Alpine fan.

Few subsurface data are available near the mouth of Weber Canyon; therefore, the contours of the surface of the Delta aquifer in this area as shown on plate 5 are largely interpretive. Certain information suggests that in this area an alternative interpretation is possible. Analysis of data obtained during aquifer tests on Bureau of Reclamation wells 1 and 3A in secs. 36 and 27, T. 5 N., R. 1 W., suggests that an impermeable boundary is near each well in the subsurface. If this boundary exists, the gravel penetrated by the wells may be wholly or partly fill in an old channel cut to an unknown depth below the present land surface and the boundary may be a wall of the channel. A separation, near the canyon mouth, of the gravel in the present channel of the Weber River from the Delta aquifer is indicated by a comparison of flow in the river with hydrographs of wells in the Delta aquifer. The high-water stages in the river do not correlate with high water levels in the wells, although pumping may obscure the effects of recharge.

LITHOFACIES MAPS

The general pattern of distribution of fine-grained sediments (clay and silt) is shown on two maps prepared from data from drillers' logs. One map shows the ratio of clay and silt to coarser materials down to 200 feet below the land surface (pl. 2); the other shows these percentages from 200 feet to total depth of the wells (pl. 3). Areas shown on the maps as being underlain by low percentages of fine material are, therefore, underlain by high percentages of sand and gravel. In terms of grain size, then, the areas shown as low in fine-grained material are presumably more favorable for development of wells of high yield because of greater permeability.

These maps also suggest that deposition in river channels was common during the history of the basin. For example, the coarse material in the area trending from Ogden Canyon toward Ogden Bay Refuge was probably deposited by the ancient Ogden River. Other areas of relatively coarse material appear on the lithofacies maps either as isolated rounded areas or as elongated areas that are probably parts of old channels of the Weber and Ogden Rivers.

A few sand layers may extend many tens or perhaps hundreds of square miles, but because of their thinness, they do not appear on the lithofacies maps. The principal example of one of these layers is a dark-gray to black sand, ranging in thickness from about 12–18 inches, which has been exposed along most of the Hooper Pilot Drain, dug by the Bureau of Reclamation in secs. 7, 8, and 18, T. 5 N., R. 2 W. Black sand is also reported at depths ranging from about 8 to 20 feet in many parts of the Weber Delta district in holes that were jetted or augered during the drainage investigation. The data suggest that the black sand may be continuous northward beyond Plain City and southward to Farmington Bay; the east-west extent of the sand is not known.

LOGS OF TEST WELLS

The Bureau of Reclamation has seven test wells (fig. 12) in the Weber Delta district, six of which were drilled immediately before, during, or just after this study. Test well 2, (B-6-2)26ada-1, was drilled long before the start of the Weber Basin Project. Test wells 1, 3A, 3B, 4A, 5A, and

5B were drilled to depths as shown in the following tabulation.

Year	Test well	Depth drilled (feet)
1952	1, (B-5-1)36bbb-1	217
1953	3A, (B-5-1)27dcc-1	350
	3B, (B-5-1)27dcc-2	115
1955	4A, (B-6-3)15dad-1	1,210
	5A, (B-5-2)16dcd-1	978
1956	5B, (B-5-2)16dcd-2	3,007

Samples were collected of the materials penetrated by these wells; graphic logs of wells 1 and 3A are shown in figure 7, and graphic logs of wells 4A and 5B are shown on plate 4. Pumping tests were made in wells 1, 2, 3A, and 3B (table 8).

Drilling for water in the Weber Delta district has been confined largely to the zone less than a thousand feet below the land surface because in most places sufficient water has been readily obtained in that zone. Until 1956, accurate logs for wells deeper than 1,000 feet were available for only three wells in the district. These were Bureau of Reclamation test well 4A, near West Warren, and two oil tests (fig. 12), Jess Hickey Oil Co. Wilcox 1, (B-3-1)26dba, 3,000 feet deep and Jess Hickey Oil Co. Rushforth 1, (B-3-1)36ddd, 2,060 feet deep, drilled near Farmington.

Generalized logs of these three wells and Bureau of Reclamation test well 5B show (pl. 4) that the size of the materials at depth varies in the district. The log of test well 4A, near West Warren, shows a succession of silt and clay beds, with sandy zones intercalated throughout but decreasing in number and thickness below about 800 feet. Examination of the cuttings showed, furthermore, that the sand was commonly fine grained and mixed with silt. The total section penetrated was dominantly fine in texture and, therefore, probably not material from which a water well could obtain a large yield.

The materials penetrated by Bureau of Reclamation test well 5B, near Roy, consisted of alternating gravel, sand, and finer materials to a depth of 1,626 feet. A gravel zone from 710–777 feet was inferred to be the Delta aquifer. The section below 1,625 feet did not contain gravel, and from about 950 feet to the bottom of the well at 3,007 feet, clay and silt predominate. The only zones below 1,200 feet that might be aquifers were at 1,462–1,485, 1,552–1,580, and 1,619–1,626 feet.

The oil tests near Farmington penetrated different materials at depth than did test well 5B. Samples were not collected from the upper parts of either oil test; but from about 800–3,000 feet in Hickey-Wilcox 1 and from 900 feet (the first samples taken) to 2,060 feet in Hickey Rushforth 1, gravel and sand predominate. The ostracodes obtained from the interval between 606 and 1,305 feet in Hickey-Rushforth 1 suggest (I. G. Sohn, written commun., 1956) that a brackish-water environment prevailed during deposition of those sediments. Based on interpretation of electric logs, aquifers will yield fresh water to depths of 1,300 feet near Bureau of Reclamation test well 5B, to about 1,100 feet near Wilcox 1, and to about 800 feet near Rushforth 1.

The oil tests near Farmington probably are close enough to the Wasatch front so that they penetrated coarse detritus. The Bureau of Reclamation test wells near Roy (5B) and near West Warren (4A) are at distances of about 5 and 13 miles, respectively, from the front and are thus farther removed from the source of coarse material.

GRAVITY SURVEY

Gravity stations were established in most of the Weber Delta district, and readings from the stations were used to plot a simple Bouguer anomaly map (fig. 8). This map implies (D. R. Mabey, oral commun. 1956) that in general the bedrock surface is in the shape of an elongated trough, the deepest part of which is in the east-central part of T. 6 N., R. 2 W., about 3 miles north of the Ogden Municipal Airport and about 5 miles west of the Wasatch front. The axis of the trough trends approximately N. 20° W., and, except along the Wasatch front and at Little Mountain, the consolidated rocks forming the trough are not exposed within the district. The gravity anomalies indicate that the unconsolidated or poorly consolidated rock in the trough has a maximum thickness on the order of 6,000–9,000 feet.

Details of the configuration of the bedrock surface cannot be determined from the gravity data. The west side of the trough probably rises fairly evenly toward a north-south line through Little Mountain. The configuration of the north and south sides is less apparent, but the data suggest that these bedrock surfaces rise less steeply. The east side may be a relatively smooth surface, or it may be a series of step faults; the Wasatch fault appears to form the boundary of the east side. The depth of the unconsolidated material on the east side of the trough is unknown but is on the order of a few thousand feet. The thickness of unconsolidated rock may be about 2,500–3,000 feet in the northern, southern, and western parts of the area, where the bedrock is shallowest.

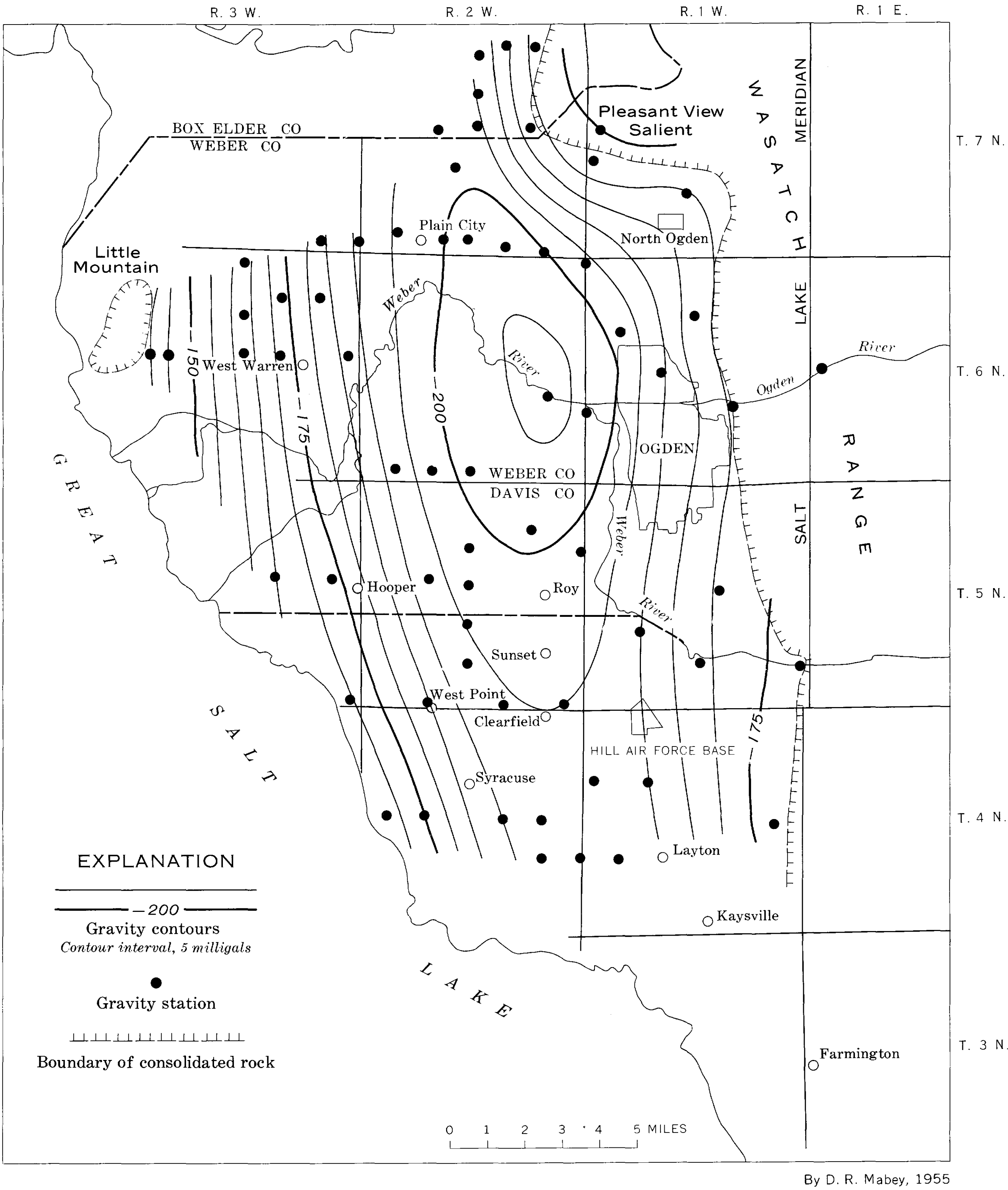


FIGURE 8.—Simple Bouguer anomaly map of the Weber Delta district.

The profile *B–B′* (fig. 9) shows the bedrock surface from the Wasatch Range to Little Mountain as determined from gravity and seismic data. This profile is discussed in the next section together with the profiles determined only from seismic data.

SHALLOW-REFLECTION SEISMIC SURVEY

A shallow-reflection seismic survey was made by Dart Wantland and Robert Keummich, of the Bureau of Reclamation. John Roller, of the Geological Survey, participated in the early stages of fieldwork. The following paragraphs summarize unpublished data (Dart Wantland, written commun., 1956) obtained during the seismic survey. Some of the results have been reported by McDonald and Wantland (1960, p. 16–22).

The seismic data include 74 determinations of the thickness of fill and 3 sets of measurements of seismic-wave velocities in drill holes. Depth determinations were made at intervals of ½–1½ miles along 60 miles of traverses across the area. The traverses were tied to records of deep wells and to bedrock at the outcrop on Little Mountain. Shot energies were sufficient to obtain reflections from bedrock to a depth of about 5,000 feet, but reflections indicated bedrock only near Little Mountain. In the rest of the area surveyed, therefore, bedrock was below 5,000 feet.

Comparison with reflections from layers of sand or clay at depths known from logs of deep wells permitted identification of extensions of 12 reflecting layers in areas peripheral to the deep wells. At test well 4A, (B–6–3)15dad–1, these layers were in the interval from the surface to a depth of 1,210 feet. About 20 comparable reflections were obtained from the undrilled interval between 1,210 and 4,120 feet, implying that about 2,900 feet of alternating sand, silt, and clay is below the bottom of the well. At test well 5A, (B–5–2)16dcd–1, reflections from below the bottom of the well at 978 feet implied that alternating layers of unconsolidated material exist to a depth of about 5,300 feet. The correlation of individual strata was not extended beyond 1 or 2 miles from individual deep wells.

Interpretation of the geophysical data, especially interpretation of the gravity survey, suggests that the bedrock surface dips eastward from outcrops at Little Mountain and westward from outcrops along the Wasatch front. The approximate bedrock profile *A–A′* (fig. 9) implies that along a north-south line through the district unconsolidated material is thickest in an area extending roughly from 1 mile south of well 5A to 2 miles north of the Weber River. There appears to be a distinct rise of the bedrock surface near Farmington Bay and a less pronounced rise on the northern end of the profile. These rises correspond to the "bow" and "stern" of the "canoe-shaped" trough used in analogy to describe the surface.

The approximate bedrock profile *B–B′* (fig. 9) that extends from Little Mountain, where bedrock crops out, to the Wasatch Range shows that the bedrock surface descends to a maximum depth of about 6,300 feet below the assumed datum of 4,225 feet above sea level and then rises to the east to about 3,000 feet below the datum. This profile is based on gravity and seismic data and is consistent with the concept of a horst of Precambrian rock extending generally south- or southwestward from Little Mountain.

Line *C–C′* (fig. 9 shows the approximate bedrock profile from near Hooper to the mouth of Weber Canyon. Data from the westernmost shot point indicate only about 2,800 feet of unconsolidated fill, and this apparent rise in the bedrock surface on the west may be related to the hypothetical horst mentioned in the preceding paragraph. A buried ridge in the bedrock may possibly extend along the entire western side of the Weber Delta district.

In profile *C–C′*, the gently sloping bedrock surface shown extending from the Wasatch Range westward nearly to the Bureau of Reclamation test well 5A at depths ranging from about 1,500 to 3,000 feet, may not be accurately located. Assumption of smaller velocities was made because of the high proportion of gravel, especially near the surface, in the area. The gravity map (D. R. Mabey, oral commun., 1956) does not show a similar bedrock profile.

VOLUME OF UNCONSOLIDATED ROCK

The geophysical data can be used to estimate the volume of unconsolidated and poorly consolidated material in the Weber Delta district. The gravity values are assumed to vary in direct proportion to the thickness of the underlying unconsolidated material. The area can be divided into segments of equal thickness bounded by the gravity contours shown in figure 8, therefore, by assuming that each increase of 5 milligals (the contour interval of the map) represents an equal increase in thickness of fill. Although the gravity values may not vary exactly in direct proportion to the thickness of fill, the resulting data may be accurate enough to permit their use in the estimate of thicknesses.

Over the deepest point of the trough the gravity

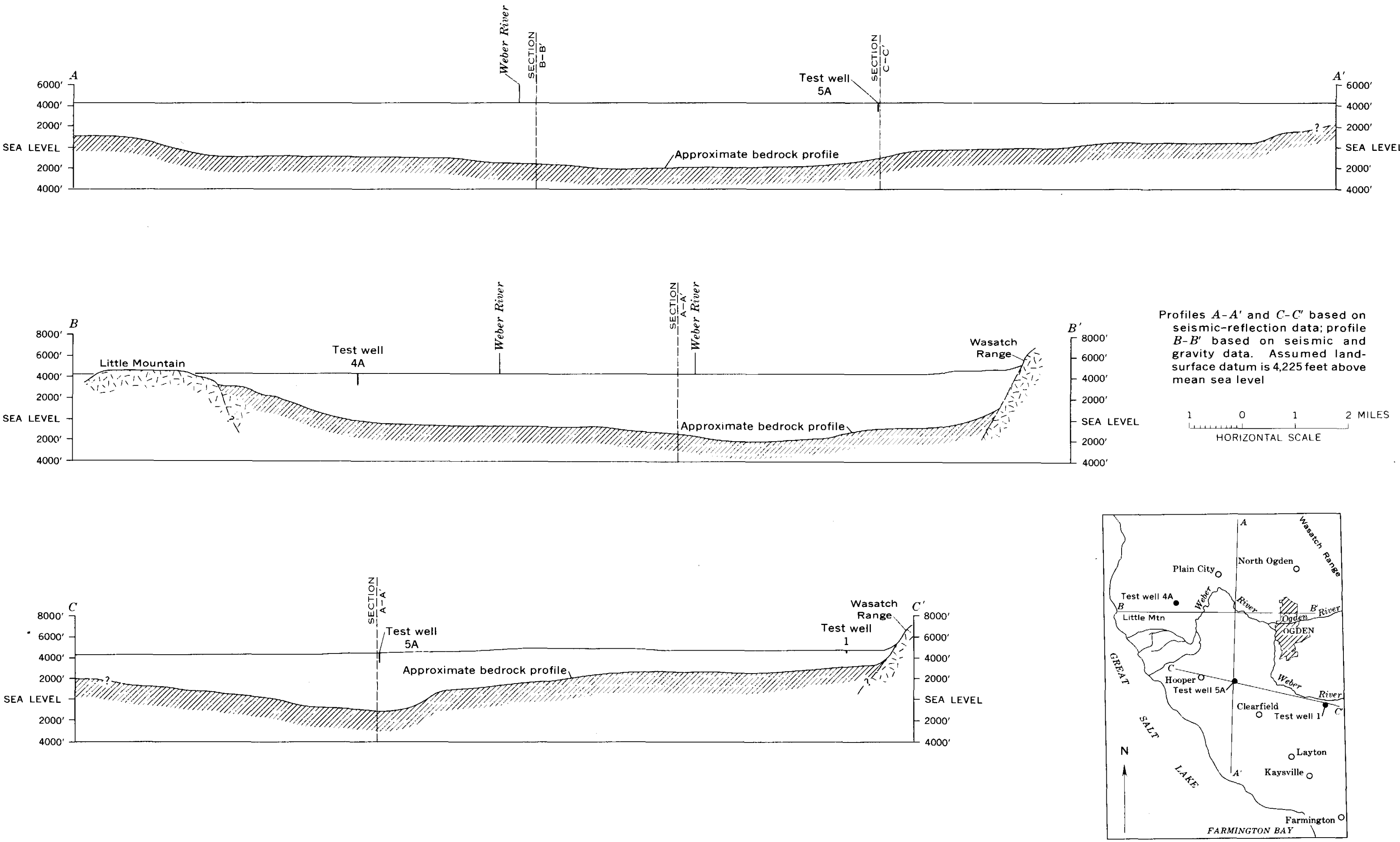


FIGURE 9.—Sections showing approximate bedrock profiles and thickness of the overlying unconsolidated material in the Weber Delta district, Utah, inferred from seismic and gravity data.

value was −205 milligals, and the highest reading, −145 milligals, was recorded over what appears to be a significant thickness of fill near Little Mountain. The gravity readings on and next to Little Mountain were not used. Thus, there are 12 increments of 5 milligals between the highest and lowest values.

The seismic profiles (fig. 9) indicate a maximum thickness of fill of about 6,300 feet. From the greatest depth, the thickness of fill is assumed to decrease in 13 intervals (one being added to account for the fill thickness at the station with the −145 milligal reading), each having a thickness of about 6,300/13 or 480 feet (9 percent of 1 mile).

Gravity data (fig. 8) are available over about 290 square miles of the Weber Delta district; the parts not covered are the Kaysville-Farmington subdistrict and the northwestern part of the Ogden-Plain City subdistrict. Using a planimeter, the area of each 5-milligal interval was measured in square miles. These areas were multiplied by the thickness of fill obtained by using the value of 9 percent of 1 mile of thickness per contour interval. The total volume of unconsolidated or poorly consolidated material underlying that part of the district covered by the gravity survey is estimated to be about 200 cubic miles.

A maximum estimate of about 280 cubic miles of fill was obtained by using the maximum thickness of 9,000 feet as determined from the gravity survey and applying the same procedure. A minimum estimate of 65 cubic miles was obtained by calculating the volume of an inverted cone with a height of 6,000 feet and a basal diameter of 15 miles (the distance from Little Mountain to the Wasatch front). The value of 200 cubic miles of fill probably approaches the true value as closely as available data permit.

FORMATION BOUNDARIES IN THE SUBSURFACE

PLIOCENE

SALT LAKE FORMATION

A basin as deep as that of the Weber Delta district can be reasonably assumed to have originated in Tertiary time. From available data, however, the Salt Lake Formation of Pliocene age is not definitely known to occur in the subsurface of the basin, and the exact position of the subsurface boundary between rocks of Tertiary and of Quaternary age is not known.

The electric log for the oil test (B–3–1)36ddd, near Farmington, indicates a definite lithologic change at 810 feet, where the test penetrated rocks that had electric resistivity two to three times as great as the overlying sediments. The test bottomed in these more resistant rocks at 2,009 feet, according to the electric log. Drill cuttings from the oil test contained volcanic glass shards and tuffaceous rock chips at depths ranging from about 1,900 to 2,000 feet. Many of the rock chips resembled rock exposed in Ogden and Weber Canyons, some miles upstream from the Wasatch front and outside the area mapped during this study. The formations that the well cuttings resemble consist of pumiceous tuff, marl, and tuffaceous marl assigned by various workers to the Salt Lake Formation. The oil test probably entered the Salt Lake Formation at 810 feet.

The electric log for the other oil test near Farmington, (B–3–1)26dba, which is about 1¼ miles farther west from the mountain front than test (B–3–1)36ddd, shows the same lithologic change at 2,570 feet. This lithologic change, however, does not appear in the electric log of the Bureau of Reclamation test well 5B, (B–5–2)15dcd–2, which bottomed at 3,007 feet but which is about 0.2 mile still farther west from the mountain front than oil test (B–3–1)26dba. The upper surface of the supposed Salt Lake Formation, therefore, dips sharply to the west in the Weber Delta district.

PLEISTOCENE(?)

The base of the Lake Bonneville Group at most places probably is less than 200 feet below the land surface, and the unconsolidated and poorly consolidated rocks between the Lake Bonneville Group and the Salt Lake Formation, assuming that the Salt Lake is present, are probably of late Pliocene and early Pleistocene (pre-Lake Bonneville) age. The exact position of the boundary between the Lake Bonneville Group and the underlying older Pleistocene(?) strata is not known from available data.

Conditions of deposition probably changed many times during pre-Lake Bonneville Pliocene and Pleistocene time. Lakes existed before Lake Bonneville, and at least some of them were saline. Scour and fill occurred repeatedly as lake levels rose and fell in response to changes in flow into the basin caused by changes in climate. These changing conditions caused variations in the deposition of sediments, but the details of these variations are not known.

PLEISTOCENE

LAKE BONNEVILLE GROUP

Alpine Formation

No criteria have been discovered by which the Alpine Formation can be recognized in the subsurface. No guide fossils are known, and examination of well logs has not revealed any persistent change in lithology that could be a formation boundary. Based on evidence from Bureau of Reclamation test well 4A, (B-6-3)15dad-1, near West Warren, however, the base of the Alpine is inferred to be at a depth of about 200 feet. In that well, cuttings from the surface to a depth of 100 feet contain (pl. 4) an assemblage of ostracodes, consisting mostly of various species of *Candona* and of *Limnocythere,* typically found in outcrops of the Alpine Formation. These ostracodes are forms common to fresh-water lakes and ponds (I. G. Sohn, oral commun., 1954). In contrast, cuttings from 303 feet below the land surface contained (I. G. Sohn, written commun., 1956) species of ostracodes found in brackish waters, which indicates a marked change in environment. As the zone from 100–303 feet deep yielded few fossils, the exact position corresponding to the environmental change cannot be fixed. The base of the Alpine Formation, therefore, is assumed to be about 200 feet below the land surface.

Ostracodes found in cuttings from below 606 feet in the oil test (B-3-1)36ddd also are reported by Sohn to be brackish-water types. Unfortunately, cuttings were not collected from the upper 300 feet of that well, and ostracodes were not found from 300–606 feet. At that locality, therefore, the base of the Alpine Formation can only be set somewhere higher than 606 feet below the land surface.

Study of cuttings from many wells and of fossils found in the Lake Bonneville and pre-Lake Bonneville deposits may eventually lead to the discovery of criteria by which the base of the Alpine Formation can be identified. In this report, the base of the Alpine Formation in the low-lying parts of the Weber Delta district is assumed to be at an altitude of about 4,000 feet. The altitude of the base of the Alpine Formation under the benchlands and foothills near the mountains is unknown.

Provo Formation

The base of the Provo Formation may be at a depth of about 50 feet in the Weber Delta district, although this estimate is based on scanty data. The only possible guide fossil in the Lake Bonneville Group is the ostracode *Cytherissa* cf. *C. lacustris* (Sars), which is apparently restricted to the Provo Formation (see col. 2). This ostracode, however, is absent from most well cuttings, including those samples obtained from shallow holes jetted specifically to collect samples for geologic study, and it has been recognized in cuttings from only two localities. A test hole, (B-6-1)8dbb, near the north edge of Ogden, yielded cuttings that included a few specimens of *Cytherissa* cf. *C. lacustris* from the surface to a depth of 50 feet. Because the test hole was jetted, the fossils recovered might all have been washed from the wall of the hole in the upper few feet below the surface. In any event, below 50 feet no further specimens of the Provo-age fossil were recovered.

An area of about 1 square mile, mostly in sec. 14, T. 7 N., R. 2 W., near the tip of the Pleasant View salient, has yielded all the other specimens of *Cytherissa* cf. *C. lacustris* (Sars) recovered from the subsurface. This fossil was found in samples of clay collected from the surface to a depth of 15 feet in test holes drilled by power auger in a meadow north of Utah Hot Springs. Between 15 feet and the bottom of an individual hole (generally about 30 ft), however, specimens of this fossil were not found. Four additional holes, the deepest of which was 100 feet, were jetted at intervals of roughly 1,000 feet along a line extending due west of Utah Hot Springs. Samples from these holes contained ostracodes which the senior author believes to be *Cytherissa* cf. *C. lacustris.* These ostracodes were recovered from a depth of 40 feet in the first hole, 1,000 feet west of the springs, and from depths of 50, 60, and 50 feet, respectively, at three successive holes westward from the first hole. The shells may have been washed from the upper part of the wall of the hole near the surface, however, as discussed above.

PALEONTOLOGY

Invertebrate, vertebrate, and some plant fossils were collected during this study, but only invertebrate fossils were of any use in determining stratigraphic relationships. Only one fossil, the ostracode *Cytherissa* cf. *C. lacustris* (Sars), was considered a possible guide fossil. This ostracode is apparently restricted to the Provo Formation and is useful in identifying that formation.

INVERTEBRATE FOSSILS

Ostracodes were collected during this study by the senior author and by I. G. Sohn, of the Geological Survey, and the collections were studied by Sohn. In addition, fossils collected by C. B. Hunt in northern Utah Valley were studied. Sohn (written commun., 1954) stated that it was not usually possible to determine sediment age within the Pleistocene using ostracodes, because the time range of the ostracodes usually was from Miocene to Recent. However, he noted that the ostracode *Cytherissa* cf. *C. lacustris* (Sars) seems to be restricted to sediments of Provo age and thus may be useful in identifying Provo sediments. These observations support the conclusions of Jones and Marsell (1955, p. 103) who stated that the *Cytherissa* cf. *C. lacustris* occurs in the Provo deposits, but that it has not been observed in the underlying Alpine Formation.

Because *Cytherissa* cf. *C. lacustris* (Sars) has a known range of Aftonian (pre-Kansan) or older to Recent, some factor or combination of factors resulted in the ostracode being restricted to the Provo stage of Lake Bonneville.

Sohn (written commun., 1954) summarized the problem as follows:

> In order to accept *Cytherissa* cf. *C. lacustris* (Sars) as a recognition criterion for sediments of Provo age, a reasonable explanation for its absence in Alpine and Recent sediments must be postulated. I believe that the following hypothesis, which has potential implications in the history of the Lake Bonneville group, is plausible. * * * *Cytherissa lacustris* is recorded as living in Asia, Europe, [and] North America, and as fossils in Interglacial of Europe and North America including an unpublished record from the Pliocene or Quaternary of Alaska. * * * the absence of *Cytherissa* cf. *C. lacustris* in sediments of Alpine and Recent age cannot be explained by a single factor, such as substrate or salinity; it can, however, be explained by a combination of factors that make up zoogeographic zones.
>
> *** [*Candona* and *Limnocythere*], the genera common to the Alpine, Provo, and Recent sediments are present because they are tolerant to all kinds of environments. *Cytherissa*, on the other hand, is restricted to the Palearctic zoogeographic zone. It should be noted that Palearctic is a general term covering a considerable range of environments.
>
> *** the combination of factors that are favorable to the presence of *Cytherissa* oscillated back and forth over the area of Lake Bonneville, presumably connected in some manner with the glacial oscillations. Conditions similar to Provo time must have existed at some earlier pre-Alpine time, and it is possible that *Cytherissa* will be found in pre-Alpine sediments.

Another group of ostracodes, although found in only two sets of samples, was useful in interpreting conditions during deposition of the basin fill. In the interval 610–615 feet in the Bureau of Reclamation test well 4A, (B–6–3)15dad–1, an ostracode species of the *Cyprideis* group was found. This group has a stratigraphic range of Miocene to Recent and lives in a brackish-water environment (Sohn, written commun., 1955). In samples from the oil test (B–3–1)36ddd, Sohn recognized ostracodes characteristic of a brackish-water environment in the intervals 606–610, 770–775, 900–905, 1,300–1,305, and 2,030–2,040 (written commun., 1956). Sohn stated that these collections indicated saline conditions but not a marine environment, and he concluded that the sediments which contained the brackish-water ostracodes were probably deposited in a saline lake.

Mollusks are among the most common fossils in the Lake Bonneville Group. Most of the mollusk specimens collected during this study were identified by J. P. E. Morrison, of the Smithsonian Institute, although D. W. Taylor, of the U.S. Geological Survey, identified specimens collected during the latter part of the study. Many of the mollusk specimens were also examined by E. J. Roscoe, of the University of Utah. All the species found in the Weber Delta district are still living in the region, and none was found to be useful in either dating or differentiating Lake Bonneville deposits.

VERTEBRATE AND PLANT FOSSILS

Vertebrate fossils collected were identified during the early part of the study by M. Jean Hough, of the U.S. Geological Survey, and later by G. E. Lewis, also of the Geological Survey, and by C. B. Schultz and L. G. Tanner, of the University of Nebraska. Hunt (Hunt and others, 1953, p. 21) stated that few vertebrate remains have been found in the Lake Bonneville deposits. Vertebrate remains were discovered at several places in the Weber Delta district, but they were either questionably fossil or were of no use in determining the age of the deposits in which they were found. In addition, much of the material could not be identified. Apparently the eastern shore of Lake Bonneville was unfavorable for vertebrates; the steep topography, for example, would not have suited large plains animals. The northern, southern, and western shores of the lake, whose unconsolidated deposits are mostly unmapped, have gentler topography and may yield more vertebrate remains.

The late R. W. Brown, of the U.S. Geological Survey, examined a few collections of plant fragments, but he found none of the assemblages to be distinctive of any age in the Pleistocene.

RADIOACTIVE AGE DETERMINATION

Several samples were collected for carbon 14 analysis. All the age determinations were made by Meyer Rubin, of the U.S. Geological Survey, and they have been published in the lists of radiocarbon dates determined by the Geological Survey. None of the dates determined were particularly significant to this study, although two determinations were made of the age of the marl (unit 5) in the measured section in the SE¼ sec. 21, T. 5 N., R.

1 W. (p. 18). On the basis of field evidence, this marl is considered to be of Alpine age, but it had a maximum radiocarbon age of 13,000 years. As post-Provo time has been variously estimated to be from 10,000 to 25,000 years (Hunt and others, 1953, p. 43), the radiocarbon age of the Alpine marl is too young. Perhaps the marl is younger than Alpine in age; or perhaps younger carbonaceous material, such as plant roots, was included in the marl sample; or possibly ground water carried younger material into the marl in some way. The exact reason for the seemingly anomalous age is not known.

WATER RESOURCES

The following sections on the water resources of the Weber Delta district emphasize ground water, its recharge, availability, development, and chemical quality. The conditions described are those prevailing during the period of study, 1953–56. Where available, information obtained before 1953 and after 1956 has been incorporated to achieve the benefits inherent in longer periods of record.

It must be emphasized that as development of the Bureau of Reclamation Weber Basin Project advances, the operation of additional water-storage facilities on the Weber River will introduce variables that cannot be evaluated in detail in this report. Virtually all the available streamflow in the Weber and Ogden Rivers presently in excess of existing rights will be utilized for project development. Further water development must be based on ground water or imported water.

The 3-year investigation in the Weber Delta district has served to show, in general, how far from complete is knowledge of the hydrology of the district. Many questions posed at the outset of the study have been answered only tentatively, and new problems have been discovered.

Although the hydrology of the Weber Delta district has already been substantially altered by the activities of man during the past century, basic data are not available to analyze all these changes in detail. This is, then, a status report of areal hydrology providing the general picture after a century of local development and before any effects of development and operation of the Weber Basin Project.

WATER BUDGET

A water budget based on records and estimates for the period 1928–47 indicates that about 950,000 acre-feet enters and leaves the Weber Delta district each year. About 570,000 acre-feet comes into the area in the Weber and Ogden Rivers (including water in a pipeline from Pine View Reservoir), in mountain-front streams, and in pipelines from the Ogden City wells in Ogden Valley; about 30,000 acre-feet comes into the area as ground-water underflow from the mountain front; and about 350,000 acre-feet falls on the area below 5,000 feet as direct precipitation. About 410,000 acre-feet of water leaves the area by the Weber River and smaller streams, by canals, drains, and sloughs, and by runoff of precipitation on the salt barrens; 520,000 acre-feet is evaporated from land and water surfaces or is transpired by plants; and about 20,000 acre-feet is unaccounted for. Although the volume unaccounted for is only about 2 percent of the annual total, and within the limits of error of the data, there are compelling reasons (p. 56–57) for believing that a quantity of this order of magnitude is discharged annually to Great Salt Lake by underflow of ground water.

The elements of the water budget are summarized in table 4 and are discussed in detail in the following sections.

TABLE 4.—*Water budget of the Weber Delta district, from an altitude of 5,000 feet to the shoreline of Great Salt Lake in 1952*

[Figures rounded to the nearest 5,000 acre-feet]

Water entering area	Thousands of acre-feet	Water leaving area	Thousands of acre-feet
Weber River	360	Weber River	330
Ogden River	160	Canals	10
Mountain-front streams	35	Drains and sloughs	20
Ogden City wells, piped into Weber Delta district from Artesian Park	15	Mountain-front stream discharge into Great Salt Lake	15
Precipitation below 5,000 ft	350	Runoff from precipitation on salt barrens	35
Ground-water inflow from mountain front	30	Evaporation and evapotranspiration:	
Underflow in Ogden and Weber River stream channels	(1)	Irrigated crops	170
		Saltgrass pasture	160
		Cattail areas	60
		Dryland crops	45
Total	950	Salt barrens	40
		Water surfaces	25
		Lawns, townsites, etc.	20
		Subtotal	930
		Discharge unaccounted for; includes leakage to Great Salt Lake	20
		Total	950

[1] Negligible.

SURFACE WATER

WATER ENTERING THE AREA

The Weber River system, including the Ogden River, contributes about 90 percent of the streamflow into the Weber Delta district. The independent streams draining the west slopes of the Wasatch Range are the remaining sources of streamflow.

An average annual flow of about 360,000 acre-feet of water entered the district from the Weber River during the period 1928 through 1947, and about 160,000 acre-feet of water entered from the Ogden River during this same period (calculated from records obtained at Geological Survey gaging stations on the Weber River near Gateway and on the Ogden River below Pine View Dam). Streams draining the west slopes of the Wasatch Range brought about 35,000 acre-feet annually (table 5) into the area in Davis and Weber Counties during the period 1928 through 1947.

Available short-term records of Ogden City were used to infer an average annual flow of 15,000 acre-feet of water into the area by pipeline from the Ogden City wells in Artesian Park. Although this is ground water in origin, it is obtained in Ogden Valley, an intermontane basin about 10 miles east of the Wasatch front. Aquifers in Ogden Valley are not connected with those in the Weber Delta district, and it appears reasonable to include this increment, by way of pipeline, with surface-water inflow.

The estimate of 350,000 acre-feet of water derived annually from direct precipitation on the 400 square mile area between altitude 5,000 feet and the 1952 shoreline of Great Salt Lake was calculated from a U.S. Weather Bureau isohyetal map that showed average annual rainfall for the period 1921–50. Planimetering the areas between contours on the Weather Bureau map resulted in the following figures:

Contour interval (inches of precipitation)	Area (sq mi)	Average annual precipitation (inches)	Factor sq mi to acres, (inches to feet)	Volume of water (acre-feet)
12–16	190	14	640/12	141,500
16–20	160	18	640/12	153,300
> 20	50	21	640/12	56,000
Total (rounded)	400			350,000

Although these figures are not adjusted to the period 1928–47, such adjustment probably would change them by only 1 or 2 percent.

WATER LEAVING THE AREA

The value of 330,000 acre-feet of water leaving the Weber Delta district annually by way of the Weber River was estimated by subtracting the amount of evapotranspiration at the Ogden Bay Bird Refuge (p. 68, 70) from the average annual flow of the Weber River for the period 1928–47 (calculated from records obtained at the Geological Survey gaging station at Plain City). This amount was subtracted because the Weber River loses this water by evapotranspiration between the gaging station at Plain City (fig. 12) and the point where it leaves the project area. The computations of discharge from the district in the Weber River are as follows:

	Acre-feet
Flow of Weber River at Plain City gage	360,000
Less evapotranspiration:	
From open-water surface:	
1,911 acres × 49.2 inches = 7,800	
From marsh area:	
4,274 acres × 61.5 inches = 21,900	29,700
	330,300
Rounded to	330,000

The Ogden-Brigham canal is the only canal carrying water out of the Weber Delta district. The flow of all other canals is accounted for within the district or is included in the flow of drains and sloughs, discussed below.

The water delivered to the area north of T. 7 N. through the Ogden-Brigham canal is based on shares or acre-feet subscribed by users of the irrigation water as follows:

Users of irrigation water	*Shares or acre-feet subscribed*
Box Elder Water Users' Assn	1,234
North Willard Irrigation Co	300
Perry Irrigation Co	484
Brigham City	2,500
Willard Water Co	600
Three Mill Irrigation Co	600
Weber-Box Elder Conservation District	5,300
Total (rounded)	10,000

The rounded total of 10,000 acre-feet is taken as the annual amount of water leaving the district through canals.

Water leaving the Weber Delta district in drains and sloughs was measured by the Bureau of Reclamation during the period June 1952 to December 1954 at gaging stations on the major sloughs. Flows from minor drains that are not tributary to major sloughs are dissipated by evapotranspiration and do not reach Great Salt Lake.

The flow in the major sloughs during 1953 is estimated to be approximately equal to the mean for the period 1928–47; therefore, the following slough records for 1953 were used to determine the total of 20,000 acre-feet that appears in the water budget:

Slough records, in acre-feet, for 1953

	Howard Slough	Hooper Slough	Walker Slough	Dixie Creek	Total
January	472	1,237	183	1,006	2,898
February	787	624	105	270	1,786
March	617	448	88	245	1,398
April	709	524	84	255	1,572
May	3,405	1,671	213	358	5,647
June	2,480	1,503	375	236	4,594
July to October	(1)	(1)	(1)	(1)	(1)
November	613	395	68	175	1,251
December	571	389	73	211	1,244
Annual	9,654	6,791	1,189	2,756	20,390

[1] Assumed to be consumptively used before reaching Great Salt Lake.

About 15,000 acre-feet annually reaches Great Salt Lake through the lower reaches of mountain-front stream channels. This water is spring runoff and return flow below irrigation diversions. It was measured or estimated in acre-feet as given below.

Kays Creek near mouth (3 forks) [1]	3,000
Holmes Creek [2]	1,300
Haight Creek [3]	1,600
Shepard Creek [4]	700
Steed Creek [4]	900
Davis Creek [4]	500
Farmington Creek [4]	7,000
Total	15,000

[1] Based on continuous records obtained by the Bureau of Reclamation during the period June 1952 to September 1954.
[2] Based on continuous records obtained by the Bureau of Reclamation during the period June 1952 to January 1953 and daily readings during the period 1948–49.
[3] Assumed as 45 percent of flow above all diversions. (Based on comparison with other mountain-front streams.)
[4] Based on daily readings below all diversions by the Bureau of Reclamation during the period 1948–50.

GROUND WATER

Ground water in the Weber Delta district occurs as shallow unconfined water, as local bodies of perched water, and as confined water in artesian aquifers which are hydraulically connected to such a degree that it is possible in some considerations to deal with them as a single system. This report will be concerned principally with the artesian aquifers, because the artesian aquifers of the district already have been developed to a significant extent and because these aquifers contain by far the greatest quantities of ground water suitable for future development.

The ground-water resources of the Weber Delta district have not been fully developed. Large quantities of confined ground water are lost principally by three means: (1) by leakage into shallow aquifers, resulting in evapotranspiration and seepage into drains; (2) by unused surface flow from uncontrolled artesian wells; and (3) by direct leakage into Great Salt Lake. Careful development of the ground-water resources would lead to recovery for beneficial use of some or most of this lost water.

OCCURRENCE

Ground water in the Weber Delta district occurs under both artesian and nonartesian conditions in the gravel, sand, silt, and clay of the valley fill to known depths of 3,000 feet and possibly to depths of more than 6,000 feet. Large but unmeasured volumes of water also percolate through fractures and joints in the rocks of the Wasatch Range. The water in the bedrock is important in recharging the valley fill, but it is not considered a part of the ground-water reservoir in the district. The artesian reservoir of the valley fill contains the bulk of the ground water.

Throughout the approximately 1,000 feet of valley fill in which ground water has already been developed, the ground-water reservoir is composed of innumerable beds and lenses of sand, silt, and clay and less abundant beds and pods of gravel intercalated. These materials are much the same throughout the depth to which they have been explored by drilling and throughout the thickness studied by means of the shallow-reflection seismic surveys described on page 28.

The major artesian aquifers in the Weber Delta district consist of relatively coarse sediments and to an extent are hydraulically interconnected. Measurements of water levels and pressures in wells of different depths in the Weber Delta subdistrict (the subdistricts are described on p. 36) indicate that at least two artesian aquifers which probably have only a slight hydraulic connection underlie most of the subdistrict at depths exceeding 200 feet. Locally, the subdistrict contains other shallow aquifers, either artesian or water table. The information available for other subdistricts does not permit identifying the aquifers as well as has been possible in the Weber Delta subdistrict. The aquifers in the other subdistricts, however, probably correspond in depth to those of the Weber Delta subdistrict. Maps of piezometric surfaces in the entire district, one for wells less than 400 feet deep (pl. 9) and the other for wells from 400 to 700 feet deep (pl. 9), show reasonable continuity of the piezometric surfaces.

Chemical-quality data suggest that water moves between aquifers through the confining layers of clay and silt. In many places in the district, the water in shallower aquifers has a significantly higher sodium-calcium ratio than water in deeper aquifers at approximately the same locality. The writers believe that this circumstance reflects the exchange of cations between clay minerals and the water as the water passes through the confining semipermeable clay beds in the course of its movement upward from deep to shallow aquifers.

GROUND-WATER SUBDISTRICTS AND THEIR AQUIFERS

The Weber Delta district has been divided into six ground-water subdistricts: the Weber Delta, Ogden-Plain City, North Ogden, West Warren, Little Mountain, and Kaysville-Farmington subdistricts (figs. 1, 10). The subdistrict boundaries are based principally on the quality of water yielded by the aquifers of the subdistricts. In some of the subdistricts, particularly in the Weber Delta subdistrict which is emphasized in this report, enough information is available to make preliminary identification of the aquifers. In others, such as the Ogden-Plain City subdistrict, the aquifers have not been differentiated because the reasons for the complex differences in chemical quality of the water have not been resolved.

The boundaries of the subdistricts are not so sharp as is indicated in figures 1 and 10; areas on each side of most of the boundaries yield water of a quality gradational between the quality of each of the adjacent subdistricts. These areas of mixed water are indicated on the map showing chemical quality (fig. 14).

At many places in the discussion that follows, chemical characteristics of water or chemical changes in water, such as cation exchange, are mentioned in general terms and without definition. A more complete discussion of these characteristics and changes is included in the section on "Chemical quality" (p. 57).

WEBER DELTA SUBDISTRICT

The Weber Delta subdistrict is the largest ground-water subdistrict in the Weber Delta district and the one in which both present development and potential development of ground water are greater than in the other subdistricts. The quality of the water in this subdistrict is good, and the water is suitable, without treatment, for most uses for which it is withdrawn. Many individuals maintain water softeners, however, and in a few localities the water contains more iron than is desirable. The subdistrict includes about 140 square miles and is named for the huge fan-shaped delta built principally by the Weber River westward from the mouth of Weber Canyon. All the boundaries of the subdistrict (fig. 10) except one were drawn on the basis of chemical quality of water. The boundary with the Kaysville-Farmington subdistrict was drawn on the basis of a bedrock high known from logs of wells near Kaysville. The subdistrict contains three smaller areas near Roy, Syracuse, and Layton in which the occurrence or the quality of the water is different from that of the water of the subdistrict as a whole. These areas are in the vicinity of the named towns, and indefinite boundaries of the Roy and Syracuse areas are shown in figure 14.

Delta aquifer

A thick and extensive deposit of interlayered gravel, sand, and silt forms a fan-shaped body extending westward in the subsurface from the mouth of Weber Canyon. Some beds reportedly also contain mixtures of materials such as "gravel and sand" or "sandy silt." This deposit is the most developed aquifer and has the greatest potential for future development of all aquifers in the Weber Delta district. It is herein named the Delta aquifer.

The top of the Delta aquifer is about 500–700 feet below the land surface at most places where it has been identified in logs of wells, and the configuration of the top is illustrated by a contour map and profile (pl. 5).

The principal part of the aquifer is probably 50–150 feet thick, but some wells have penetrated greater thicknesses without locating a lower boundary. The exact thickness of the aquifer remains unknown because most wells are drilled into the aquifer only to the depth needed to produce water in the quantity desired. Materials composing the Delta aquifer become progressively finer at increasing distances from the mountains, and the aquifer loses identity near the line separating Tps. 2 and 3 W.

Many pumped wells of large yield obtain their water from the Delta aquifer; for example, those at Hill Air Force Base, the municipal wells at Sunset, and various of the larger wells near Clearfield. The results of aquifer tests suggest that the permeability of the aquifer is high. The water obtained from the Delta aquifer is of chemical character suited to most uses for which it is pumped, although it is hard, containing much dissolved calcium and magnesium.

The shape of the piezometric surface and chemical analyses suggest that much of the recharge to the Delta aquifer is from the Weber River; the rest of the recharge is from surface and subsurface flow from the mountain front. The piezometric surface shown on plate 9 is based mostly on measurements in wells in the Delta aquifer. The configuration of the piezometric surface indicates movement of the water in the aquifer radially outward from the mouth of Weber Canyon, generally northwestward toward Riverdale, westward toward Hooper, and southwestward toward Clearfield. Chemical data (Smith, 1961) show that the water obtained from the Delta aquifer at Hill Air Force Base, at Hinckley Field (Ogden City Airport), at Clearfield, and at other places where wells penetrate the aquifer is chemically similar to, but somewhat more highly mineralized than, water from the Weber River. In general, the percentage of sodium is greater in the ground water than in the river water, but not more so than can readily be explained by cation exchange which may occur during percolation of water through the sediments. The chloride content in both river and well water is in the same range of concentration.

Despite the evidence that the Weber River recharges the aquifer, there remains some doubt that the river is the main source of recharge because changes of stage in the river are not reflected by corresponding changes in water levels in the aquifer. Heavy withdrawals of water from the aquifer by pumping, however, may cause water-level fluctuations that mask any fluctuations produced by changes in flow of the river.

Sunset aquifer

A shallower and less productive water-bearing zone than the Delta aquifer is herein named the Sunset aquifer because the town of Sunset is near the center of the area underlain by the aquifer. Wells as shallow as 200 feet tap this zone, but in most places the upper surface of the Sunset aquifer is 250–400 feet below the land surface. The configuration and profile of the upper surface of this aquifer are shown on plate 6, and the configuration of the piezometric surface shown on plate 9 is based largely on water-level measurements in wells tapping the Sunset aquifer. Drillers' logs indicate that the aquifer is from 50 to as much as 250 feet thick and consists largely of sand or mixtures of gravel, sand, and silt or of sand and silt. The Sunset aquifer is less permeable than the Delta aquifer, and no wells of large yield are known to obtain water from the Sunset aquifer. Water in the Sunset aquifer is similar in chemical quality to water in the Delta aquifer.

Shallow aquifers

Shallow aquifers, which supply water to wells in the vicinity of Roy and Syracuse, have been delineated largely from chemical quality-of-water data. (See p. 60.) In the Roy area the shallow aquifer probably has little hydraulic connection with deeper aquifers, whereas in the Syracuse area the shallow and deeper aquifers are probably connected.

In the Roy area (fig. 14) a shallow aquifer yields water to wells 50–150 feet deep. Water from this aquifer is more highly mineralized than water in the underlying deeper aquifers, and the piezometric surface in the shallow aquifer is higher than that in the deep Delta aquifer. The differences in quality and differences in pressure in the two aquifers suggest that they are only slightly connected, if at all. The shallow aquifer in the Roy area is relatively small in areal extent, and water discharges from it through several seepage areas which are around the periphery of the area as shown in figure 14. Normally, in deep aquifers in the unconsolidated deposits of the valleys west of the Wasatch Range in Utah, water is under higher static pressure than is the water in the overlying shallow aquifers. In the Roy area, pumping from the deep Delta aquifer apparently has lowered the pressure in that aquifer, so that it is less than the pressure in the shallow aquifer.

In the Syracuse area (fig. 14) the chemical quality of water from wells less than 250 feet deep might indicate that the shallow aquifer is not connected to the deeper aquifers which yield water that contains less dissolved minerals. However, the altitude of the piezometric surface is about the same in each of the water-bearing zones, which indicates that the shallow and deep aquifers are connected. It is suggested, therefore, that the difference in chemical quality is due to cation exchange and an increase in total mineralization, both of which occur during upward leakage of the water from the deeper to shallower aquifers.

OGDEN-PLAIN CITY SUBDISTRICT

The Ogden-Plain City subdistrict is north of the Weber Delta subdistrict. The boundaries of the Ogden-Plain City subdistrict are shown in figures 1 and 10, but because of insufficient data, the northern boundary is not defined. Large yields can be obtained from wells in parts of the subdistrict, but in places the water contains considerable sodium and chloride in solution. Individual aquifers in this subdistrict have not been identified because it is not known whether the complex pattern of occurrence of water of various chemical types is caused by many discontinuous aquifers or water of different chemical type in a few continuous aquifers. Wells in the subdistrict are from 50 to 900 feet deep, but most wells are from 250 to 600 feet deep.

NORTH OGDEN SUBDISTRICT

The boundaries of the North Ogden subdistrict, which is north of the Ogden-Plain City subdistrict, are shown in figures 1 and 10. Because of insufficient data, the northern boundary of the subdistrict is not defined.

The artesian aquifer in the North Ogden subdistrict is at relatively shallow depth near North Ogden, but it apparently extends southwestward beneath a thick cover of clay. Although the aquifer consists of coarse sand and gravel, the wells tapping it have relatively small yields. Exceptionally high artesian heads in the aquifer permit the water to rise in wells to levels above 4,300 feet, the approximate maximum altitude at which wells flow in other subdistricts. The aquifer yields water of excellent chemical quality. The water contains less dissolved minerals than does water from artesian aquifers in nearby areas. The differences in pressure and quality indicate that the aquifer in this subdistrict is at least partly separated from the aquifers in adjacent subdistricts. Water in the overlying water-table aquifer is very hard and generally requires softening for domestic use.

WEST WARREN SUBDISTRICT

The West Warren subdistrict lies west of the Ogden-Plain City subdistrict and northwest of the Weber Delta subdistrict. The boundaries of the West Warren subdistrict are shown in figures 1 and 10, but because of insufficient data, the northwestern boundary is not defined. The ground water in the subdistrict is satisfactory for culinary use, but it generally is not satisfactory for irrigation because it is of sodium bicarbonate type. Individual aquifers have not been identified in this subdistrict, but most wells are 300–600 feet deep.

LITTLE MOUNTAIN SUBDISTRICT

The Little Mountain subdistrict includes the area from Little Mountain to Hooper Hot Springs and much of the Ogden Bay Bird Refuge (figs. 1, 10). The ground water in this subdistrict contains considerable sodium chloride and probably is unsatisfactory for most common purposes. Few wells are known to be in the subdistrict, partly because it consists mostly of mudflats and saltgrass pastureland, but also, perhaps, because the quality of water encountered by wells has not encouraged widespread drilling. Individual aquifers have not been identified, but most wells are about 190–325 feet deep.

KAYSVILLE-FARMINGTON SUBDISTRICT

The Kaysville-Farmington subdistrict is south of the Weber Delta subdistrict (figs. 1, 10). Wells in the Kaysville-Farmington subdistrict near the Wasatch Range generally have small yields, but the water is of good chemical quality. Farther westward, the sodium content is increased by cation exchange, and the water becomes less suitable for irrigation.

The aquifers in the subdistrict are separated from the aquifers of the Weber Delta subdistrict by a bedrock high which is encountered in wells a few hundred feet deep in Kaysville. South of Kaysville, pressure heads are generally small. In the area extending from 1½ miles north to 3 miles south of Farmington, and from Farmington westward to the lake, the distance above land surface to which water from wells will rise decreases toward the west. This unusual pressure condition, in which the hydraulic gradient is steeper than the topographic slope, is probably caused by the low permeability of the aquifers and the flatness of the topography.

RECHARGE

SOURCE OF RECHARGE

The ultimate source of all ground water in the Weber Delta district is precipitation which falls mostly in the form of snow on the drainage basin in varying quantities from year to year. Some of the runoff resulting from this precipitation contributes the principal recharge to the groundwater reservoir, either directly from the streams that drain the mountains, or indirectly as seepage from canals and irrigation. On the benchlands along the mountain front, a part of the precipitation percolates directly to the aquifers, after evapotranspiration losses have occurred and soil-moisture deficiencies have been satisfied. Direct precipitation and irrigation on the flatlands west of the mountain front contribute little or no recharge to the deep aquifers, but they probably contribute to recharge of the shallow aquifers.

PRINCIPAL RECHARGE AREA

The zone most favorable for recharge to the artesian aquifers in the Weber Delta district extends, at the most, only about 1½ miles westward from the mountain front. This zone consists basically of two parts: the channel of the Weber River from the mouth of Weber Canyon to a point 1½ miles to the west and a belt of gravel and sand, ranging in width from a few feet to a few thousand feet, that lies just west of the mountain front throughout most of the district (fig. 10). The recharge zone readily absorbs underflow from the mountain front, part of the runoff from the major and lesser streams, and some moisture directly from precipitation. Other zones, farther from the mountain front, accept direct infiltration from precipitation and from irrigation, although probably less readily than the zones closer to the mountains.

The belt of gravel and sand close to the mountain front is formed of high-level bench gravels occupying terraces near the 4,800-foot (Provo) and 5,200-foot (Bonneville) shorelines and occurring at points between these two shorelines. In places where the present canyons cut deeply through the terraces, it is apparent that in some areas clay and silt extend nearly to the hard rock of the Wasatch Range. In others, however, beds of gravel extend well up toward, and probably in many places make actual contact with, the rock of the Wasatch Range.

A gravel pit in North Ogden reveals some of the relationships that must exist at various places throughout the district. This pit is in the SW¼ SW¼ sec. 27, T. 7 N., R. 1 W., where, at various stages of the history of the Bonneville Basin, sediments might easily have been derived from North Ogden and Coldwater Canyons and the next canyon south. The pattern of crossbedding in the sand and gravel exposed in the pit suggests that at various times each canyon contributed material to the sediments now displayed in the walls of the pit. The gravel is inferred to be part of an old alluvial fan or near-shore delta formed by discharge of sediments jointly from North Ogden and Coldwater Canyons. The north wall of the pit is formed entirely of clay and silt of the Alpine Formation. The clay and silt on the east wall of the pit form a tongue projecting above and covering the sand and gravel of the older deposit. Evidently in this area, deposits of highly permeable sand and gravel were laid down adjacent to the mountain front and for some distance into the basin. When lake levels again rose in the basin, the flanks and top of the gravels were enclosed in silt and clay of the Alpine Formation. Whether the enclosed sand and gravel represent an earlier stage of Alpine deposition or whether they are pre-Alpine in age is not know. Comparable conditions probably occur at many points and at various levels in the subsurface along the mountain front where streams have built deposits largely of coarse-grained permeable material which were later enclosed by finer grained lake sediments.

The Wasatch fault zone extends along the front of the Wasatch Range, and is marked by many cross faults and branch faults in a strip about 1 mile wide. In many places, late Pleistocene and Recent movement of these faults has cut the fine-grained Alpine sediments, and some recharge may percolate to the deeper aquifers along these faults (Dennis, 1952, p. 9).

SUMMARY OF RECHARGE

The calculated mean annual recharge to the aquifers in the Weber Delta district is 70,000 acre-feet of water. The various sources of recharge and the estimated volumes of recharge are as follows:

	Acre-feet
Surface streams:	
Weber River near canyon mouth	16,000
Ogden River near canyon mouth	2,000
Mountain-front streams	3,000
Mountain-front subsurface flow	30,000
Direct infiltration:	
Precipitation	10,000
Irrigation seepage and canal losses to benchlands and flood plains	6,000
Total (rounded)	70,000

RECHARGE FROM SURFACE STREAMS

WEBER RIVER

The Weber River is the most important localized source of recharge to the aquifers of the Weber Delta district. When the Weber Basin Project reaches full development, however, only flood flows will reach the most favorable recharge areas, and therefore, the recharge from this source may be diminished.

A series of measurements of seepage losses was made in the channel of the Weber River downstream from the point where the river emerges from the mountains. These measurements show that in the first 1½ miles the loss of flow in the river ranges from 0 to as much as 18 percent of the total discharge. The mean value calculated for the loss is about 7 percent of the discharge. Based on this calculation, estimates were made of infiltration for the year 1934, one of very low flow, and for the year 1952, one of near maximum flow. These estimates show infiltration in the first 1½ miles west of the mouth of Weber Canyon of 9,000 acre-feet in 1934 and 100,000 acre-feet in 1952.

Inflow-outflow studies for the reach between the Geological Survey gaging stations at Gateway and Ogden on the Weber River suggest a mean annual recharge of about 20,000 acre-feet for the period 1951–58. For the reference period 1928–47, the adjusted annual recharge was 16,000 acre-feet. Of

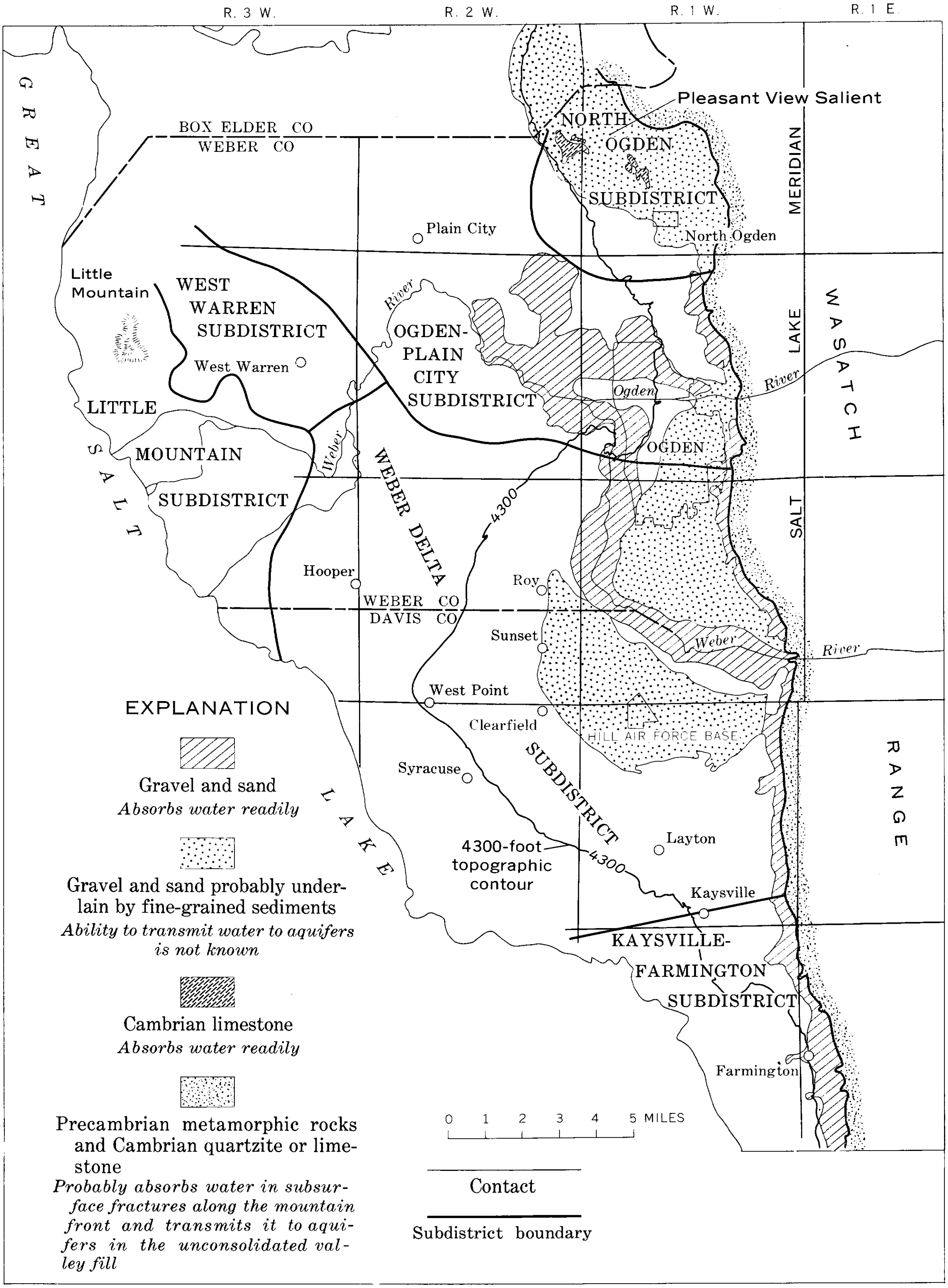


FIGURE 10.—Map of ground-water subdistricts in the Weber Delta district showing probable areas of ground-water recharge.

this, probably about 14,000 acre-feet infiltrates in the 1½ mile stretch just west of the mouth of Weber Canyon.

The piezometric-surface maps (pls. 9, 10) show a marked pressure bulge westward in Tps. 4 and 5 N. that reflects recharge from the Weber River. The isopiestic lines bow outward away from the canyon mouth more than do the land-surface contours, indicating that a large volume of water is being added to the aquifers from the vicinity of the mouth of Weber Canyon and southward.

In the principal recharge area, just west of the Wasatch Range, the flood plain of the Weber River is underlain by coarse gravel and sand, and the water table in this area, on the average, is about 160 feet below the land surface. Recharge is rapid because the sediments have high permeability and are hydraulically connected with aquifers of high permeability. During the summer of 1955, a trench about 15 feet deep was dug across the channel of the Weber River to permit installation of a pipeline, part of the Weber Aqueduct of the Bureau of Reclamation. The trench showed that at low-water stages in the river, recharge occurs vertically downward. The gravels of the flood plain were entirely dry to maximum depth of the trench, except just below the wetted part of the river channel.

Near the west border of the recharge area, a few shallow wells ranging in depth from 60 to 115 feet show the presence of a perched water table that slopes eastward contrary to the slope of the land (pl. 9). Shallow ground water in that part of the river flood plain moves eastward above a clay layer that becomes progressively thinner to the east and wedges to disappearance about 1½ miles west of the Wasatch front. There the water spills over the clay lip adding to the recharge of the deeper aquifers.

OGDEN RIVER

The annual recharge from the Ogden River is much less than that from the Weber River. Seepage measurements made in a reach of about 1 mile just west of the mouth of Ogden Canyon suggest a net loss of flow of about 3 cfs (cubic feet per second) at the times of measurement. Using the loss rate of 3 cfs, an arbitrary estimate of 2,000 acre-feet per year is calculated as the annual recharge from the Ogden River. This is probably a minimum value.

MOUNTAIN-FRONT STREAMS

The estimate of runoff from mountain-front streams is about 35,000 acre-feet per year (table 5). The perennial flow of most of these streams is conducted in pipes or canals across the highly permeable recharge zone adjacent to the mountains, but some of the high spring runoff and water from flash floods in the summer bypasses the diversions and enters the ground in the recharge areas. Probably about 10 percent of the total runoff, or about 3,000 acre-feet per year, actually recharges the aquifers.

TABLE 5.—*Estimated annual runoff from mountain-front streams, T. 3 N. to T. 7 N., inclusive*

Stream	Runoff (acre-feet)	Stream	Runoff (acre-feet)
Rice	[1] 600	North Fork of Holmes	[1] 1,800
North Ogden	[1] 1,000	Holmes	[3] 2,800
Coldwater	[1] 1,000	Haight	[1] 3,500
Taylor	[2] 500	Shepard	[1] 1,900
Waterfall	[2] 500	Farmington	[3] 10,000
Strongs	[2] 500	Steed	[1] 2,000
Burch	[1] 2,000	Davis	[1] 1,200
Spring	[1] 300	Others	[2] 500
North Kays	[1] 1,400		
Middle Kays	[1] 1,400	Total	34,900
South Kays	[1] 1,400	Total rounded	35,000
Snow	[1] 600		

[1] Estimated from spot measurement.
[2] Estimated.
[3] Calculated from stream-gage records.

MOUNTAIN-FRONT SUBSURFACE RECHARGE

A large quantity of water, admittedly difficult to estimate, recharges the aquifers in the Weber Delta district by subsurface flow from the bedrock and overlying surficial material of the Wasatch Range. The presence of subsurface flow is supported by the configuration of the piezometric surface of the aquifers in the district, by chemical-quality data, by evidence from radon studies, and by measurements of water in Gateway Tunnel.

The total amount available for recharge by subsurface flow is estimated in the following manner to be about 30,000 acre-feet (table 6). The volume of precipitation over the Wasatch Range, from an altitude of 5,000 feet to the crest of that part of the range just east of the Weber Delta district (excluding the areas which drain directly into the Weber and Ogden Canyons) is calculated by increments of elevation from data of the U.S. Weather Bureau. The loss by evapotranspiration is also calculated by increments of elevation, using data from U.S. Forest Service studies on the watershed. The estimated evapotranspiration and the runoff from mountain-front streams are deducted, and the remainder, 30,000 acre-feet, is the calculated volume of average annual subsurface recharge along the mountain front.

EVIDENCE FROM THE PIEZOMETRIC SURFACE AND FROM CHEMICAL-QUALITY DATA

The slope of the piezometric surface away from the mountain front toward Great Salt Lake indicates that the mountain front is a linear source of

TABLE 6.—*Calculation of volumes of water available for recharge by subsurface flow from the mountain front, T. 3 N. to T. 7 N., inclusive*

MOUNTAIN-FRONT PRECIPITATION

Amount of precipitation [1]				Area between isohyetal lines along mountain front (acres)	Annual volume of precipitation (acre-feet)
October to April		Annual average			
Range (inches)	Average (inches)	Inches	Feet		
12–16	14	21.0	1.75	5,700	10,000
16–20	18	26.0	2.17	12,000	26,000
20–24	22	31.0	2.58	11,000	28,000
24–28	26	36.0	3.00	14,000	42,000
28–32	30	41.0	3.42	6,900	24,000
32	32	43.5	3.62	3,900	14,000
Totals (rounded)				53,000	144,000
Adjustment of total volume to 1928–47 period: 144,000 × 96 percent					138,000

ESTIMATED EVAPOTRANSPIRATION [2]
Mountain front, 5,000 feet to crest

Elevation zones (feet)	Annual rate		Area (acres)	Annual volume (acre-feet)
	Inches	Feet		
5,000–6,000	20.0	1.67	14,000	23,000
6,000–7,000	17.5	1.46	18,000	26,000
7,000–8,000	15.0	1.25	14,000	17,500
8,000–9,000	12.5	1.04	4,500	4,700
9,000–10,000	10.0	.83	2,400	2,000
Totals (rounded)			53,000	73,000

Computed annual ground-water inflow (recharge), in feet, along the mountain front:

Mountain-front precipitation (above)		138,000
Less evapotranspiration (above)	73,000	
Less mountain-front streams (table 8)	35,000	
		108,000
Net ground-water inflow		30,000

[1] October–April data from the U.S. Weather Bureau, Annual data converted from October–April data using Weather Bureau correction factors.
[2] U.S. Forest Service unpublished data.

recharge (pl. 9). This is particularly evident in the southern part of the area extending about from Kaysville to Bountiful (pl. 9). During spring runoff, large volumes of water enter the rock of the mountain mass itself through fissures, joints, and other openings. In addition, water enters the soil on the mountain front, and in most years enough water is available to satisfy the field capacity of the soil, so that some water can percolate down to the weathered-rock mantle. This water within and on top of the rock probably moves gradually downward and finds its way into the sand and gravel aquifers along the mountain front.

In a 3- to 4-mile-wide band parallel to the southern border of the Weber Delta subdistrict, through the town of Layton, water from wells has smaller concentrations of dissolved solids and chloride than does water from the Weber River. (See analyses for wells (B–4–1)20cbb–1 and (B–4–2) 26aaa and the Weber River in table 9.) This water is chemically similar to water from mountain springs and from Gateway Tunnel (analyses for springs (B–5–1)25d and (B–7–1)22abc and Gateway Tunnel in table 9), and, therefore, presumably is derived from recharge along the mountain front. Further evidence that the mountain front provides subsurface recharge is presented in the section on "Chemical quality."

EVIDENCE FROM WEBER CANYON RADON STUDIES

Radon studies made on a reach of the Weber River that showed gains in flow indicated that the source of the water was bedrock rather than discharge from bank storage. Seepage measurements were made on a reach of the Weber River between a powerplant near the mouth of Weber Canyon and a diversion dam 1¾ miles upstream. At low-water stages these measurements showed that the river consistently gains about 5 cfs in the reach, mostly from the south side in the lower half a mile of the reach.

In an attempt to determine the source of this water, A. S. Rogers, of the Geological Survey, made a study of the radon content of the water; his work (Rogers, 1958, p. 205–208) indicated that the bulk of the inflow in the reach of the Weber River was derived from bedrock sources and not from bank storage in alluvial materials that are present at some places along the river. The rocks of the Wasatch Range are evidently contributing an appreciable volume of water to the Weber River; the rocks of the range, therefore, are assumed to be capable of yielding water to aquifers along the west front of the range.

EVIDENCE FROM GATEWAY TUNNEL

Further knowledge of the water-bearing properties of the bedrock in the Wasatch Range was gained during the drilling of the Gateway Tunnel. This tunnel, shown in figure 12, is one of the facilities of the Weber Basin Project. It extends 3.3 miles from the mouth of Weber Canyon upstream through metamorphic rocks, thus penetrating a main ridge of the Wasatch Range. A considerable flow of water was encountered about 1,100 feet from the west portal. During the rest of the tunneling operations additional flows of water were encountered at various points. In July 1953, a 6-inch Parshall flume was installed in a ditch that drained water from the west portal of the tunnel. Except for minor interruptions, the flume was operated until September 1954. Records obtained from this flume do not show all water yielded by the tunnel because it was necessary to pump water from the tunnel at various times during the drilling operation. A hydograph (pl. 7) based on the flume records and measurements made after the flume was removed shows, however, that during the period July 1953 to March 1955 the tunnel discharged from about 180 to 450 gpm. A peak flow of 580 gpm was recorded, but it was not long sustained.

The hydograph on plate 7 is definitely not a depletion curve such as would be expected if the tunnel derived water only from storage in rock fissures. Rather, the hydrograph suggests that the fissures receive recharge from snowmelt which would probably find its way through fissures in the rock to the valley aquifers if it were not intercepted by the tunnel. A spring below the tunnel diminished in flow during the drilling of the tunnel, thus suggesting that some of the water encountered in the tunnel may have normally discharged from this spring.

RECHARGE FROM PRECIPITATION, IRRIGATION, AND CANALS

Direct infiltration of precipitation, seepage from irrigated areas, and seepage from canals supply recharge to the artesian aquifers. Much of the water from these sources evaporates or is transpired by vegetation, but about 16,000 acre-feet (25 percent of the total available) might recharge the ground-water aquifers in areas above an altitude of 4,300 feet. Below 4,300 feet this water could only penetrate to the water table because artesian pressures would prevent recharge to the artesian aquifers.

DIRECT INFILTRATION OF PRECIPITATION

Some of the precipitation that falls on the more permeable surfaces of the Weber Delta district percolates downward toward the aquifers. No attempt was made to measure the actual recharge from precipitation in the large area of the district. Instead, it is estimated that 25 percent of the precipitation reaches the ground-water body. This estimate is probably reasonable, because it is comparable to an estimate based on laboratory determinations of the permeability of samples of surficial materials collected in the district.

The area between an altitude of 4,300 feet and the mountain front and between the Box Elder County line and the north boundary of T. 2 N. that is underlain by reasonably permeable materials is about 60 square miles (measured by planimeter on fig. 10). The October-April precipitation which is available for recharge in that area ranges between 12 and 16 inches, with an average of about 14 inches (fig. 2). If 25 percent of this precipitation infiltrates to the ground-water reservoir, the amount of recharge is (adding factors to change inches to feet and square miles to acres):

$$0.25\times14\times1/12\times60\times640=11{,}200 \text{ acre-feet.}$$

An estimate of the amount of recharge from direct precipitation on the area between 4,300 feet and the mountain front, therefore, is about 10,000 acre-feet per year.

An unknown, but probably large amount, of the Weber Delta district has reasonably permeable materials at the surface, but it is underlain at depth by clay that is less permeable than the surface material. Some of the clay, being only slightly permeable, supports perched water bodies; but other clay layers, because of internal structural arrangement, are sufficiently permeable to permit water to pass through them and recharge the underlying ground-water body.

Laboratory tests of vertical permeability were made on four undisturbed clay samples which were obtained from depths of 5–9 feet in the Bureau of Reclamation B–5 drain area in sec. 16, T. 4 N., R. 2 W. The vertical permeabilities determined after 271 hours were as follows:

Sample	*Permeability (inches per hour)*
1	0.002
2	.001
3	.000
4	.000
Average	.00075

It can be assumed that in the area of 60 square miles which is underlain by reasonably permeable materials, these materials, in turn, are underlain by clay whose vertical permeability may be about 0.00075 inch per hour. This area then would be capable of accepting recharge as follows:

0.00075 in per hr=0.0015 ft per day =0.55 ft per yr.

On this basis, therefore, an area of 60 square miles, or about 38,000 acres, could accept about 20,000 acre-feet of recharge per year. As there is very little runoff from this area and the clay may accept recharge at this rate, the original estimate of about 10,000 acre-feet of recharge per year from precipitation is reasonable.

SEEPAGE FROM IRRIGATED AREAS AND CANALS

The 60 square miles that are underlain by reasonably permeable materials include about 4,600 acres of irrigated land on which the annual diversion of water is about 3½ acre-feet per acre. If 25 percent of the water diverted infiltrates to the ground-water reservoir, then the amount of recharge from this source is about 4,000 acre-feet.

Water is diverted from the Weber River in unlined irrigation canals which cross the principal recharge area of the Weber Delta district near the mountains. (See p. 38.) These canals divert about 7,200 acre-feet per year, and they undoubtedly lose water to the recharge area. The loss from the canals is estimated to be 25 percent of the water diverted; thus, the recharge from these unlined canals is about 2,000 acre-feet per year.

Differences in the quality of the water (p. 60) in the deep and shallow artesian aquifers in the Roy area suggest that the shallow aquifers are recharged by infiltration of excess irrigation water applied to the benchlands east of Roy. The exact amount of this recharge, however, is not known.

ARTIFICIAL RECHARGE EXPERIMENTS

The flood plain of the Weber River, near the mouth of Weber Canyon, is underlain by permeable sand and gravel to at least 217 feet. This is the depth of Bureau of Reclamation test well 1, (B–5–1) 36bbb–1, which was drilled in December 1952 to be used as an observation well during artificial recharge experiments. In an earlier investigation, Dennis (1952) considered the mouth of Weber Canyon to be the area where recharge is greatest and concluded that artificial recharge should be tried there.

In February and March 1953, recharge experiments were made near the mouth of Weber Canyon by running surplus flows of the Weber River into a pit having an area of 3¼ acres and a depth of 30 feet. The two experiments lasted a total of 7 weeks, and about 2,170 acre-feet of water infiltrated into the pit, equivalent to a continuous flow of 7 cfs per acre. The recharge affected the water level in test well 1 of the Bureau of Reclamation 3 days after the experiment began, and the water level rose 34 feet during the experiment (fig. 11). Test well 1 is a quarter of a mile west of the recharge pit; therefore, under unconfined conditions, the velocity of the water was about 440 feet per day.

The available evidence is inconclusive, but apparently the pressure wave from the recharge experiments affected observation wells to a distance of about 6 miles. No observation wells were available west of the Bureau of Reclamation test well 1 for a distance of about 3 miles; but, in observation wells 3–6 miles from the recharge pit, water levels rose nearly simultaneously about 1 month after the experiment began. This probably was caused by the recharge water entering an artesian aquifer.

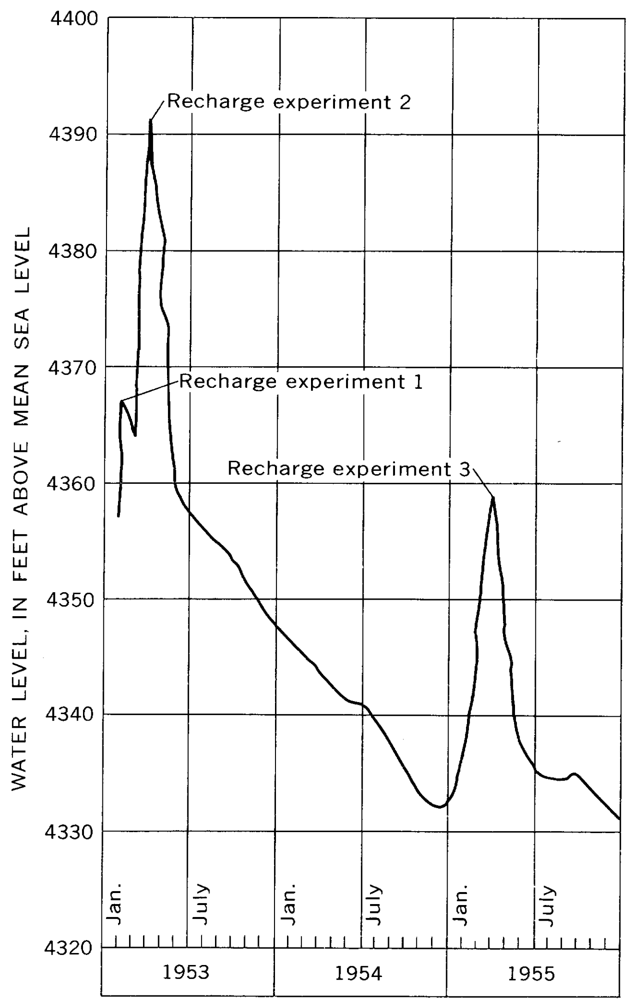


FIGURE 11.—Hydrograph of Bureau of Reclamation test well 1, (B–5–1) 36bbb–1, January 1953 to December 1955, showing effects of artificial recharge.

The confining layer over the artesian aquifer in this area consists of a clay layer that thins toward the east. The Bureau of Reclamation test well 3A, (B–5–1)27dcc–1, was drilled in November 1953 about 1½ miles west of test well 1. Test well 3A, which is 350 feet deep, was drilled to act as an observation well in recording the pressure wave from the recharge pit and to determine the thickness of the confining clay layer. The confining layer was found to be 74 feet thick and to lie between 110 and 184 feet below the land surface. The areal extent of the clay layer is not known and, therefore, the eastern edge of artesian conditions is unknown.

A third recharge experiment was attempted from December 1954 to March 1955. Exceptionally cold weather froze the recorder floats in the observation wells and froze the water in the delivery canal.

Later, high-stage turbid waters interfered with recharge by depositing silt in the pit. Although the experiment failed to produce continuous records, the effect of recharge was recorded at both wells, reaching test well 1 in 5 days and test well 3A in 13 days. A fourth recharge experiment was conducted from November 1957 to February 1958, but figure 11 does not include this period and therefore does not show the effects of this experiment on water levels in test well 1. This experiment is discussed on page 47. The artificial recharge experiments showed that the area is definitely one in which natural recharge occurs and in which artificial recharge is possible.

STORAGE

In water-table aquifers, water fills the voids or spaces between the mineral grains that form the aquifers; in artesian aquifers, the water fills the voids and also is under pressure, because it is confined by overlying and underlying beds that are less permeable than the aquifers. Because water is slightly compressible and because the materials that make up artesian aquifers are slightly elastic, the removal of water from an artesian aquifer results first in an overall pressure adjustment within the aquifer, rather than the actual dewatering of the aquifer. As more and more water is removed from an artesian aquifer, parts of the aquifer may be dewatered. When this happens, the aquifer reverts to water-table conditions and continued declines of water level reflect the unwatering of the sediments, rather than the compression of the aquifer.

The principal aquifers in the Weber Delta district are artesian, and calculations were made to determine the total amount of water in storage in the aquifers and to determine how much they would yield for different changes in head. The yields were calculated for changes in pressure before dewatering the artesian aquifers and also for changes after dewatering began. The calculations were based on data obtained by measuring wells, by pumping tests, and by recharge experiments.

VOLUMES OF WATER IN THE GROUND-WATER RESERVOIR

The quantity of ground water in storage in the Weber Delta district could be determined if the volume and porosity of sedimentary materials were known. Available data, however, permit only approximate calculations, and these calculations must be considered from several points of view. Data from the Bureau of Reclamation test well 5B, (B-5-2)16dcd-2 (pl. 4), indicate that at depths between about 1,300 and 3,007 feet (maximum penetration) in the heart of the Weber Delta district, the sediments are mostly fine grained; thus, yields from aquifers below 1,300 feet probably would be small.

Large areas in the Ogden-Plain City subdistrict are underlain by fine-grained sediments, and yields from many wells are small. Thus, despite the large volume of valley fill in the Weber Delta district and the presumed large total volume of water contained in the fill, only a part of the total can be readily recovered by wells.

Meinzer (1923a, p. 10–11) reported the following determinations of the porosity of rock materials: the range in porosity of uniform sands was from 26 to 47 percent, the average being 35 percent; mixed sands ranged from 35 to 40 percent and averaged 38 percent; clay ranged from 44 to 47 percent and averaged 45 percent. Field tests of porosity of glacial materials in Pomperaug Valley, Conn. (Meinzer, 1923a, p. 11), showed the following: Fine stream-deposited sand, 48 percent; various glacial-outwash sands, sand-gravel mixtures, and silt and clay, 18–37.6 percent; and lake-deposited silt, 36 percent.

Available information on the porosity of unconsolidated materials and on the character of sedimentary materials underlying the Weber Delta district suggests that an estimate of 25 percent porosity for the entire body of sediment is reasonable and conservative. In the discussion on subsurface geology (p. 30), it was estimated that the prism of unconsolidated sediments underlying the district (excepting the Kaysville-Farmington subdistrict and the northwestern part of the Ogden-Plain City subdistrict) has a volume of about 200 cubic miles. From this estimate, the following calculation may be made:

$$200 \text{ cubic miles} \times 640 \text{ acres} \times 5{,}280 \text{ feet} \times 0.25 \text{ (porosity)} = \text{about } 170{,}000{,}000 \text{ acre-feet.}$$

The estimated volume of 170 million acre-feet of water is contained in the sedimentary prism that constitutes about three-fourths of the Weber Delta district and has a thickness of about 6,000 feet of fill at the deepest point. Much of this water in storage is unavailable or of poor quality. It is desirable, therefore, to consider how much of this water is available for use by determining the effects of changes in storage on the piezometric surface.

CHANGES IN STORAGE IN THE WEBER DELTA SUBDISTRICT

Changes in artesian pressure are the results of elastic adjustment of the aquifer materials and the materials making up the confining layers of the system. The amount of water actually taken into or released from an artesian aquifer, when pressure is increased or decreased, is very small, because the volume change results from very slight contraction or expansion of the water and by slight structural adjustments among the mineral grains composing the aquifer. Pressure changes caused by adding water to, or withdrawing water from, the artesian system appear to be out of proportion to the volume of water added or withdrawn.

The extent to which small changes in amounts of water in the system can cause relatively large changes in pressures in wells is illustrated by the following calculations for an area corresponding approximately to the Weber Delta subdistrict, excluding 10 square miles of the subdistrict in which ground water is unconfined (p. 47). The area includes about 130 square miles which is largely underlain by the Delta aquifer (pl. 5). The results of three aquifer tests at wells penetrating the Delta aquifer (table 8) indicate an average coefficient of storage (see definition, p. 52) of 8×10^{-4}. This average figure is within the range cited by Brown (1953, p. 849) as being characteristic of storage coefficients in artesian systems, and it is considered reasonable to use in calculations. During the period December 1954 to December 1955, the average decrease in artesian pressures in the Weber Delta subdistrict was 5 feet, and the decrease in storage that caused that water-level decline is calculated to be as follows:

$$(8 \times 10^{-4}) \times 130 \text{ square miles} \times 640 \text{ acres} \times 5 \text{ feet head differential} = 333 \text{ acre-feet.}$$

Thus, a change in a storage in the artesian aquifers of about 300 acre-feet may lower the piezometric surface about 5 feet. The many uncertainties involved in the data—the small number of aquifer tests, the large area, the partial separation of the artesian system into semiindependent aquifers, and the use of wells of many differing depths to obtain an average value of 5 feet of change in the piezometric surface—suggest that the value obtained by calculation is not strictly accurate. The 5-foot average decline in head observed between 1954 and 1955 in aquifers underlying an area of 130 square miles probably reflected a decrease of water in storage of less than 1,000 acre-feet.

ACTIVE STORAGE IN THE WEBER DELTA SUBDISTRICT

The term "active storage" may be used to describe the water that can be readily developed and manipulated without dewatering the artesian aquifers. This water would be obtained by lowering water levels in the artesian aquifers and in the recharge area, where ground water is under water-table conditions, by an assumed maximum of 150 feet. In the following discussion, the number and distribution of the wells that would be involved has not been considered.

Estimates of active storage have been calculated for the artesian aquifers in the Weber Delta subdistrict by two methods: (1) using the artesian coefficient of storage of 8×10^{-4}, or a calculated change in storage of about 300 acre-feet for a change in pressure of 5 feet, and (2) using data obtained from the recharge experiments. The two calculations give reasonably comparable results. The first method indicates that about 100,000 acre-feet in excess of annual recharge might be removed from storage in the artesian and nonartesian aquifers of the Weber Delta subdistrict before dewatering of the artesian aquifers began; the second method indicates that about 80,000 acre-feet might be withdrawn from the same area without dewatering the artesian aquifers.

METHOD 1

Three factors must be considered in estimating active storage in the artesian aquifers of the Weber Delta subdistrict. First is the lowering of artesian pressure. As has already been shown, even small changes in amounts of water in storage in artesian systems may result in relatively large changes in pressure head. Water levels range from 20 feet above to more than 150 feet below the land surface in the subdistrict, but for convenience in calculation it is assumed that the average water level is 50 feet below the land surface.

Second, it is assumed that water levels will decline an average of 150 feet. Thus, no actual dewatering of artesian aquifers will take place because water levels will be at or above the top of the Sunset aquifer which is at an average depth of 200 feet below the land surface.

Third, it is assumed that the water table will decline at about the same rate as do artesian pressures. For this assumption to be valid, it would be necessary to have wells drawing from the water-table aquifer as well as from the artesian aquifers.

Using the above assumptions, the following calculations can be made:

	Acre-feet
Water released by lowering the artesian pressure 150 ft in the artesian aquifers in the Weber Delta subdistrict (60 acre-feet per foot of pressure decline)	9,000

	Acre-feet
Water released by lowering the water table 150 ft in material with an average specific yield of 10 percent (assumed) in an area of 10 square miles $150 \times 10 \times 640 \times 0.10 =$	96,000

Thus, about 100,000 acre-feet of water in excess of annual recharge might be removed from storage in artesian and nonartesian aquifers in the Weber Delta subdistrict before dewatering of the artesian aquifers began. This may be a conservative figure because as artesian pressures decline, the hydraulic gradient through the confining beds between the artesian aquifers and the overlying unconfined aquifers in places may be reversed. Thus, the artesian aquifers may receive additional recharge from the beds directly above.

METHOD 2

Estimates of active storage also can be made by using data from artificial recharge experiment 4 conducted by the Bureau of Reclamation.

From November 11, 1957, to February 11, 1958, about 1,500 acre-feet of water from the Weber River was put into a recharge pit at the mouth of Weber Canyon, and the effects on water levels or artesian heads were measured in nearby wells. The increases in head, as shown in the following tabulation, were the changes measured in the various wells after the initial ground-water mound in the recharge area had dissipated.

Well and location	Head increase (feet)	Distance from recharge pit (miles)	Type of aquifer well penetrates
Bureau of Reclamation:			
Test well 1, (B-5-1) 36bbb-1	6.0	0.3	Water table.
Test well 3A, (B-5-1) 27dcc-1	5.0	1.8	Do.
Hill Field 4, (B-5-1)33cda	5.0	3.4	Artesian.
Laytona, (B-4-1)8add	4.0	4.6	Do.
Sunset, (B-5-2)25bcd-2	3.5	6.7	Do.
U.S. Bureau of Reclamation:			
test well 5A, (B-5-2) 16dcd-1	4.0	9.3	Do.
Prevedale, (B-6-2)33ddc	3.0	10.5	Do.
Bingham, (B-5-2)31cbc	2.5	10.5	Do.
Arave, (B-5-2)18cba	2.5	11.9	Do.

These data show that the average rise measured was 5.5 feet in the unconfined (water-table) zone and 3.5 feet in the confined (artesian) zones.

If the unconfined zone affected during the recharge experiment extends outward from the mouth of Weber Canyon for a distance of at least 2 miles, as data from Bureau of Reclamation test well 3A indicate, and if the zone has the rough shape of a 140° segment of a circle with a 2-mile radius, then the area of the zone is $\frac{140}{360} \times \pi \times (2 \text{ miles})^2$ or about 5 square miles. In addition to this area, the aquifers in the Weber Delta subdistrict contain unconfined water in and just downdip of the principal recharge area (see p. 38)—a zone about half a mile wide extending 5 miles south and 4 miles north of the fan, with a total area of about 5 square miles. Thus, the total area of the unconfined aquifer in the Weber Delta subdistrict is on the order of 10 square miles. An area of 130 square miles, mostly in the Weber Delta subdistrict, is underlain by artesian aquifers (p. 36).

Using an average storage coefficient of 8×10^{-4} (from p. 46), and an average head increase of 3.5 feet, the increase in storage in the confined zone resulting from the test is computed to be about 200 acre-feet, as follows:

$$(8 \times 10^{-4}) \times 130 \text{ square miles} \times 640 \text{ acres} \times 3.5 \text{ feet} = 230 \text{ acre-feet.}$$

The amount of water taken into storage in the unconfined aquifers near the mouth of the canyon is then

$$1{,}500 \text{ (the total amount infiltrated)} - 230 = 1{,}300 \text{ acre-feet (rounded).}$$

Using the above figures and assuming that the coefficients of storage and the areal extent of both the confined and unconfined aquifers would remain about the same for an assumed maximum water-level decline of 150 feet, the change in storage (Δ) in the fan-shaped part of the unconfined zone is computed as follows:

$$\frac{5.5 \text{ feet}}{150 \text{ feet}} = \frac{1{,}300 \text{ acre feet}}{\Delta} \text{ or } \Delta = 35{,}000 \text{ acre feet.}$$

As the area of the fan-shaped part of the unconfined zone constitutes about half of total unconfined area, the total change in storage in the unconfined zone would be 70,000 acre-feet. The change in storage in the confined zone has been calculated in method 1 as 9,000 acre-feet (p. 46); thus, the total change in storage for a water-level decline of 150 feet would be about 80,000 acre-feet.

WATER RECOVERABLE BY PARTIAL DEWATERING OF THE ARTESIAN AQUIFERS

WEBER DELTA SUBDISTRICT

Estimates of the amount of water recoverable by partial dewatering of the artesian aquifers in the Weber Delta subdistrict have been made (1) by applying arbitrary figures for specific yield to the sediments below 200 feet and (2) by re-estimating the amount of water recoverable based on a specific yield calculated from the recharge experiments. For both estimates it was assumed that the maximum depth from which usable water may be recovered economically is 1,300 feet below the land surface. The first method indicates that if the upper 50 feet of the artesian aquifer were dewatered, the volume of water recoverable would be about 600,000 acre-feet; the second method indicates that 300,000 acre-feet of water would be recoverable if the upper 50 feet of the artesian aquifer were dewatered. Despite the wide range, the estimates of the amount of water available by partial dewatering of the artesian aquifers in the Weber Delta subdistrict seem reasonable for use as minimum and maximum values.

Method 1

Calculations of the amount of water in storage in the 1,100-foot thick prism from 200–1,300 feet in the 130 square miles underlain by the Delta and Sunset and deeper artesian aquifers in the Weber Delta subdistrict are based on interpretation of plate 3 by applying arbitrary specific yields of 25 percent for the coarser materials and 5 percent for the finer materials. These values are generalized from estimates of specific yield by Thomasson, Olmsted, and LeRoux (1960, p. 283–287). It is assumed further that the clay-silt percentage shown on plate 3 represents the distribution of fine materials throughout the interval from 200–1,300 feet below the land surface and that the sediments are saturated throughout that depth.

The following areas were obtained from plate 3:

Area (square miles)	*Percent of underlying materials that is fine grained*
2	≧-20
17	20–40
45	40–60
64	60–80
2	80

For those areas having a range of fine-grained material, the median value was used in the following calculations:

Area	Fine-grained materials		Coarse-grained materials	
Square miles	Percent	Area-grain size factor (sq mi)	Percent	Area-grain size factor (sq mi)
2	20	0.4	80	1.6
17	30	5.1	70	11.9
45	50	22.5	50	22.5
64	70	44.8	30	19.2
2	80	1.6	20	.4
Total 130		74		56

The amounts of recoverable water in storage were calculated as follows:

74 × 640 acres × 1,100 feet × 0.05 specific yield = 2,600,000 acre-feet, or about 3,000,000 acre-feet recoverable from fine-grained material.

56 × 640 acres × 1,100 feet × 0.25 specific yield = 9,900,000 acre-feet or about 10,000,000 acre-feet recoverable from coarse-grained material.

The calculations show that about 13 million acre-feet of water theoretically is available for withdrawal from the 1,100-foot prism of sediments in the 130 square miles underlain by the artesian aquifers in the Weber Delta subdistrict. Of course, only part of this amount can be manipulated during the operation of the subsurface reservoir. Complete dewatering of the 1,100 foot thickness would be required to obtain the 13 million acre-feet in storage—and such dewatering is neither desirable nor possible. It is feasible, however, to consider dewatering a few tens of feet of the artesian aquifer. Thus, if we assume that a thickness of 50 feet of aquifer might be dewatered during a period of crisis, such as a long drought, the amount of water recoverable would be about 600,000 acre-feet.

The calculations of yield by method 1 are based on the assumption that the sediments will actually give up a percentage of water equal to the estimated specific yield—5 percent for fine-grained material and 25 percent for coarse-grained material. The calculation of specific yield by method 2 which follows, however, indicates that the coarse-grained materials will not accept, and hence probably not yield, water at the rate calculated by method 1. Therefore, the estimate of 25 percent for coarse-grained materials as used in method 1 may be too high.

Method 2

As previously estimated on page 47, the quantity of water taken into storage in the nonartesian aquifers during the recharge experiment was about 1,300 acre-feet, and this resulted in a rise in head of 5.5 feet. Over an area of 5 square miles, or 3,200 acres, this 1,300 acre-feet is equivalent to an average depth of 0.4 foot of water. Therefore, the coefficient of storage or specific yield of these materials is $\frac{0.4}{5.5} = 0.073$ or 7.3 percent. This is slightly less than the specific yield of 10 percent that was assumed when estimating the yield of the unconfined aquifers (p. 47) and appreciably smaller than the specific yield of 25 percent that was used to calculate the water to be obtained by dewatering the coarse-grained materials of the artesian aquifers (see Method 1).

By using a specific yield of 7.3 percent, the water recoverable by dewatering the coarse-grained material in the artesian aquifers is shown in the following calculation:

56 × 640 acres × 1,100 feet × 0.073 specific yield = 3,000,000 acre-feet.

If an additional 3 million acre-feet of water is recoverable from fine-grained material (p. 48), the total recoverable from both fine- and coarse-grained material would be about 6 million acre-feet. Thus, if the upper 50 feet of aquifer were dewatered, the volume of water recoverable would be about 300,000 acre-feet.

OTHER AREAS

Calculations were made to determine the maximum amount of water recoverable from other areas in the Weber Delta district. The calculations were made before the Weber Delta district was divided into subdistricts; therefore, some of these areas do not correspond exactly with subdistricts. However, the Kaysville-Farmington area is equivalent to the Kaysville-Farmington subdistrict; the Ogden-West Ogden area includes all the Ogden-Plain City subdistrict, except its northwestern part; the North Ogden area is about the same as the North Ogden subdistrict; and the western and northwestern areas include the Little Mountain subdistrict, most of the West Warren subdistrict, and the northwestern part of the Ogden-Plain City subdistrict, excluding the salt flats bounding this area on the west and northwest.

The calculations that follow were made using 25 percent as the specific yield of coarse-grained materials; hence, they should be considered as maximum values.

Area	Area (sq mi)	Water stored in zone 1,100 ft thick (acre-feet)	Water obtainable by dewatering topmost 50 ft of aquifer [1] (acre-feet)
Kaysville-Farmington	34	3,000,000	90,000
Ogden-West Ogden	55	5,000,000	200,000
North Ogden	11	800,000	40,000
Western and northwestern areas [2]	89	8,000,000	400,000

[1] In addition to amount obtainable by lowering the artesian pressure to the top of the artesian aquifer. In the Weber Delta subdistrict this amounts to 80,000–100,000 acre-feet. Comparable amounts presumably could be obtained from other areas.

[2] The preponderance of fine-grained materials in this area would materially restrict development of water in storage.

LONG-TERM FLUCTUATIONS IN ARTESIAN PRESSURE

Water levels in many observation wells in Utah have been measured periodically by the U.S. Geological Survey since 1935. Hydrographs of selected wells in the Weber Delta district are presented on plate 8 to show long-term fluctuations, which are related to changes in volumes of water in storage in the aquifers.

A general decline was recorded in many wells during the period 1953–61, although some wells do not show the decline in pressure head (Smith and Gates, 1963, p. 25). The maximum declines in the Weber Delta district are in the general vicinity of Hill Air Force Base, an area of heavy pumping (Smith and Gates, 1963, pl. 2). Elsewhere in the district, although there is general decline in artesian pressures, flowing wells continue to flow. Considering the relatively large change in pressure head that results from a small change in the volume of water in storage, as calculated in this report (p. 46), it appears that the amount in storage in the district has changed little in the period 1936–61. The production of additional water from the aquifers is possible, although if a large volume of water is produced, a significant lowering of pressure head will result. The rate of decline of pressure in response to increasing draft upon the aquifers cannot, at this stage of knowledge, be predicted; but estimates of the amount of water that might be withdrawn by lowering the pressure a specific amount were given in the discussion on storage. It is certain, however, that effective development of an artesian basin requires that the pressure be lowered so that recharge to the system may be increased and so that wastage may be reduced. Smaller artesian flows—or a change from flowing wells to pumped wells—is the price that must be paid for the full development of an artesian system.

DISCHARGE

Ground-water is discharged in the Weber Delta district from both flowing and pumped wells, as well as by natural means, such as springs, seepage into drains and sloughs, and by evaporation and evapotranspiration from croplands, open-water surfaces, saltgrass pastures, cattail swamps, and mud surfaces. Detailed studies of evaporation and transpiration were made to determine the total amount of water that is discharged from the district, and these studies are discussed in the section on evaporation and evapotranspiration.

DISCHARGE FROM WELLS

Discharge from wells is only a small part of the total discharge of ground water in the Weber Delta district. It is, however, that part of the total discharge which is under man's control and which is best known. The district contains many pumped wells of large yield and thousands of flowing wells —characteristically those used by individuals for domestic or stock supply. In 1954, discharge from wells of both categories was determined to be about 25,000 acre-feet (table 7).

Most of the pumped wells of large yield are east of the 4,300-foot topographic contour, in areas where wells do not flow. All wells in the area that have large yields tap the Delta aquifer. These wells range in diameter from 8 to 20 inches and dis-

TABLE 7.—*Discharge from wells in the Weber Delta district in 1954*

Flowing wells

Township	Acre-feet	Township	Acre-feet
T. 3 N., R. 1 E	250	T. 6 N., R. 2 W	2,700
T. 3 N., R. 1 W	2,000	T. 6 N., R. 3 W	750
T. 4 N., R. 2 W	3,700	T. 7 N., R. 1 W	3,000
T. 5 N., R. 2 W	2,200	T. 7 N., R. 2 W	500
T. 5 N., R. 3 W	1,600	T. 7 N., R. 3 W	220
T. 6 N., R. 1 W	800		
		Subtotal	17,720

Pumped wells of large yield

Owner	Coordinate	Acre-feet
Kaysville	(B-4-1)	130
Kaysville Canning Co	(B-4-1)	140
Layton	(B-4-1)	150
Woods Cross Canning Co	(B-4-2)	140
Smith Canning Co	(B-4-2)	120
West Point	(B-5-2)	40
Syracuse	(B-4-2)	120
Clearfield	(B-4-2)	1,090
Naval Supply Depot Clearfield	(B-4-2)	730
Washington Terrace	(B-5-1)	440
South Ogden	(B-5-1)	200
Hill Air Force Base	(B-5-1)	1,630
Ogden	(B-5-2)	1,320
Riverdale	(B-5-1)	120
Sunset	(B-5-2)	320
Roy	(B-5-2)	550
Other	-------	430
Subtotal		7,670
Total (rounded)		25,000

charge from 200 to 1,800 gpm. Pumping lifts range from 100 to 400 feet, depending on location, and the depth of the wells ranges from 300 to 1,000 feet.

Most flowing wells are below (west of) the 4,300-foot topographic contour, except in the North Ogden subdistrict. The flowing wells are of small diameter, commonly 2 inches, range in depth from 100 to 800 feet, and discharge from less than 1 to 80 gpm.

DISCHARGE BY SPRINGS

Discharge by springs, which is on the order of a few thousand acre-feet per year, constitutes a very small part of the total discharge of ground water in the Weber Delta district. Several springs discharge water ranging in temperature from 50° to 60°F along the mountain front, and local recharge supplies water for a few seeps and small springs along the edge of the delta deposits, especially in the valley cut by the Weber River. Most of the springs in the district are of small yield, typically only a few gallons per minute.

A group of springs of large yield, however, is in sec. 36, T. 5 N., R. 1 W. The total discharge of these springs is on the order of hundreds of gallons per minute, and they were used as a source of supply for many years by military installations on the Weber Delta. Another spring in sec. 25 of the same township furnishes part of the water supply for the town of South Weber.

Warm springs, which discharge water that contains a relatively high content of dissolved minerals, are principally in three locations in the district (fig. 12). Utah Hot Springs, which discharge about 2 cfs, emerge from Cambrian quartzite approximately on the Weber County-Box Elder County line in sec. 14, T. 7 N., R. 2 W. The temperature of water from these springs is 134°F, and the water has been used in the past for public baths. The spring area is marked by extensive iron-stained deposits, and the saline water (table 10) contaminates ditch water for miles distant from the source. The water also has a high natural radioactivity (table 10).

El Monte Spring, near the mouth of Ogden Canyon in sec. 23, T. 6 N., R. 1 W., supplies heat for a public swimming pool. The discharge was not measured during the investigation, but it is some tens of gallons per minute, at 135°F. The water is less saline (table 9) than that of Utah Hot Springs (table 10) and discharges into the Ogden River. The spring emerges from rock of the Wasatch Range at an altitude of about 4,520 feet above sea level—far above the general level of artesian flow in the district—whereas Utah Hot Springs emerge at 4,300 feet, an altitude that generally is the upper limit of artesian flow in the district.

Hooper Hot Springs, in sec. 27, T. 5 N., R. 3 W., form a mound about one-eighth of a mile in diameter on the flatlands near the shore of Great Salt Lake. A series of orifices discharges a total of about 15 gpm of saline water (table 10), which is dissipated by evapotranspiration in saltgrass meadows. The highest water temperature measured was 140°F. A few small satellite warm springs are nearby.

A line of low spring mounds extends northwestward from Hooper Hot Springs toward the southern tip of Little Mountain (fig. 12). Most of them discharge small volumes of moderately mineralized warm water to the mudflats of Great Salt Lake. The mineral content of the water apparently differs, as some of the mounds support growths of sunflowers and other plants that are thought to require water of low mineralization, whereas other mounds are not vegetated or bear only salt-tolerant plants, such as pickleweed and saltgrass.

Warm saline water rises along the Warm Springs fault in the Bountiful district (Thomas and Nelson, 1948, p. 115–118) and probably rises

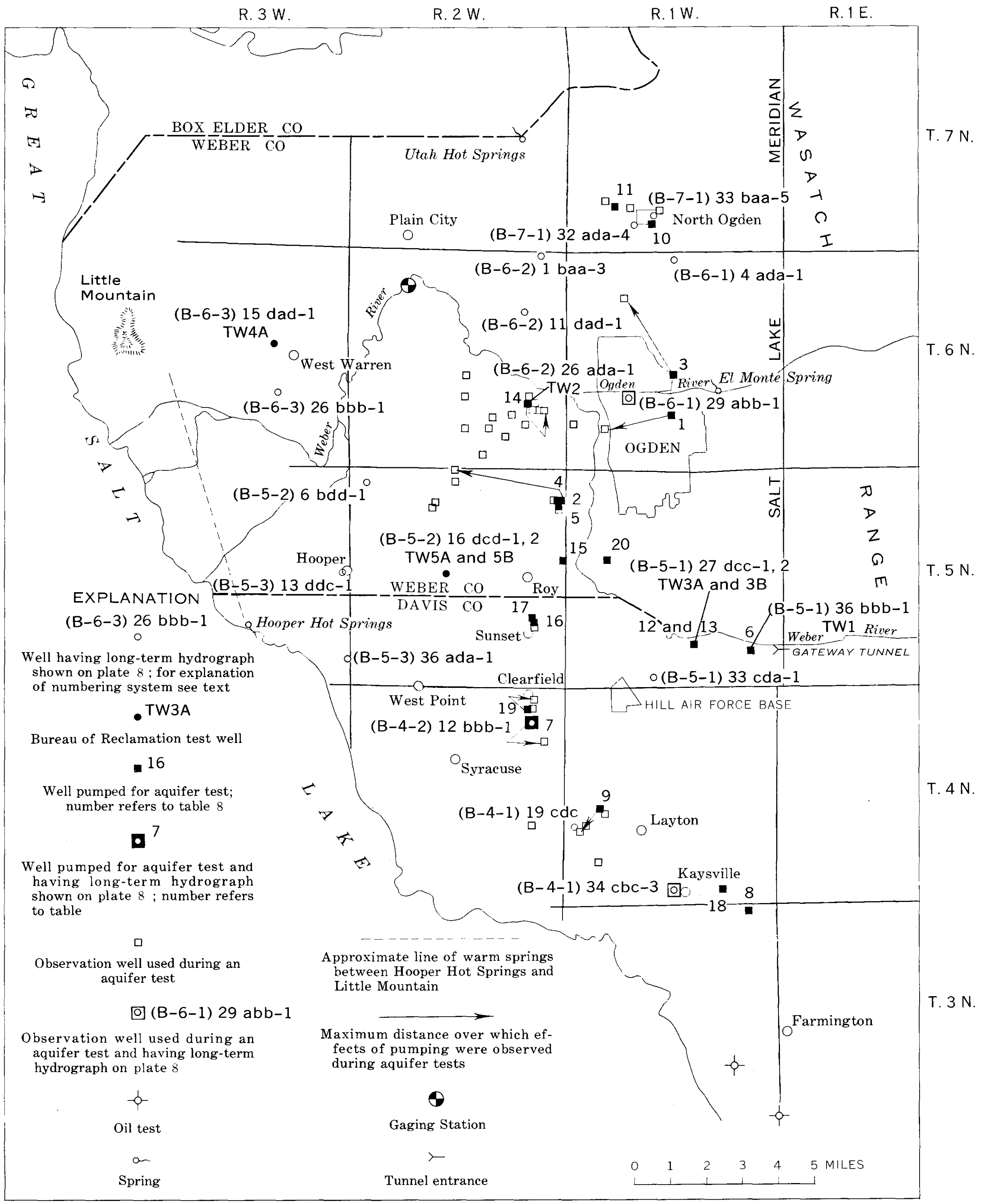


FIGURE 12.—Map of the Weber Delta district, Utah, showing selected hydrologic data.

along faults at several places in the Weber Delta district. The linear arrangement of the mounds on the salt barrens implies that they mark the trace of a fault. Evidence of faulting is conspicuous at Utah Hot Springs and is probably present at El Monte Spring. Wells near the thermal springs yield saline ground water, thus suggesting that there is some discharge of salty ground water through fault zones into the aquifers.

AQUIFER TESTS

HYDRAULIC CHARACTERISTICS

Twenty aquifer tests were made to determine hydraulic characteristics of the aquifers in the Weber Delta district. The wells used in making these tests are shown in figure 12. The results of the tests are given in table 8. The Bureau of Reclamation made 15 of the tests between December 1952 and February 1956. The other five were made by the Geological Survey between October 1944 and June 1946. Data from all tests were analysed using procedures described by Theis (1935) or by Jacob and Lohman (1952).

The ability of an aquifer to transmit water is expressed by its coefficient of transmissibility, which is expressed as the rate of flow of water, at the prevailing water temperature, in gallons per day, through a vertical strip of the aquifer 1 foot wide extending the full saturated height of the aquifer under a hydraulic gradient of 100 percent.

The coefficient of storage of an aquifer is defined as the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface. This coefficient is a dimensionless number. The coefficient of storage of a nonartesian aquifer is nearly identical with the specific yield of the aquifer. Specific yield is defined (Meinzer, 1923b, p. 28) as the ratio of the volume of water which, after being saturated, a rock or soil will yield by gravity to its own volume.

In an ideal aquifer test, there should be a pumped or flowing well and one or more observation wells, all fully penetrating the same homogeneous extensive aquifer. No other wells should be discharging from the aquifer. The depths of the zones of perforation of the wells should be known. The coefficients of transmissibility and storage are assumed to be constant at all times and in all parts of the aquifer.

Unfortunately, not all the above conditions could be met in the Weber Delta district. The district contains numerous interconnected aquifers and in many places the degree of penetration of a particular aquifer by a well could not be determined. Observation wells were not available in some of the test areas, and in some areas the flow from wells not being used in the test could not be controlled.

Of the 15 tests by the Bureau of Reclamation 12 were made on pumped wells, keeping the discharge constant and allowing the drawdown to vary. The data obtained were analysed by means of a formula derived by Theis (Brown, 1953, p. 852). Of the 12 tests, 9 were of artesian aquifers and 3 of water-table aquifers. The other 3 tests were made on flowing wells, keeping the drawdown constant and allowing the discharge to vary with time (Jacob

TABLE 8.—*Results of aquifer tests in the Weber Delta district*

Test [1]	Date of test	Subdistrict [2]	Well	Well depth	Pumped or flowing well	Type of aquifer	Aquifer	Coefficient of transmissibility (gpd/ft)	Coefficient of storage	Tested by
1	10-31-44	OP	(B-6-1)28dab	600	Pumped	Artesian	-------	300,000	-----------	U.S. Geol. Survey.
2	1-17-45	WD	(B-5-2)1ddd-1	527	---do----	-----do------	Delta	36,000	-----------	Do.
3	4-13-45	OP	(B-6-1)21add-1	210	---do----	-----do------	-------	130,000	-----------	Do.
4	6-28-45	WD	(B-5-2)1ddd	472	---do----	-----do------	Delta	64,000	-----------	Do.
5	6-19-46	WD	(B-5-2)12aab	507	---do----	-----do------	---do--	84,000	-----------	Do.
6	12-18-52	WD	(B-5-1)36bbb-1 [3]	217	---do----	Water table	-------	30,000	-----------	U.S. Bur. Reclamation.
7	4-27-53	WD	(B-4-2)12bbb-1	774	---do----	Artesian	Delta	190,000	7.9×10^{-4}	Do.
8	8- 7-53	KF	(B-3-1)1bbc-1	300	---do----	Water table	-------	40,000	-----------	Do.
9	10-14-53	WD	(B-4-1)19daa-1	616	---do----	Artesian	Delta	110,000	1.5×10^{-3}	Do.
10	10-22-53	NO	(B-7-1)33bac-5	252	Flowing	-----do------	-------	4,000	2.5×10^{-4}	Do.
11	11- 4-53	NO	(B-7-1)29cdb-2	165	---do----	-----do------	-------	5,000	-----------	Do.
12	11-30-53	WD	(B-5-1)27dcc-1 [4]	350	Pumped	-----do------	-------	110,000	-----------	Do.
13	12-29-53	WD	(B-5-1)27dcc-2 [5]	115	---do----	Water table	-------	40,000	-----------	Do.
14	4- 6-54	OP	(B-6-2)26ada-1 [6]	600	Flowing	Artesian	-------	15,000	3.9×10^{-4}	Do.
15	12- 8-55	WD	(B-5-2)13dad	514	Pumped	-----do------	Delta	95,000	-----------	Do.
16	12-12-55	WD	(B-5-2)25bcb-2	704	---do----	-----do------	---do--	25,000	-----------	Do.
17	12-13-55	WD	(B-5-2)25bbc	505	---do----	-----do------	---do--	70,000	-----------	Do.
18	12-15-55	KF	(B-4-1)35cdb-1	260	---do----	-----do------	-------	2,000	-----------	Do.
19	1- 9-56	WD	(B-4-2)2dad	675	---do----	-----do------	Delta	110,000	6.6×10^{-5}	Do.
20	2- 8-56	WD	(B-5-1)17cbd-1	550	---do----	-----do------	---do--	120,000	-----------	Do.

[1] Locations of test wells are shown in figure 12.
[2] KF, Kaysville-Farmington subdistrict; NO, North Ogden subdistrict; OP, Ogden-Plain City subdistrict; WD, Weber Delta subdistrict.
[3] U.S. Bur. of Reclamation test well 1.
[4] U.S. Bur. of Reclamation test well 3A.
[5] U.S. Bur. of Reclamation test well 3B.
[6] U.S. Bur. of Reclamation test well 2.

and Lohman, 1952). The 5 tests by the Geological Survey were made on artesian aquifers using pumped wells.

The tests in the Weber Delta subdistrict (table 8) indicate that aquifers to depths of about 700 feet have fairly large coefficients of transmissibility. Therefore, it is likely that the amount of recharge, rather than the coefficient of transmissibility, will be the limiting factor in ground-water development of the subdistrict.

Outside the Weber Delta subdistrict, it was difficult to find both a suitable discharging well and suitable observation wells at a given location. A few tests made, however, indicate that aquifers in the North Ogden subdistrict have a much lower coefficient of transmissibility than does the Delta aquifer; the aquifers in the Ogden-Plain City subdistrict have a relatively large average coefficient of transmissibility; and the aquifers in the Kaysville-Farmington subdistrict have considerable range in transmissibility.

All 20 aquifer tests were made in the eastern part of the Weber Delta district, where conditions for testing were most favorable. A definite need exists for aquifer tests in the western part of the district, but this area contains few wells suitable for testing. The wells in the western part of the district are almost all of small diameter; they are used mainly for domestic purposes at individual homes; and they were all flowing during the period 1953–56. Many well owners refused to permit their wells to be closed, because they cannot be without water for extended periods of time and because sand enters the wells when flow is restricted.

WELL INTERFERENCE

Well interference is determined by the extent of the cone of depression around a discharging well. In a nonartesian aquifer, a local cone of depression develops in the water table as the aquifer becomes dewatered in the immediate vicinity of a discharging well. The point of greatest depression is at the well, which is the axis of an inverted cone, and the base of the cone is the surface of the water table. Under artesian conditions, the cone of pressure relief that develops around a pumping or flowing well differs from the cone of depression of the unconfined aquifer in that the artesian aquifer is not actually being dewatered. The cone of pressure relief is imaginary, but it is similar in shape to the cone of depression. That is, the pressure reduction is greatest at the well, becoming less with increasing distance from the well.

The rates at which the cones develop and spread are related to the fundamental difference between water-table and artesian conditions. Under water-table conditions, the cone develops slowly because considerable water must drain by gravity from the pore spaces in the aquifer in order that a cone of depression may form. Under artesian conditions, the cone of pressure relief spreads much more rapidly and over a greater area than does the water-table cone.

The reason for the widespread and rapid effect of pressure relief in an artesian aquifer is found in one of the fundamental principles of the behavior of a hydrostatic system. In an ideal case, where pressure is applied to—or removed from—any point in a confined body of fluid, the pressure, or release of pressure, becomes immediately effective at all other points in the fluid body. The artesian aquifer constitutes such a confined body in that the water is the fluid, and semipermeable layers above and below the aquifer confine the water. The artesian aquifer differs from the ideal case, however, in two important respects. The gravel and sand composing the aquifer offer frictional resistance throughout the system, and the system is not completely confined because the layers of silt and clay that lie above and below the aquifer are not entirely impermeable. Furthermore, the system must be effectively open at the upper end, else recharge could not occur.

The "open-end" system is comparable to a city water-supply system where the reservoir—or municipal standpipe—provides a body of water that both supplies the system and, being elevated, causes pressure to form in the distribution pipelines. In the Weber Delta district artesian system, the water in the recharge areas (the "reservoir" of the analogy) near the mountains is at higher elevation than the water in the aquifer (the "pipeline"), as the aquifers dip deeper below the land surface progressively from the mountains toward the lake.

An artesian system rapidly (in theory instantaneously) shows the effect of changing pressure. Although the effect is widespread, it decreases sharply with distance from the discharging well and, therefore, cannot be observed throughout a large artesian aquifer. Nevertheless, the release of pressure that occurs when any well is allowed to flow affects every part of the artesian aquifer, even though the effect at some distance is too slight to be measured.

During 9 of the 20 aquifer tests made in the Weber Delta district, measurable effects were observed in observation wells. The maximum distance over which effects were observed was 3.2 miles (fig. 12). Of course, if the tests had been longer or the rate of pumping greater, the area affected probably would have been larger. During four tests, water levels in the observation wells were not affected, perhaps because the discharging wells were not pumped long enough, or because the discharging wells and the observation wells were in different aquifers. No observation wells were available during 7 of the 20 tests.

MOVEMENT

DIRECTION

Ground water in the aquifers of the Weber Delta district moves down gradient in response to the influence of gravity. The direction of movement, in general, is westward, from recharge areas near the Wasatch Range toward Great Salt Lake. The pattern of movement is shown by the piezometric-surface map (pl. 9). This map was prepared on the basis of water-level measurements from wells less than 400 feet deep and from wells from 400–700 feet deep. The pressures in the aquifers in the district vary, usually increasing with depth; therefore, plate 9, which was prepared by grouping water levels from wells chosen on the basis of depth rather than aquifer, is greatly generalized and does not portray conditions in any one aquifer. No interpretations should be made that involve any of the numerous small irregularities in the two piezometric surfaces as drawn, and calculations made using the hydraulic gradients shown on the map are at most approximate.

Both the shallower and the deeper aquifers show generally similar configurations of the piezometric surface, although the deeper aquifers provide a more varied pattern. The most significant feature of the map is the shape of the piezometric surface in the Weber Delta subdistrict. Here the contours bulge far westward and are widely spaced, indicating considerable recharge—much of it presumably from the Weber River—and suggesting that materials of the Delta and Sunset aquifers are highly permeable.

Few wells are in the northern part of T. 7 N., and little is known about the movement of ground water in the area. The piezometric surface has a steep gradient in the North Ogden subdistrict, in the southwest corner of T. 7 N., R. 1 W. The steepness may result from the slow movement of water through the relatively impermeable clay that underlies the subdistrict (pls. 2, 3). The subdistrict is unique in that wells flow at altitudes greater than 4,300 feet, whereas elsewhere in the Weber Delta district, the 4,300-foot topographic contour marks the approximate upper limit of flowing wells. This suggests that the North Ogden subdistrict may be hydraulically separated from adjacent areas on the west and southwest, by extensive clay deposits.

In the eastern part of the Ogden-Plain City subdistrict, opposite the mouth of Ogden Canyon, contours showing the piezometric surface in the shallower aquifers bend toward the mountain (pl. 9). This suggests that the Ogden River supplies little recharge to the ground-water aquifers. This suggestion is substantiated by the subsurface lithofacies map (pl. 2) which shows that in the zone extending from the surface to 200 feet the material near the mouth of Ogden Canyon is mostly fine grained and by seepage measurements in the Ogden River which show that, at periods of low flow, the river does not lose much water to its channel (p. 41).

The map (pl. 9) includes contours on the perched water table underlying the Weber River flood plain in the eastern part of T. 5 N., R. 1 W. (p. 41). These contours indicate that in this area the water table slopes generally eastward, opposite to the westward gradient found in aquifers elsewhere in the Weber Delta district.

VOLUME OF WATER MOVING THROUGH THE WEBER DELTA SUBDISTRICT

Calculations based on permeability and hydraulic gradient indicate that in the Weber Delta subdistrict about 40,000 acre-feet of ground water annually flows through the section between the surface and a depth of 1,300 feet. Some of this water is discharged by wells in the subdistrict, but probably about 20,000 acre-feet continues westward toward the lake. These calculations are based on several assumptions, but the results seem to be of the correct order of magnitude. Aquifer characteristics in other parts of the Weber Delta district are too little known to permit a calculation of the volume of water in motion.

The following method was used in calculating the underflow. The permeabilities of various aquifers in the area were calculated from the results of 13 aquifer tests (p. 52). The transmissibility determined from each test was assumed to be attributable to the total thickness of sand and gravel, as obtained from the driller's well log, between the first clay layer above the perforated zone and the first clay layer below the perforated zone. The transmissibility from each test was divided by this total estimated effective thickness to get the permeability. Then the permeabilities were plotted against the assumed grain size of the predominant

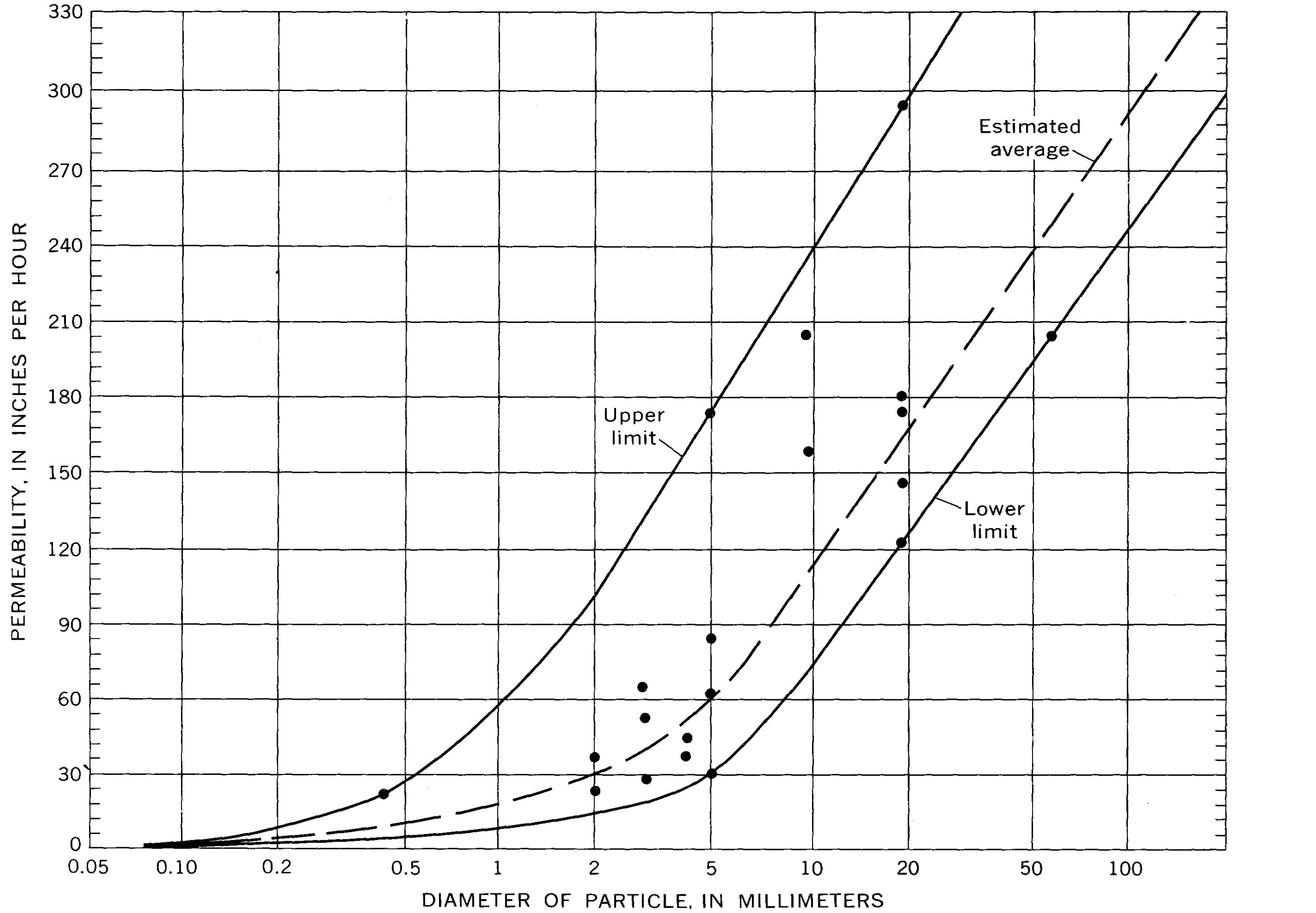


FIGURE 13.—Relation between permeability and assumed grain size.

material of the corresponding perforated zones (fig. 13), and a curve was drawn showing the estimated average relationship between assumed grain size and permeability. The values shown below were then taken from the intersection of the estimated average curve and the median-size values for each grain-size class. The terms used by the drillers were assumed to be approximately equivalent to the terms used in the U.S. Bureau of Reclamation classification.

Predominant material (from well logs)	Grain size [1]	Estimated permeability	
		Gal/ft ^{2}/day	In/hr
Cobbles	127	4,580	306
Coarse gravel	38.1	3,230	216
Gravel	19.1	2,420	162
Fine gravel	9.52	1,620	108
Coarse sand	3	670	45
Medium sand	.9	300	20
Sand (undifferentiated)	.6	209	14
Fine sand	.18	60	4

[1] Median-size values for each grain-size class from classification of the U.S. Bur. of Reclamation; assumed to be the median size for material described in well logs.

The total thickness of each class of sand and gravel was determined for each well from the log of the well. A transmissibility was then determined for each class by multiplying the thickness of the class and the corresponding permeability estimated above. The total transmissibility for the full thickness of sand and gravel between the datum of 4,300 feet and the bottom of the well was then determined by adding the calculated transmissibilities of the various classes of material. This value then was arbitrarily used to obtain the transmissibility of the section between the bottom of the well and the altitude of 3,000 feet. The two values of transmissibility were added to produce a transmissibility for the full 1,300-foot section. Projection of the values of transmissibility from the tested wells to the entire thickness of 1,300 feet used in the calculation does involve a sweeping generalization. The records of a few deep test wells drilled by the Bureau of Reclamation and the results of seismic surveys, however, indicate that similar alternating beds of coarse and fine material persist to, and below, the altitude of 3,000 feet. This test drilling also indicated that conditions may be favorable for future development of ground water to depths of 1,300 feet below the land surface.

A line of reference was selected for the calculation of underflow through the Weber Delta subdistrict. This reference line was drawn through most of the wells used in the aquifer tests, hence across the area where aquifer characteristics are best known. The hydraulic gradient in the Delta aquifer was determined for segments of the reference line using periodic water-level measurements made in 1960 and 1961 in wells tapping the Delta aquifer. The slopes of the water surfaces are generally similar in the Sunset and Delta aquifers, and the configuration of the piezometric surface of each aquifer is also similar. Applying the hydraulic gradient, which was determined by using wells in the Delta aquifer, to the entire section, including the Sunset aquifer and zones below the Delta aquifer, probably does not introduce a serious error into the calculations. The line of reference and the gradient for March 1960, a typical hydraulic gradient in the Delta aquifer, are shown on plate 10. The gradients for 1954 were estimated from the 1960–61 data. The gradients shown on the piezometric surface maps (pl. 9) were not used because the 1960–61 data were more complete along the line of reference and because the data used to prepare plate 9 were not differentiated according to aquifers.

The volume of water moving under each segment of the line of reference on plate 10 was calculated by using (1) the observed hydraulic gradient and (2) the appropriate transmissibility calculated for the segment. The calculations were made using the general equation:

where

$Q = TIL$

Q = Volume of water in gallons per day.

T = Transmissibility in gallons per day per foot.

I = Hydraulic gradient in feet per mile.

L = Length of the line segment in miles.

The results of the calculations are summarized in the following table. In the summary, the amount of underflow in gallons per day was converted to acre-feet per year, the total underflow past the line of reference was obtained by adding the underflows for the segments, and the weighted average gradient of the entire line of reference was used instead of the gradient for each segment.

Records of well discharge (table 7) show that about 3,000 acre-feet per year is pumped from

Year	Month	Weighted-average gradient (feet per mile)	Calculated annual flow (acre-feet)
1961	February	2.34	28,900
1960	March	2.82	34,700
	June	3.22	39,600
	September	2.01	34,700
	December	2.87	35,400
1954	March	3.64	44,900
	June	2.87	35,400
	September	2.82	34,800
	December	2.55	31,400
Average			36,000

wells upgradient from the line of reference, and about 5,000 acre-feet is pumped in the vicinity of the reference line. In addition, about 12,000 acre-feet of water is discharged annually from flowing wells downgradient from the reference line.

The 3,000 acre-feet pumped east of the reference line was added to the 36,000 acre-feet of water moving past the line, to derive a total of about 39,000 acre-feet that is calculated to move each year beneath the Weber Delta subdistrict. The 3,000 acre-feet withdrawn, however, does not reach the line of reference along which the calculation was made.

The total amount of water that moves westward in the Weber Delta subdistrict past the areas of withdrawal by wells and is discharged by upward leakage and evapotranspiration and by seepage into Great Salt Lake is about 19,000 acre-feet. This value was obtained by subtracting the total withdrawal of 20,000 acre-feet from wells downgradient from the reference line from the total of 39,000 acre-feet moving through the subdistrict.

The amount calculated to move through the subdistrict, however, may be less than the actual amount. Many of the wells measured to obtain the hydraulic gradient are within the areas of interference of the pumped wells. Because most of these pumped wells are on or upgradient from the reference line, the hydraulic gradient between the areas of influence of the pumped wells may actually be steeper than the gradient shown on plate 10 and, therefore, the total discharge may be greater than 39,000 acre-feet. If the actual underflow is greater, then the actual discharge by evapotranspiration and seepage into the lake will be greater by the same amount. Perhaps 40,000 acre-feet and 20,000 acre-feet are reasonable estimates of the total underflow through, and the amount of water moving out, of the subdistrict each year, respectively.

LEAKAGE INTO GREAT SALT LAKE

The water budget (table 4) for the entire Weber Delta district shows an estimate of 20,000 acre-feet of unidentified discharge, some part of which is assumed to be direct leakage into Great Salt Lake. This estimate is based on the calculated difference between volume of water entering the district and discharge from all sources evaluated during the study and is equal to the 20,000 acre-feet of water calculated to be moving out of the Weber Delta subdistrict. Although the equivalence of these estimates is fortuitous, it indicates that they are of the correct order of magnitude. It was not possible to measure directly the actual volume of water leaking into the lake by diffuse seepage or through undetected sublacustrine orifices. Search during the investigation did not succeed in detecting any springs of major size.

Peck (1954) reported that the annual average "change of volume (inflow)" of Great Salt Lake during the period 1910–50 was about 2.6 million acre-feet. Much of the change observed can be accounted for by variations in streamflow into the lake. Peck's data show, however, that fluctuations in precipitation in the drainage areas tributary to Great Salt Lake have a carryover effect recognizable over a period of about 4 years. The carryover effect according to Peck, results from discharge from deep artesian aquifers into the lake. The carryover effects (Peck, 1954, fig. 6) are:

	Volume change
Current year	No effect.
Previous year:	
1st	Do.
2d	0.01
3d	.03
4th	.1
5th	< .01
Total carryover effect	.14

Using the total figure of 0.14 of volume change, it is calculated that of the total annual average volume change of 2.6 million acre-feet in the lake, 360,000 acre-feet may be leakage from deeper aquifers. The areas on the southern, eastern, and northeastern sides of Great Salt Lake contribute most of the surface water, and probably most of the ground-water inflow to the lake; the low arid western side of the lake probably contributes little surface or subsurface water. Because the Weber Delta district is about 20 percent of the periphery of the lake that is believed to contribute most of the underflow, it probably contributes about 20 percent of the total underflow to the lake, or about 70,000 acre-feet per year. Although this estimate is more than three times the estimate of 20,000 acre-feet from the water budget (table 4), it is of the same general order of magnitude.

Calculations in the section on evaporation and evapotranspiration (p. 70) indicate that some 6,000 acre-feet of water annually might be moving upward through clay underlying the salt barrens above the 1952 shoreline of Great Salt Lake. During periods when the lake level is high and the salt barrens flooded, this 6,000 acre-feet would be included in the total estimate of from 20,000 to 70,000 acre-feet per year of ground-water inflow; at other times, the 6,000 acre-feet would evaporate directly from the barrens and contribute nothing to the lake.

CHEMICAL QUALITY

COMPILATION AND ANALYSIS OF DATA

The chemical quality of ground and surface water in the Weber Delta district is known from analyses of more than 500 samples. When the present study began in 1953, 67 analyses had been made by the U.S. Geological Survey, the Utah State Health Department, and others. In addition, several partial determinations, principally of chloride, were available for water samples obtained during the drilling of the Ogden City well at 23d Street and Van Buren Avenue and for samples from a test well at Utah General Depot. During the period March 1953 to March 1956, the U.S. Bureau of Reclamation analyzed 426 samples of water from the Weber Delta district and the Geological Survey analyzed 12 additional samples. Chemical analyses of representative ground and surface waters in the district are given in table 9.

A modification of the trilinear-diagram method of analyzing chemical-quality of water data (Piper, 1944) was used to interpret chemical relationships (pl. 11). Graphs were made to show changes in chemical quality of water with distance from an assumed source of recharge and with increasing depth. Contour maps were prepared of the content of specific dissolved constituents, and the results of the entire study of quality of water were summarized on a map (fig. 14) showing areas of different water types. Individual analyses show clearly the mingling of waters from adjacent areas of different types; therefore, the boundary lines drawn in figure 14 do not represent sharp boundaries.

Results of the chemical analyses are expressed in two ways in this report. Where no chemical calculations or quantitative comparisons are made, such as in table 9, results are given in parts per million. Where chemical computations have been made, or where quantitative comparisons are in-

TABLE 9.—*Chemical analyses of representative samples of ground and surface water in the Weber Delta district*

[Analyses of U. S. Bur. of Reclamation, unless otherwise noted]

Well No. or location	Subdistrict[1]	Depth of well (feet)	Date of collection	Temperature (°F)	Parts per million														Percent sodium	Sodium adsorption ratio (SAR)	Specific conductance (micromhos/cm at 25°C)	pH
					Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Na + K: Sodium (Na)	Na + K: Potassium (K)	Bicarbonate (HCO_3)	Carbonate (CO_3)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Boron (B)	Dissolved solids[2]	Hardness as $CaCO_3$	Alkalinity as $CaCO_3$				
Samples from representative wells																						
(B-3-1) 2dcc-2	K	386	7- 9-54	--	21	39	16	35	2.3	219	----	24	33	----	-----	266	162	-----	32	-----	482	---
14abb-3	K	640	7- 9-54	68	27	17	4.6	88	2.0	240	6.3	4.3	30	0.8	0.22	282	61	207	75	4.8	486	8.4
(B-4-1)9cbb-1	D	25	9-15-53	--	36	61	76	139	16	550	28	155	65	54	.43	891	462	497	39	2.8	1,410	8.2
20cbb-1	D	572	3- 9-54	60	22	33	7.1	13	2.0	120	16	--------	14	----	-----	162	112	125	--	.53	297	8.5
(B-4-2)lacd 1	D	730	11- 8-54	56	18	65	18	22	4.7	292	5.1	22	27	.5	0	308	237	248	16	.64	557	8.3
16add-4	D	180	11-25-55	--	----	13	10	160	12	476	----	--------	33	----	-----	478	72	-----	80	-----	803	---
20daa-1	D	685	2-14-56	--	----	35	12	19	3.1	203	----	--------	17	----	-----	203	137	-----	23	-----	353	---
26aaa-2	D	597	11- 5-54	58	21	24	7.8	17	3.1	137	2.1	1.4	12	.1	0	150	92	116	28	.77	265	8.4
(B-5-1) 27abd-1	D	71	3-16-54	56	1.9	12	4.8	12	2.7	68	0	2.9	15	6.2	.15	92	50	56	32	.73	180	8.0
27dcc-1	D	350	11-30-53	51	13	63	15	13	1.2	242	0	26	16	3.0	.05	252	219	199	12	.38	467	7.9
29bdc-1	D	627	9-15-53	56		30	19	23	2.3	191	4.5	36	19	----	-----	-------	155	164	24	.81	439	8.2
(B-5-2) 3ddd-1	D	70	4-11-55	--	----	99	61	48	18	650	----	--------	73	----	-----	642	497	-----	17	-----	1,130	---
6bdd-1	D	304	3- 5-54	56	32	37	14	36	8.2	239	7.8	0	20	.8	0	276	149	209	33	1.3	459	8.1
7dcb-1	D	688	3- 5-54	60	20	38	11	19	2.7	190	0	--------	18	----	0	203	141	156	22	.70	382	8.0
16ddc-1	D	750	8-30-56	--	----	44	13	13	1.6	197	----	2.9	21	----	-----	233	163	-----	15	-----	402	---
33ddc-1	D	808	3- 9-54	58	17	55	14	17	2.7	228	4.2	18	24	1.3	.01	247	197	194	15	.53	466	8.1
(B-5-3) 15dda-1	D	649	9-15-53	72	25	18	6.2	56	3.1	178	11	1.0	25	2.4	.31	226	71	164	62	2.9	386	8.5
(B-6-1) 5dad-1[3]	O	345	5-13-43	53	----	22	15	[4] 112		404	0	0	19	.2	.55	[5] 368	116	331	68	4.5	642	---
5ddd-1[3]	O	265	5-14-43	52	----	95	303	[4] 3,230		1,270	0	1,000	4,550	----	.18	[5] 9,800	1,480	1,040	83	36	15,600	---
6caa-1[3]	N	640	4-14-43	63	----	32	10	[4] 14		146	12	4.0	6.0	.3	-----	150	121	139	20	.55	290	---
8dbb-2	O	142	2-17-55	--	----	57	16	328	36	252	----	16	526	----	-----	1,110	207	-----	74	-----	2,100	---
8dbd-1	O	145	3- 3-54	--	19	32	12	152	20	324	7	1.4	148	.1	-----	548	130	-----	68	-----	1,000	---
29ccc[3]	O	755	5-13-43	59	16	232	57	363	35	118	0	6.6	1,100	.5	.37	1,990	814	97	48	5.6	3,490	7.5
(B-6-2) 1ada-1	N	639	11- 4-54	62	20	33	11	10	1.6	153	6	.5	11	1.5	0	155	127	136	15	.39	298	8.5
5acb-2	O	850	3- 4-54	58	25	17	5.2	90	2.3	264	3.6	1.4	30	1.5	.15	306	65	222	74	4.9	507	8.4
10abd-1	O	260	9-15-54	54	29	18	4.5	166	32	300	0	1.0	153	.4	.33	545	64	246	78	9.0	952	7.9
19abd-1	W	300	1-13-55	--	22	23	6.3	48	2.3	193	----	1.9	24	.2	-----	214	85	-----	55	-----	369	---
(B-6-3) 19acc	L	187	9-27-55	--	----	76	14	301	9.8	149	----	1.4	557	----	.23	1,150	246	123	72	8.4	2,060	7.9
23bad-1	W	529	9-15-54	62	25	17	6.3	56	3.5	190	4.5	0	24	.2	.10	212	69	164	63	2.9	389	8.3
25cbb-1	D	330	10- 7-54	62	26	27	6.7	38	2.3	171	9.6	2.9	18	.2	.05	220	96	157	45	1.7	354	8.7
(B-7-1) 30abb-1	N	47	4-21-54	54	22	84	18	19	.8	348	0	30	15	----	-----	361	286	286	13	.49	604	8.2
31bdb-1	N	482	3- 2-54	50	21	35	8.1	11	.8	150	6.3	4.8	9.6	1.3	.03	177	105	133	19	.44	296	8.3
32cdd-2	N	310	5-27-54	56	18	36	7.3	9.7	.8	144	7.8	6.7	7.1	----	0	158	120	131	15	.38	280	8.3
(B-7-2) 26dac	N	510	3- 3-54	62	53	34	7.3	43	3.9	261	3.9	2.9	7.1	.2	.11	271	115	221	44	1.7	404	8.2
36cca-2	O	22	5-27-54	54	23	64	67	213	18	497	70	68	237	14	.35	1,010	435	523	50	4.5	1,766	8.1
(B-7-3) 33cdd	W	399	5-26-54	70	27	6.8	2.9	139	9.0	336	21	4.3	31	.1	.38	413	29	310	88	11	653	8.4
35 add-1	O	485	5-26-54	62	28	18	9.3	234	13	145	14	4.3	334	.6	.27	700	83	143	84	11	1,360	7.8
Samples from sources other than wells																						
Great Salt Lake surface[3]	----	---	10-13-54	--	6,5	407	6,940	86,500	4,070	263	----	17,700	143,000	85	24	268,000	29,800	216	85	220	165,000	7.4
Weber River[6] (B-5-1) 25d	----	---	4- 53	--	----	43	12	14	2.0	158	8	23	18	----	.1	231	157	143	16	.49	371	8.5
	----	---	8-13-54	--	----	64	14	14	2.0	341	11	28	18	----	-----	249	-----	-----	12	-----	453	---
	----	---	2-17-56	--	----	75	20	20	2.7	227	26	46	28	----	.17	345	269	273	13	.53	-------	8.3
Ogden River at Ogden	----	---	5-25-56	--	----	34	7.2	7.6	1.2	105	12	11	12	----	-----	159	115	106	12	.31	254	8.4
Farmington Creek near Farmington	----	---	7- 9-54	68	----	11	3.7	7.4	1.1	47	2	9.1	5.3	----	-----	68	42	46	27	.48	124	8.4
(B-5-1) 25d[7]	D	---	12- 9-53	--	9.4	15	2.7	8.0	1.2	52	0	15	7.4	1.7	-----	77	48	43	26	1.0	147	8.3
(B-6-1) 23dcb[3,7]	O	---	4-27-43	--	----	355	11	[4] 3,000		208	----	102	5,080	----	-----	[5] 8,650	931	-----	88	-----	14,700	---
(B-7-1) 22abc[7]	N	---	4- 5-55	50	----	33	11	4.6	.8	137	0	18	5.3	----	.07	136	128	112	7	1.6	263	8.0
Gateway Tunnel, Sta. 479+30 (A-5-1) 28	----	---	1-28-54	54	11	28	7.3	12	1.2	112	2.1	12	14	4.9	.22	142	100	96	20	.52	261	8.3
Gateway Tunnel, Sta. 608+66 (A-5-1) 31	----	---	11- 8-54	54	11	17	3.1	7.6	1.2	57	3.3	13	6.4	1.3	0	91	55	52	23	.44	159	8.3

[1] Subdistricts: D, Weber Delta; K, Kaysville-Farmington; L, Little Mountain; N, North Ogden; O, Ogden-Plain City; W, West Warren.
[2] Residue on evaporation at 180°C.
[3] Analysis by U.S. Geological Survey.
[4] Sodium and potassium calculated as sodium (Na.)
[5] Calculated from determined constituents.
[6] Average of several samples, prorated in relation to volume of flow.
[7] Spring.

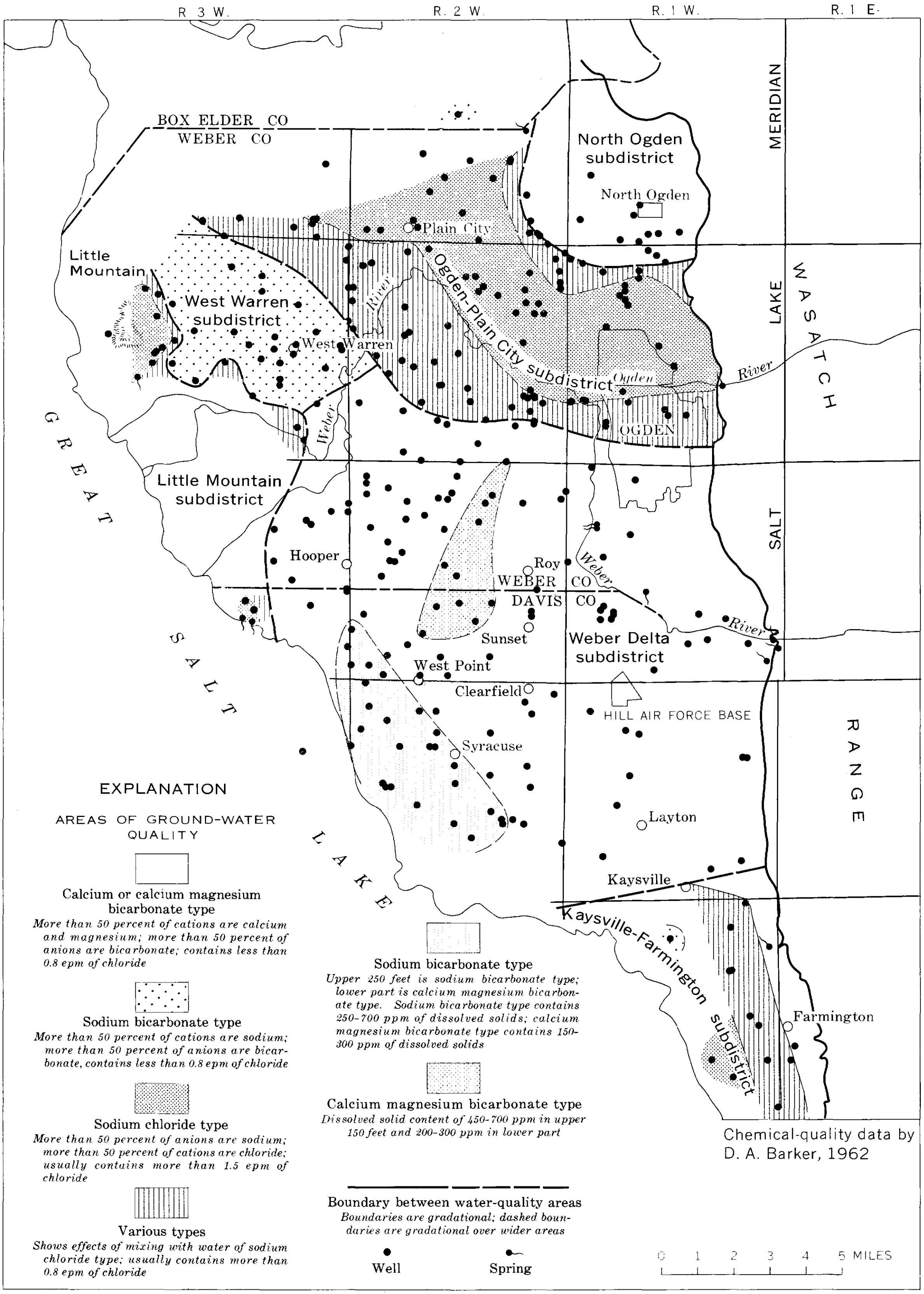


FIGURE 14.—Map showing chemical character of ground water in the Weber Delta district.

tended, such as in figure 15, results are given as equivalents per million.

CHEMICAL QUALITY OF GROUND WATER BY SUBDISTRICTS

Three principal chemical types of ground water were recognized in the Weber Delta district—calcium magnesium bicarbonate, sodium bicarbonate, and sodium chloride. The calcium magnesium bicarbonate and the sodium chloride types are considered to be original types. The sodium bicarbonate type presumably results from cation exchange between the calcium magnesium bicarbonate type water and the clays that underlie much of the district. The distribution of these main chemical types of ground water and border areas where adjacent types apparently intermingle is shown in figure 14. Quality of ground water was the major factor in determining the boundaries of the subdistricts of the Weber Delta district (fig. 10), and in general the subdistricts coincide with areas that yield one chemical type of water.

Electric-log data (p. 26) suggest that below 1,300 feet in the Weber Delta subdistrict and below 800–1,100 feet in the Kaysville-Farmington subdistrict, water contains so much dissolved solids that it cannot be used for most purposes.

WEBER DELTA SUBDISTRICT

The water in the Weber Delta subdistrict is mostly of the calcium magnesium bicarbonate type, but three areas within the subdistrict contain water of a slightly different quality (fig. 14). Most of the water has a fairly low concentration of dissolved solids, and it is suitable for most uses without treatment. Many individuals maintain domestic water softeners, however, and in a few localities the iron concentration is high enough to result in a precipitate which colors the water red.

In most of the subdistrict, the quality of ground water indicates that it was derived by recharge from the Weber River and the mountain front. The concentrations of dissolved solids and individual constituents in the ground water are similar to the corresponding concentrations determined from samples taken from the Weber River at various times of the year and at various stages of flow. (See wells (B–5–1)27dcc–1 and (B–5–2)33ddc and analyses for the Weber River in table 9.) Locally, however, the concentration of dissolved solids in the ground water exceeds or is less than that characteristic of water from the Weber River.

An area just west of the city of Roy contains water in a shallow artesian aquifer that is different in chemical quality from the subdistrict as a whole (fig. 14). The shallow aquifer extends only to depths of about 150 feet (p. 37). Waters in the shallow aquifer and in the deeper artesian aquifers are of the calcium magnesium bicarbonate type; but the water in the shallow aquifer contains from 450 to 700 ppm of dissolved solids (see well (B–5–2)3ddd–1, table 9), whereas the water in the deeper aquifers contains from 200 to 300 ppm of dissolved solids (see well (B–5–2)16ddc–1, table 9). The writers conclude that the difference in degree of mineralization occurs because the recharge area of the shallow aquifer is an area of irrigation where the surficial material is fine grained, whereas the recharge area of the deeper aquifers probably is nearer the mountain front and the surficial material is largely coarse grained and uncultivated.

A few of the shallow wells in the Roy area yield water that is not suitable for irrigation because of its high sodium content. Otherwise, both the shallow and deep wells in the area yield water that is suitable for most uses.

In an area near Syracuse, in the west half of T. 4 N., R. 2 W., water in aquifers extending to about 250 feet below the land surface differs in chemical quality from water in deeper aquifers (fig. 14), The water from the shallow aquifers in the Syracuse area is of the sodium bicarbonate type and contains from 250 to 700 ppm of dissolved solids (see well (B–4–2)16add–4, table 9), whereas water from the deeper aquifers is of the calcium magnesium bicarbonate type and contains from 150 to 300 ppm of dissolved solids (see well (B–4–2)20daa–1, table 9).

Pressure relations in the water-bearing zones indicate that the shallow and deep aquifers are connected (p. 37), and the differences in water quality apparently result from cation exchange during upward leakage from the deeper to the shallower zones in the system. Accompanying this exchange is an increase in total mineralization.

Wells from both aquifers in the Syracuse area yield water that is suitable for most uses. Many shallow wells, however, yield sodium bicarbonate type water that is not suitable for irrigation. (See well (B–4–2)16add–4, table 9.)

A narrow area extending from the mountain front westward through Layton contains water that has a slightly lower dissolved-solids content than does the water in the remainder of the Weber Delta subdistrict. The Layton area is not differentiated in figure 14; but its southern boundary corresponds to the southern boundary of the Weber

Delta subdistrict, and its northern boundary is approximately parallel with, and 3–4 miles north of, the southern boundary.

In this area, wells yield water which contains concentrations of dissolved solids and chloride that are less than those characteristic of water from the Weber River (see well (B-4-1)20cbb-1, table 9). The water is a dilute calcium magnesium bicarbonate type, similar to water from mountain streams and springs and to water from the Gateway Tunnel. It is probable, therefore, that recharge from mountain-front sources supplies the water to the aquifers in the Layton area.

OGDEN-PLAIN CITY SUBDISTRICT

The ground water in the Ogden-Plain City subdistrict ranges more widely in chemical type than does the ground water in any of the other subdistricts. Separate strata in a well may yield water of different chemical composition. For example, in well (B-6-1)7cca-1, gravel encountered from 195–238 feet yielded a relatively large amount of water containing 2,510 ppm chloride; a zone from 450–480 feet yielded a small amount of water containing 360 ppm chloride; and a stratum of large quartzite boulders and coarse gravel between 743 and 768 feet yielded water containing 2,540 ppm chloride.

Wells of closely equivalent depth within half a mile of one another in the subdistrict commonly yield water of different quality. One well will yield water of a quality generally suitable for domestic use, and another will yield water totally unsuited to domestic, stock, agricultural, or industrial use because of a high concentration of dissolved solids, principally sodium and chloride. (See wells (B-6-1)8dbd-1 and (B-6-1)8dbb-2, table 9.)

The reasons for the variations in quality is not clearly understood. A. M. Piper (oral commun., 1956) suggested that pockets of salty connate water, pans of salt, lenses of heavily salt-impregnated sediments, or all of these may be preserved in the alluvial fill. On the basis of Piper's comments it is tentatively suggested that the complex pattern of chemical quality of ground water results from the unique depositional environment in the subdistrict, relative to the rest of the Weber Delta district. Logs of many wells show that a large proportion of the subsurface material in the Ogden-Plain City and North Ogden subdistricts is clay (pls. 2, 3). This proportion of clay suggests that for a long time there was a bay between Ogden and the Pleasant View salient that was sheltered from the waves and currents of Lake Bonneville and earlier lakes. In the quiet water of this bay, clay was the predominant deposit.

The Pleasant View salient is a mass of rock of Cambrian age (pl. 1) that projects westward from the Wasatch Range. This spur forms the northern boundary of the area of thick clay deposition; the southern edge of the area is coincident with the Ogden River. The inferred bay could have been formed when southward-moving lake currents built a bar south from the salient, almost isolating the bay from the main lake. The delta and alluvial-fan deposits of the Ogden River probably formed the southern edge of the bay. At certain levels of the various lakes, the bar may have completely isolated the bay on the west, and the bay may have partly or completely evaporated, resulting in the deposition of beds of salt. Separate salt beds may have been deposited in small subbasins in the bay. The bar may have been breached periodically by the Ogden River when the river was flowing over the northern part of its fan. The breaching of the bar would have rejoined the bay and the main lake, and the conditions under which salt beds were deposited would temporarily cease to exist.

Salt may have also been furnished to the bay by Utah Hot Springs and El Monte Spring. Utah Hot Springs apparently has discharged into the basin from near the tip of the Pleasant View salient for a long time. Pillars and algal reefs(?) of calcareous tufa are exposed east of, and a few feet to a few hundreds of feet above, the present spring, suggesting that the spring has deposited calcareous material during long time intervals and at various lake stages (Feth, 1955, p. 60). El Monte Spring, in the mouth of Ogden Canyon, may also have been tributary to the ancient bay, although evidence that El Monte Spring existed during Pleistocene time is not so clear as such evidence at Utah Hot Springs. Masses of gravel cemented by calcium carbonate, however, are plastered against the walls of Ogden Canyon as far as three quarters of a mile upstream from the canyon mouth, and they may be erosional remnants of Pleistocene spring deposits. At high lake stages, the lower part of the canyon may have been choked with gravel deposited by the Ogden River, and warm mineralized waters from the hot springs or their earlier equivalents may have permeated these gravels, in part cementing them. The Ogden River then removed most of the gravel in the lower canyon, leaving the present isolated outcrops.

In summary, the depositional environment in the area between Ogden and the Pleasant View salient, including much of the Ogden-Plain City and North Ogden subdistricts, was probably varied, but it was generally favorable for the deposition of fine-grained material and, at times, perhaps local beds of salt. This variation in the deposits of the area is probably the cause of the complex pattern of occurrence of fresh and salty water. The local salt beds have been buried by younger sediments and now probably form lenses of high salt content in the general mass of nonsaline or less-saline deposits. The saline water in the area is probably either connate water of the ancient bay trapped in the fine-grained material or water that has moved through local beds of salt and has become mineralized by dissolving some of the salt. Therefore, nearby wells of the same depth could readily penetrate material of different salt content and yield water of different chemical composition.

NORTH OGDEN SUBDISTRICT

Some of the least mineralized water in the entire Weber Delta district is found in the North Ogden subdistrict, and the preponderance of wells yield water that can be used for most purposes without treatment. (See fig. 14 and wells in T. 7 N., R. 1 W., table 9.) Recharge to aquifers underlying the subdistrict probably comes from the bedrock of the Wasatch Range and by infiltration from streams which discharge across the highly permeable zone adjacent to the mountains. The deposits under the southwestern part of the North Ogden subdistrict contain a large proportion of clay (pls. 2, 3). This clay also underlies much of the Ogden-Plain City subdistrict, as discussed in the preceding section. Any connate water that was trapped in the clay in the North Ogden subdistrict evidently has been displaced by fresh water moving southwestward from the mountain front.

The boundary area between the North Ogden and Ogden-Plain City subdistricts contains water which is of various types but which generally contains more than 30 ppm of chloride (fig. 14). There is an indication that water in the deep aquifers is of the calcium magnesium bicarbonate type, whereas water in the shallow aquifers is of the sodium chloride type. In the southwestern part of the North Ogden subdistrict, well logs show that the upper 400–500 feet of material is silt and clay with a few stringers of intercalated sand. Logs of wells that penetrate below this zone indicate that it is underlain by a zone of coarse sand and gravel. Apparently in the boundary area, fresh water has displaced mineralized water in the deep aquifers, but the shallow aquifers have not been flushed because they are less permeable.

WEST WARREN SUBDISTRICT

In the West Warren subdistrict, wells of all depths yield water of the sodium bicarbonate type (fig. 14). Many samples of water had concentrations of dissolved solids and other constituents similar to those of water from the Weber River, the inferred source of much of the water in the subdistrict. For example, the chloride-ion concentrations fall within the range of concentrations of Weber River water sampled at various seasons and at various stages of flow near the mouth of Weber Canyon. (See wells (B–6–3)23bad–1 and (B–6–2)19abd–1 and analyses of water from the Weber River, table 9.) For these reasons, and for those cited below in the discussion of chemical-quality changes in the subsurface (p. 63), it is concluded that the source of recharge for the ground water in the West Warren subdistrict is water from the Weber River and underflow from the Wasatch Range. The predominance of sodium in the water is due to cation exchange, wherein some of the calcium and magnesium originally present was exchanged for sodium. The less mineralized water in the subdistrict probably originated as recharge from the mountain front rather than from the Weber River.

The ground water in the West Warren subdistrict is suitable for most uses without treatment. However, the water cannot be readily used for irrigation because prolonged use of sodium bicarbonate type water on sodium-rich clay soils might prove detrimental, leading in extreme cases to development of nearly impervious solonetz soils.

LITTLE MOUNTAIN SUBDISTRICT

Sodium and chloride are the dominant chemical constituents in the ground water of the Little Mountain subdistrict, and the water is so highly mineralized that it is used only for stock (fig. 14; well (B–6–3)19acc, table 9). Near the base of Little Mountain a group of mounds yields a small flow of water of the sodium chloride type, and in an embayment west of Little Mountain a well about 55 feet deep discharges salty water. The association of warm saline water with the line of springs on the salt barrens, together with other information presented in the discussion on geologic structure (p. 22), suggests that the saline ground water in the Little Mountain subdistrict rises along a major fault zone from shattered bedrock at depth.

KAYSVILLE-FARMINGTON SUBDISTRICT

The Kaysville-Farmington subdistrict contains water of several types (fig. 14). Close to the mountain front, the water is of the calcium magnesium bicarbonate type, but it contains more chloride than does water from small streams draining the Wasatch front in the subdistrict. (See well (B-3-1)2dcc-2 and sample from Farmington Creek, table 9.) Farther west, the water is of various types, all of which show the effects of mixing with water of the sodium chloride type. It is inferred that small quantities of water with a high chloride content rise along the Wasatch fault zone, move into the aquifers in this area, and mix with water of the calcium magnesium bicarbonate type that has its source of recharge in the mountain front.

Scanty data indicate that the aquifers along the western margin of the subdistrict contain water of the sodium bicarbonate type. This implies that cation exchange takes place within a short distance of the mountain front. The gradient on the piezometric surface (pl. 9) in the subdistrict is far steeper than gradients throughout most of the Weber Delta district. The steeper gradients probably reflect the presence of a large proportion of fine-grained material in the valley fill which impedes the movement of water. Sodium in the fine-grained material probably is exchanged for calcium and magnesium in the water within a short distance from the source of recharge.

Most of the ground water in the subdistrict can be used for most purposes without treatment. In general, water near the mountains is low in dissolved solids. Farther from the mountains the water is soft and suited for domestic use, but it is of sodium bicarbonate type and is generally unsuitable for use in irrigation. Some wells in the Farmington area, especially those 2 miles or more from the mountains, yield water that is unpleasant to the taste because of its high chloride content.

CHEMICAL-QUALITY CHANGES IN THE SUBSURFACE

The map of quality-of-water areas (fig. 14) shows that about 12–15 miles northwest of the assumed area of recharge near the mouth of Weber Canyon, the water type changes from calcium magnesium bicarbonate to sodium bicarbonate. This change is illustrated graphically in figure 15. At the left end of the graph is a series of plots of the content of calcium, sodium, and chloride in water samples taken from the Gateway Tunnel, from mountain springs, and from the Weber River at several times of the year. Points across the graph to the right represent similar plots of chemical-quality data from a series of wells at progressively increasing distances from the assumed area of recharge. The horizontal dashed lines enclose all plots of chloride content and show that the chloride concentration remains within the limits of chloride concentration of the inferred source water, even as far as 21 miles from the source, the maximum distance to which wells were sampled. The stable chloride content indicates that there is no appreciable mixing with water of a sodium chloride type. From about 9–21 miles from the source, the sodium concentration tends to increase and the calcium content to decrease by equivalent amounts, as indicated by the sloping trend lines. The progressive replacement of calcium ions by sodium ions, the volumes of clay present in the area, and the effectiveness of clays as agents in promoting cation exchange all suggest that these changes result from cation exchange.

The average sulfate content of ground water in the Weber Delta district in townships 5–7 decreases westward from the area of recharge and the bicarbonate content generally increases in the same direction (table 9). Renick (1924, p. 668–684) has shown that organic materials in aquifers reduce sulfate and that bicarbonate commonly takes its place. Zones of clay, silt, and sand rich in organic material are common in the sediments underlying the Weber Delta district, and probably reactions similar to those discussed by Renick cause the low sulfate content of some ground-water samples miles from the recharge area. Fetid-odored pyrite-bearing clays have been found in well cutttings at various depths, further indicating the presence of organic matter and reducing environments.

NATURAL RADIOACTIVITY OF GROUND WATER

By A. B. Tanner

As is true of ground water in general, the ground water of the Weber Delta district contains measurable amounts of natural radioactivity, some components of which were determined by airborne radioactivity surveying, by radiochemical analyses, and by a study of the distribution of radon in water from wells and springs.

Anomalous gamma radioactivity of the ground surface in the vicinity of Utah Hot Springs was observed in the course of a survey conducted with airborne scintillation apparatus of the Geological Survey (J. L. Meuschke, written commun., 1960). A radioactive high about 20 times the local background was approximately coextensive with the orifices, hardpan deposits, and runoff ditches associated with the hot springs, and it was caused by

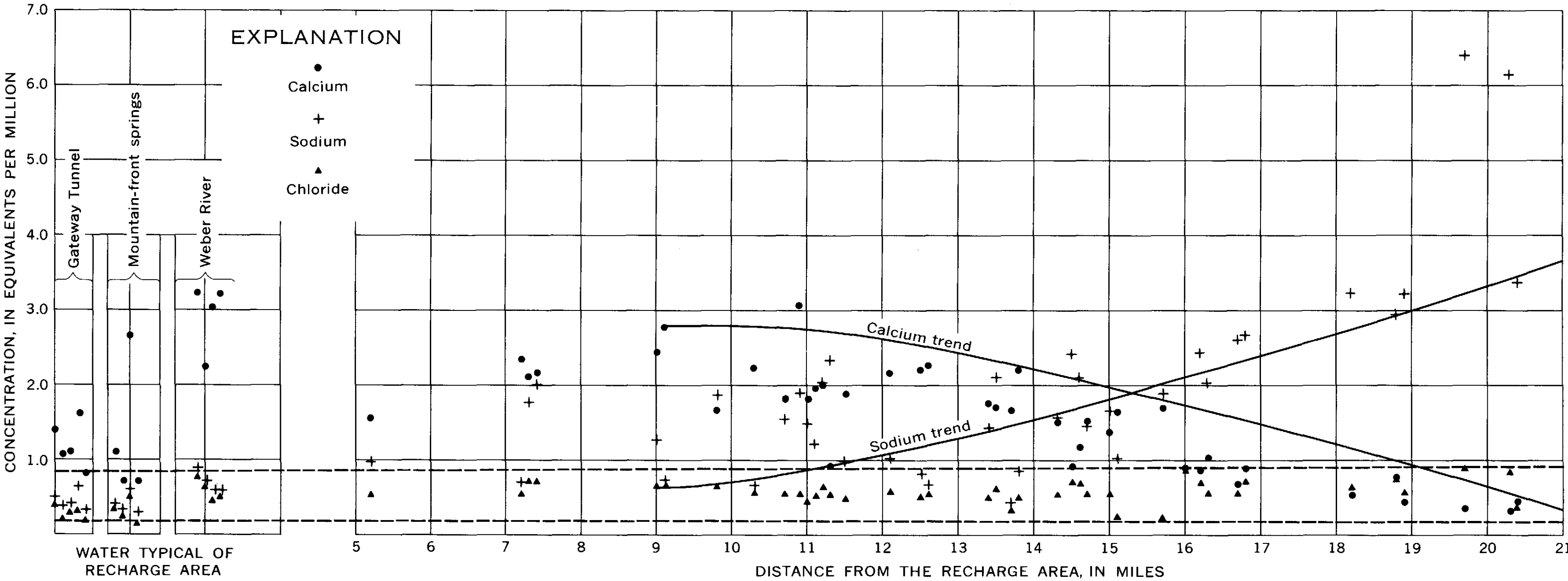


FIGURE 15.—Graph showing progressive cation exchange in ground water at increasing distances from the mouth of Weber Canyon. Each trio of points in a vertical line represents the concentrations in a single water sample. Dashed lines indicate range of chloride-ion concentration in water from recharge area.

the cumulative deposition of radium-226 and its decay products (radon-222, polonium-218, lead-214, bismuth-214, and others) on the surface over which the hot-spring water flows. Chemical and radiochemical analyses of waters from Utah Hot Springs and Hooper Hot Springs (not included in the airborne survey) are shown in table 10.

TABLE 10.—*Chemical and radiochemical analyses of waters from Utah Hot Springs and Hooper Hot Springs*
[Analyses by J. D. Hem, U.S. Geol. Survey]

	Utah Hot Springs, SE¼ sec. 14, T. 7 N., R. 2 W., northernmost orifice of four	Hooper Hot Springs, SW¼ sec. 27, T. 5 N., R. 3. W., easternmost orifice of many
Date sample collected	June 8, 1954	June 20, 1957
Temperature (°F)	134	130
Discharge (gpm)	[1] 15	[1] 5
Specific conductance (micromhos per cm at 25°C)	38,800	14,300
pH	7.0	7.8
Chemical components (ppm):		
Silica (SiO_2)	38	34
Aluminum (Al) (total)	.6	.4
Iron (Fe) (total)	7.6	----
Iron in solution when analyzed	.03	.00
Manganese (Mn) (total)	1.8	1.6
Calcium (Ca)	1,180	519
Magnesium (Mg)	36	85
Sodium (Na)	7,610	2,420
Potassium (K)	1,040	168
Bicarbonate (HCO_3)	198	297
Carbonate (CO_3)	0	0
Sulfate (SO_4)	198	40
Chloride (Cl)	14,400	4,940
Fluoride (F)	2.6	0.9
Nitrate (NO_3)	----	.0
Phosphate	----	.0
Radiochemical data:		
Eh	----	+.198 volt
Beta-gamma activity (micromicrocuries per liter)	1,500	<700
Radium (Ra) (micromicrocuries per liter)	39	100
Uranium (U) (micrograms per liter)	.3	.4

[1] Estimated.

The hot-spring waters are of the sodium chloride type and contain concentrations of radium that are as much as 100 times the normal concentration, less than 1 picocurie per liter, in water from nearby wells in the alluvium. The field relations indicate that the hot-spring waters rise from faults in bedrock.

The distribution of radon in ground water in the Bountiful area south of the Weber Delta district was studied by A. S. Rogers (1955, 1956, and written commun. 1956). He collected about 350 water samples from wells in an area of about 15 square miles and determined their radon concentrations by the method he described in 1958 (Rogers, 1958). Greater radon concentrations were observed in water from wells in thick valley fill in the vicinity of known or inferred faults in bedrock than in water taken from wells distant from the surface projections of the fault zones.

In order to see whether similar results might be obtained in the Weber Delta district, Rogers and H. B. Evans (written commun., 1956) collected water samples from wells in the area southwest and west of the town of North Ogden and determined their radon concentration. The only trend observed was an increase toward the southwest, by about one-half, in the average radon concentration of water from wells near the southern margin of the Pleasant View salient and in the vicinity of projections of fault traces into the area covered by unconsolidated sediments.

The disposition of wells having water of anomalously high radon content in proximity to known or inferred fault zones suggests that the radon is derived from radium-bearing water of the Utah Hot Springs type, rising from the fault zones. However, consideration of the mechanism leading to enrichment of the water in radon and consideration of the physical characteristics of the sediments and the chemical regime in them suggests other sources of the radon. The short (3.8 days) half-life of radon does not permit it to migrate more than a few tens of feet, even at the rather rapid rate of ground-water movement of several feet per day; the radium source of radon, therefore, must be located in the sediments.

The concentrations of radium in the water which recharges the aquifers in the district are far too small to provide the observed concentrations of radon. It must be assumed, therefore, that the radium sources are fixed in the sediments, and that a given radon concentration observed in water from a well is indicative of radium exposed in the sediments in the subsurface probably only a few feet from the well bore. The radium may be fixed either by adsorption on clay or by coprecipitation with another constituent, such as calcium carbonate or hydrated ferric oxide, as a result of chemical reaction.

The radium may have been immobilized on clay in the body of fine-grained material in the valley fill west and southwest of North Ogden (pls. 2, 3). The northern margin of this body of predominantly fine-grained and relatively impermeable material is in the same general area as is the zone of anomalously high radon concentration and inferred or known faults (pl. 1). Assuming that clay in the fine-grained material did immobilize radium, then the slight anomalously high radon concentration observed in the ground water could result whether the water was fault derived or water of lower radium content derived elsewhere.

Chemical reactions leading to coprecipitation of radium with another constituent may be responsible for immobilizing radium in the sediments. In a geologically similar environment in the Bountiful district in Davis County, the pattern of radon concentrations in ground water suggests a relation between radon highs and buried faults (Rogers, 1955, 1956). A study (Tanner, 1964) of the chemical constituents in the water of some wells near Woods Cross in the same district failed to show a definite relation between subsurface faulting and the distribution of radon or radium, but it showed that both calcium carbonate and hydrated ferric oxides are present in excess concentrations in the ground water and should be tending to precipitate in the aquifer. Both constituents tend to immobilize radium and thereby to provide radon sources not directly related to faulting. The question of whether the radon anomalies are linked to subsurface faults thus reduces itself to a question of whether the faults add sufficient calcium, carbonate, or iron to the aquifers to cause supersaturation, and whether radium is available for coprecipitation when it occurs. The chemical conditions in the mixing zones in the aquifers are not well enough known at present to fix the cause of coprecipitation in either the Bountiful district or the area near North Ogden.

EVAPORATION AND EVAPOTRANSPIRATION STUDIES

A program was begun in the spring of 1954 to determine the amount of water discharged in the Weber Delta district by evaporation from wetted surfaces and by transpiration from plants. The area studied extended from an altitude of 5,000 feet adjacent to the mountains to the 1952 shoreline of Great Salt Lake (fig. 16). A vegetation survey of the district was made, evapotranspiration-tank studies were made at the Ogden Bay Bird Refuge west of Ogden, and evaporation studies were made on the salt-crust barrens west of the Ogden Bay Bird Refuge. No attempt was made to segregate the source of the water discharged by evaporation and evapotranspiration; thus, the water discussed in this section came from direct precipitation and from surface and underground sources.

EVAPORATION

A Class A weather station was installed at the Ogden Bay Bird Refuge in cooperation with the U.S. Weather Bureau. The weather station consisted of a 4-foot evaporation pan, a rain gage, an anemometer, and maximum and minimum thermometers; the gages were read daily by Noland Nelson of the Bird Refuge. The observed evaporation rate for the 1955 growing season at the Ogden Bay Bird Refuge weather station was similar to the evaporation rate for the same period of time at the Bear River Bird Refuge weather station, about 20 miles to the north (table 11). The evaporation rate at the Bear River Bird Refuge for the 1955 growing season was near the average rate for the period 1949–55 (table 11). Thus, the evaporation rate at the Ogden Bay Bird Refuge for the 1955 growing season is assumed to be an approximately average figure for the period 1949–55. This figure is further assumed to be the average evaporation rate for the entire Weber Delta district.

TABLE 11.—*Comparison of evaporation of water from standard Weather Bureau pans at the Ogden Bay Bird Refuge and the Bear River Bird Refuge, for the period May-October 1955; and May-October evaporation from 1949 to 1955 at the Bear River Bird Refuge*

	Evaporation at	
1955	*Ogden Bay Bird Refuge (inches)*	*Bear River Bird Refuge (inches)*
May	8.65	7.88
June	8.17	8.74
July	10.60	11.27
August	7.60	8.73
September	5.97	5.94
October	4.05	3.33
	45.04	45.89

May-October evaporation at Bear River Bird Refuge from 1949 to 1966

Year	*Inches*
1949	43.93
1950	[1]
1951	47.31
1952	[1]
1953	46.48
1954	50.42
1955	45.89
1949–55 average	46.81

[1] Record incomplete.

EVAPOTRANSPIRATION

To determine the amount of water discharged by transpiration, a vegetation survey was made in the Weber Delta district. The land included in the vegetation survey (fig. 16) extends from the east edge of the cultivated irrigated fields at an altitude of 5,000 feet near the foot of the Wasatch Range to the shore of Great Salt Lake on the west, and from T. 3 N. to T. 7 N., inclusive. An area of

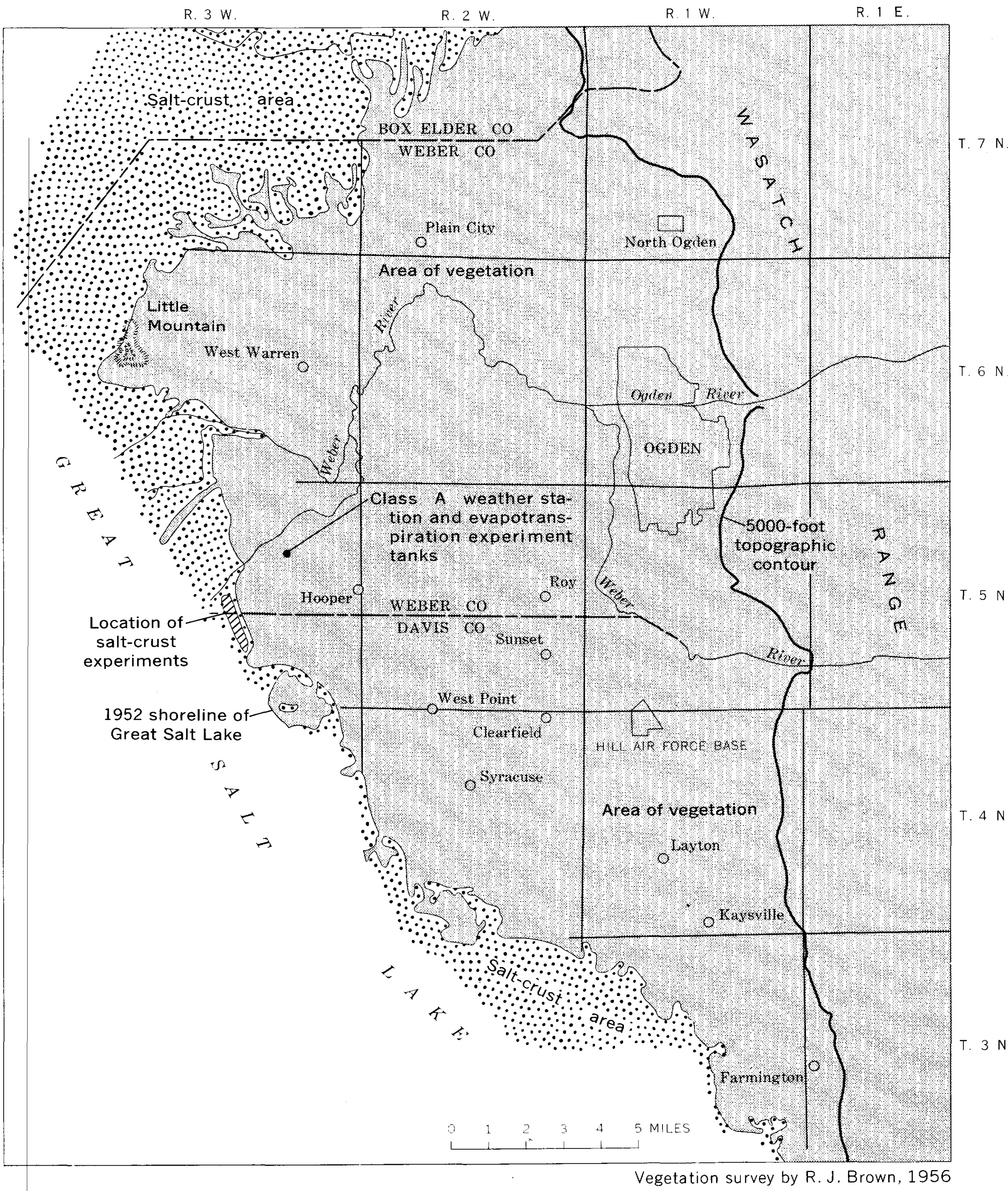


FIGURE 16.—Areas of vegetation and of salt crust from an altitude of 5,000 feet to the 1952 shoreline of Great Salt Lake.

TABLE 12.—*Size of areas in acres, having different evapotranspiration characteristics in the Weber Delta district*

[The composition of each vegetation group in a given area is discussed in the text]

Location		Size, in acres, of numbered areas							Total
Township	Range	1	2		4	5	6	7	
3 N	1 E	720	180	15	85			1,560	2,560
3 N	1 W	4,180	4,200	540	2,520	4,210	530	350	16,500
3 N	2 W		340	60		5,000	30		5,430
4 N	1 W	10,300	750	240	6,800	6	150	1,470	19,700
4 N	2 W	10,400	6,450	1,300	290	2,220	160	1,150	22,000
4 N	3 W	1	630	160		720	60		1,570
5 N	1 W	3,500	740	990	9,800		140	2,750	17,900
5 N	2 W	12,500	6,000	160	2,700	25	210	1,440	23,000
5 N	3 W	3,500	4,140	2,460	30	5,320	1,720		17,200
5 N	4 W					160			160
6 N	1 W	3,300	1,240	430	2,300		50	6,740	14,000
6 N	2 W	13,100	6,180	2,000	1,090	40	340	300	23,000
6 N	3 W	1,700	12,000	1,510	2,490	4,230	520	620	23,100
6 N	4 W		90	10	910	7,460	3		8,470
7 N	1 W	2,800	1,070	140	1,530		15		5,560
7 N	2 W	7,600	8,130	1,100	2,300	2,360	280		21,800
7 N	3 W	420	2,500	420		18,100	1,570		23,000
7 N	4 W					9,530			9,530
Totals (rounded)		74,000	54,600	11,535	32,800	59,400	5,800	16,400	254,000

about 254,000 acres (table 12) was included in the survey.

A detailed land-classification survey made by the Bureau of Reclamation during the 1950–52 period was used as an aid in the survey. At each site where the soil had been sampled, the type of vegetation in the immediate vicinity had been recorded. An average of 50 borings was made in each 640-acre section, resulting in adequate data from which to prepare a map of the distribution of vegetation. Aerial photographs taken in the fall of 1952 were also used after the type of vegetation on the ground was correlated with its appearance on the photographs. Fieldwork was done in areas in which the vegetation could not be determined from the land-classification data or from the photographs. The distribution of the different vegetation groups was drawn on a map at a scale of 2,000 feet to the inch and acreages of the groups were measured.

As it was impractical to study individual plant species when making the vegetation survey, plants of similar water requirements were placed in a single vegetation group and evapotranspiration for each vegetation group was determined. Then the area of study was divided among seven categories, five of which were of specific vegetation groups and two of which were unvegetated. Evapotranspiration rates for crops were taken from published data, evapotranspiration for two vegetation groups was determined by experiments, evapotranspiration for the remaining two vegetation groups was estimated, and evaporation from the two unvegetated areas was determined by experiment and published data. Table 12 summarizes the results of the study.

AREA 1—CULTIVATED CROPS DEPENDING ON IRRIGATION

Evapotranspiration rates typical of cultivated irrigated lands in the Weber Delta district were obtained from estimates by Roskelly and Criddle (1952). These rates, plus an additional 5½ inches to account for evaporation during the nongrowing season, were used to determine evapotranspiration from the area. Table 13 gives the acreage and the evapotranspiration rate of each crop. Cultivated irrigated crops grown in the area have an average annual evapotranspiration rate of 170,000 acre-feet.

TABLE 13.—*Annual consumptive use of water by various crops in the Weber Delta district*

[Use during the growing season, after Roskelly and Criddle (1952)]

Crop	Area (acres)	Evapotranspiration during the—		Annual total (inches)	Annual consumptive use (acre-feet)
		Growing season (inches)	Non-growing season (inches)		
Hay	33,100	28	5.5	33.5	92,000
Corn	1,630	20	5.5	25.5	3,500
Small grains	15,700	15	5.5	20.5	27,000
Peas	3.260	10	5.5	15.5	4,300
Potatoes	2,960	18	5.5	23.5	5,800
Sugar beets	5,480	23	5.5	28.5	13,000
Tomatoes	4,370	23	5.5	28.5	10,300
Other vegetables	2,890	12	5.5	17.5	4,200
Fruits	4,150	21	5.5	26.5	9,300
Seeds	520	15	5.5	20.5	900
Total	74,060				170,000

AREAS 2 AND 3—SALTGRASS PASTURE AND CATTAILS

Three experimental tanks were used to determine the consumptive use of water by native vegetation in areas 2 and 3. Field conditions were reproduced as nearly as possible by growing saltgrass (*Distichlis stricta*) and cattails (*Typha*) in tanks filled with soil and equipped with automatic devices for supplying measured amounts of water to the points by subsurface irrigation. The circular tanks were metal and were 4 feet in diameter and 4 feet deep.

Mature saltgrass sod was placed in two tanks and cattails in the third. The tanks containing saltgrass were in a saltgrass meadow, and the cattail tank was nearby in a slough filled with cattails. These locations were selected to make conditions affecting transpiration as nearly natural as possible. The saltgrass and cattails were planted in the tanks in the spring of 1954, but no records were kept until 1955 to allow time for the saltgrass to recover from transplanting and for the cattails to become fully grown. The results for the 1955 growing season are consistent with results of tank studies made in other areas (Robinson, 1958, p. 58). The saltgrass used 33.21 inches of water with the water table 10 inches below the surface and 32.65 inches of water with the water table 24 inches below the surface. The cattails used 60.42 inches of water. The results of the study are given in table 14.

TABLE 14.—*Consumptive use of water, in inches, by saltgrass and cattails grown in tanks at the Ogden Bay Bird Refuge during the 1955 growing season*

1955	Saltgrass		Cattails
	Water used for average depth of 10 inches to water table	Water used for average depth of 24 inches to water table	Water used for average depth of water 2 inches above soil surface
May	2.87	1.68	4.24
June	6.01	6.44	11.81
July	8.45	9.36	17.92
August	8.24	7.00	13.61
September	4.96	5.74	9.34
October	2.68	2.43	3.50
Total	33.21	32.65	60.42

In area 2, the water table is about 24 inches below the land surface, and the soil is usually saline. The area contains small stands of greasewood and other phreatophytes, but as the most common type of vegetation is saltgrass, consumptive-use data for saltgrass are applied to the entire area.

The evapotranspiration from the tank (table 14) probably was slightly more than evapotranspiration under natural conditions; therefore, it was estimated that the evapotranspiration from saltgrass pasture was 30 inches for the growing season. Using this rate and a rate of evaporation of 5.5 inches during the nongrowing season, the calculated evapotranspiration from 54,600 acres of saltgrass pasture is 162,000 acre-feet.

The predominant types of vegetation in area 3 are cattails, rushes, and reeds, usually growing in swamps near the edge of Great Salt Lake. Small areas in which willow and cottonwood trees grow are included in this group as they have a similar evapotranspiration rate. Cattails were selected for the tank experiments as studies in other areas (Blaney, 1952, p. 63) indicate that the evapotranspiration rate of cattails is near the average for this vegetation group.

The results of the evapotranspiration studies at Ogden Bay Bird Refuge for the 1955 growing season show that the cattails growing in water 2 inches above the surface of the ground had an evapotranspiration rate of 60.42 inches. It was estimated that cattails growing under natural conditions would have an evapotranspiration rate of 56 inches for the growing season. The evapotranspiration for the entire year, including 5.5 inches during the nongrowing season, would be about 61.5 inches. The total discharge of water by evaporation and transpiration for the 11,500 acres of area 3 is 59,000 acre-feet.

AREA 4—DRY-LAND CROPS, GRASSES, AND SHRUBS

Dry-land crops, grasses, and shrubs that depend on precipitation for growth probably use practically all the precipitation that falls on areas in which they grow. Although the soil can at most times absorb all moisture as it falls, some precipitation may be lost by surface runoff. This possible loss by surface runoff is probably balanced by the use of a small amount of ground water by the vegetation. Thus, it is assumed that the precipitation is equal to the evapotranspiration. The average precipitation on area 4 is estimated to be 16.4 inches annually; thus, the annual discharge by evapotranspiration from the 32,800 acres covered by area 4 is 45,000 acre-feet.

AREA 5—NO VEGETATION—SALT-CRUST BARRENS

About 60,000 acres (fig. 16) along the shore of Great Salt Lake was salt-encrusted mudflats, completely barren except in scattered small areas where upward seepage of relatively fresh ground water supported vegetation. Experiments were conducted during the growing seasons of 1954 and 1955 to measure the amount of brine that seeps upward, evaporates, and leaves a salt-crust residue. These experiments have been summarized by Feth and Brown (1962).

The mudflats west of Ogden Bay Bird Refuge were selected as being representative of area 5 and were used in the salt-crust evaporation studies. Five square feet of salt crust was removed from each of three plots, and the plots were visited at intervals until a new layer of salt accumulated. The new salt crust was then removed, separated from silt, and weighed, thus giving the amount of salt deposited by evaporation of brine for a given period of time. The brine, obtained from a shallow well dug near the experimental areas, was analyzed, and the amount of brine necessary to produce the salt crust was calculated.

The results of the salt-crust experiments are summarized in table 15. The calculated average annual rate of upward leakage of 0.1 foot per year is little more than a "best guess" because of the wide range in values included in the average. If the rate of upward leakage in the 60,000 acres of salt-crust barrens is assumed to be 0.1 foot per year, then about 6,000 acre-feet per year is evaporated from this source in area 5.

TABLE 15.—*Computation of upward leakage from salt-crust evaporation experiments*

Plot [1]	Period (days)	Salt accumulation (grams) [2]		Water evaporated		Annual rate of leakage (feet)
		Total	Per square foot	Grams per square foot	Cubic feet per square foot [3]	
A	13	92.4	18.5	199	0.00703	0.198
A	20	84.9	17.0	183	.00646	.118
B	33	70.3	14.1	152	.00535	.059
B	22	41.4	8.3	89	.00316	.052
C	55	73.3	14.7	158	.00562	.037
Average						.1

[1] Area of each plot was 5 sq. ft.
[2] Brine was 93,000 ppm by weight; therefore, each 93 g of salt accumulation was equivalent to 1,000 g of water.
[3] 2.832×10^{4} cc (or g) of water = 1 cu ft.

In addition to the water from upward leakage, about 68,000 acre-feet of water falls as precipitation on the salt barrens above the 1952 shoreline of Great Salt Lake. Probably about half this water runs off into Great Salt Lake, and the other half evaporates. The total evaporation from the salt barrens then consists of 6,000 acre-feet from upward leakage and 34,000 from direct precipitation, or about 40,000 acre-feet.

AREA 6—NO VEGETATION—WATER IN DRAINS, CANALS, AND STREAMS[1]

The evaporation from open surfaces of drains, canals, and streams was computed from existing data. The evaporation records at Ogden Bay Bird Refuge and Bear River Bird Refuge are for the May to October period only. Correlation with year-long evaporation records at Lehi, Utah, about 55 miles south of Ogden, gives a 19-year annual average evaporation rate of 49.2 inches at Bear River Refuge. As the evaporation rates at the Bear River Refuge and Ogden Bay Refuge are similar (table 11), the evaporation rate of 49.2 inches per year can be applied to the 5,800 acres covered by water in the Weber Delta district. The natural discharge by evaporation from water surfaces thus is calculated to be 24,000 acre-feet annually.

[1] Does not include the water of Great Salt Lake.

AREA 7—VEGETATION DIVERSE—SCATTERED MUNICIPAL AND INDUSTRIAL AREAS

Municipal and industrial areas cover some 16,400 acres in the Weber Delta district which support diverse types of vegetation. About one-half the annual precipitation that falls on such areas is assumed to be evaporated or transpired—the remainder becomes surface runoff and is accounted for in calculations of discharge by rivers, drains, and sloughs. About 11,000 acre-feet of water, therefore, is evaporated or transpired from area 7. Perhaps an additional 11,000 acre-feet per year is used for watering lawns and small gardens, for a total of 22,000 acre-feet from area 7.

FUTURE DEVELOPMENT

The population of the Weber Delta district has grown rapidly in the past 25 years and will probably continue to increase. The demand for water will likewise increase, possibly beyond the ability of the water resources of the area to meet the demand. Surface water probably will be developed to its economic limit, thus reducing both natural recharge to the ground-water body from surface flow and the flow of surface water into Great Salt Lake. In addition to the usable ground water that has been the principal subject of this report, surface and ground waters of poor quality and industrial and sewage waste waters could be developed. The following section is a discussion in general terms of the utilization of water not now used and recommendations for the development of additional ground water.

UTILIZATION OF SUBSTANDARD WATER

This report has been concerned principally with the availability of ground water that is suitable for most uses, but water that is unsuitable for many uses is also available to be developed in the Weber Delta district.

In many parts of the United States, sewage and industrial waste waters are purified, either for immediate reuse or to prevent pollution of surface water. The amount of such waste water that might be reclaimed in the district is not known; but as all water that is used to carry waste to

Great Salt Lake is polluted by waste, salvage of the carrier water without actually reusing any of the waste water itself would represent a sizable savings.

Much of the sodium chloride type water could be desalinized (Dodge, 1960). The salt content of this water is less than that of sea water, and it would, therefore, be less costly to desalinize than is sea water, using some processes. The present cost of desalination would prohibit its use for irrigation, but industry might profitably use such water if other water of suitable quality could not be obtained.

Development of saline water might result in benefits additional to that of obtaining more water. By withdrawing water from aquifers containing salty water, pressure in those aquifers would be reduced and there would be less tendency for saline water to move into and contaminate aquifers that presently produce water of good quality. This would be an important benefit because future large-scale development of fresh ground water in the district might cause saline water to migrate toward the areas of fresh water.

A transitional stage in ground-water development possibly may occur during which it will be desirable to pump water from saline-water aquifers, such as in Tps. 6 and 7 N., in order to reduce pressures and thereby protect fresh-water aquifers in adjacent areas from contamination. During such a transitional period, the saline water pumped may have to be wasted to Great Salt Lake until the demand for water becomes sufficiently great to make desalinization economically feasible.

DEVELOPMENT OF GROUND WATER

Several steps should be taken in order to develop efficiently the ground-water resources of the Weber Delta district. Withdrawal of ground water should be increased to lower the artesian pressure and reduce wastage; continuing studies should be made of changes in water levels and artesian pressures, changes in discharge, and changes in chemical quality; and recharge experiments should be continued in order to determine the feasibility of large-scale induced recharge. Eventually, the ground-water body should be operated as a reservoir, where excess water during wet periods is stored to be used during periods of drought.

Additional development of ground water in the Weber Delta district would reduce wastage by seepage and use by nonbeneficial vegetation. A total of about 90,000 acre-feet in the district is lost each year by evaporation from the saltflats, by seepage out of the area, and by evapotranspiration from nonbeneficial vegetation. This 90,000 acre-feet includes 60,000 acre-feet lost by evapotranspiration from cattails, 20,000 acre-feet of ground-water underflow out of the area, and 6,000 acre-feet of evapotranspiration from the saltgrass pastures, although saltgrass is not here considered as nonbeneficial vegetation. Furthermore, about 9,000 of the 18,000 acre-feet of water discharged by flowing wells in the district is put to little or no beneficial use, and might be considered wastage. If water levels were lowered so that most wells stopped flowing, well owners would probably pump only those wells that now discharge water that is beneficially used and, therefore, much of the 9,000 acre-feet now wasted could be salvaged. The total amount of water that could be salvaged is not known, however, it might be as much as one-fourth of the amount being wasted.

Recharge experiments made during this investigation indicate that the gravel near the mouth of Weber Canyon is highly receptive to induced recharge and is directly connected with the artesian aquifers. Additional experiments are needed to determine the most feasible and economic means of inducing recharge during periods when the river contains water in excess of water rights and to determine whether desilting works will be needed in permanent recharge operations. Public ownership of the flood plain near the mouth of Weber Canyon would insure that this area would always be available to be used for artificial recharge.

As the drilling of new wells proceeds in the district and discharge increases, records of water levels and volumes of water discharged by wells should be maintained, and the significance of these data should be evaluated periodically. The report on ground-water conditions in the East Shore area by Smith and Gates (1963) is the first such evaluation that has been made. Quantitative records of discharge can be compared to changes in water levels to determine whether or not the ground-water reservoir is being developed efficiently. Over long periods of time, comparing water levels with precipitation will permit the differentiation of climatic effects from the effects caused by man's use of water. Determining the effect of each will help in managing the reservoir.

Studies of chemical quality of water should be continued in the Weber Delta district. The present study has established the broad patterns of occurrence of water of various chemical types, has aided in determining areas of recharge and directions of movement, and has yielded some information regarding chemical-quality boundaries. The district, however, is large, the water-quality relations are complex, and the water quality in strata more than 1,300 feet below the land surface is not fully known.

Water samples from all new wells should be obtained and analysed. This information should be examined periodically to determine whether the current conclusions regarding the location and nature of water-quality boundaries need modification and to confirm or change other conclusions drawn from chemical-quality data.

Selected wells near boundaries between different chemical types of water should be sampled periodically to determine any migration of waters of one chemical type toward areas containing water of a different type. The effect of heavy development in any area must be observed, and such areas protected against migration of water of undesirable quality, if need for such protection should be discovered. Smith and Gates (1963) evaluated the chemical-quality data collected through 1961, and concluded (p. 39) that no relation between groundwater development and changes in chemical quality was yet evident.

Finally, as the demand for ground water increases, the quality of water in the deeper strata should be more completely determined. Such a determination will help clarify present thinking about upward leakage from aquifer to aquifer; about the relative amount of lateral movement and of upward movement of ground water in the western part of the area; and, in general, about the volume of ground water that is available for sustained use in the area.

Efficient, orderly development of the groundwater resources in any area requires that it be clearly recognized that the aquifers constitute a reservoir analogous in most respects to a surface reservoir. As more accurate data on the amount of recharge and discharge in the district become available, the operation of the reservoir can be planned. Over a long period of time, the amount of ground water in storage, as measured by water levels in key observation wells, may be reduced in times of need, such as dry years, and increased during exceptionally wet years.

Operation of a surface reservoir involves withdrawal of water for use in times of demand with a resultant lowering of the water level in the reservoir. During periods of lesser demand, the water level in the surface reservoir is permitted to rise. In like manner, operation of a subsurface reservoir requires a fluctuation of the water level. Maintaining at all times a static water level—or pressure head—inevitably means that operation of the reservoir is wasteful and inefficient, because an unchanging water level or piezometric surface requires that the subsurface reservoir be filled at all times to the same level. In analogy, it is as though a surface reservoir were kept at all times filled to spillway level and that at all times water was being allowed to waste over the spillway. The "spillway waste water" from the subsurface reservoir of the Weber Delta district is that water which is discharged to the atmosphere through consumptive use by nonbeneficial vegetation, and that which is evaporated from saturated land surfaces or from Great Salt Lake after upward leakage from the aquifers. This wastage is about 100,000 acre-feet annually, and by proper management of the reservoir it could be reduced appreciably.

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