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Water-Supply Bulletin No. 33

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ABSTRACT

Ground water available for large-scale withdrawal in east-central Washington occurs principally in a thick sequence of basalt flows known as the Columbia River Group. Permeable flow-contact zones within the sequence form the major aquifers of the region, and their slight regional dip to the southwest partly controls the general direction of ground-water movement. Ground water in the flow-contact zones normally is confined by dense basalt of low permeability, and the heads in the basalt sequence generally decrease with increasing aquifer depth.

Uncased well bores, 500-1,000 feet deep, interconnect a series of aquifers that otherwise are poorly connected hydraulically. Water from upper aquifers, used chiefly for domestic and stock supplies, drains continuously in most areas through the uncased irrigation wells into deeper aquifers having lower artesian pressures. This short-circuiting effect has contributed to the declines of water levels in upper aquifers, especially in the intensively pumped Odessa area.

Basalt aquifers throughout most of east-central Washington are capable of yielding water to wells at high rates, but store only a small volume per unit volume of rock. The median specific capacity determined for 342 multi-aquifer wells is about 12 gallons per minute per foot of drawdown. Storage coefficients, computed by volumetric analyses of large seasonal pumping depressions in the potentiometric surfaces in two areas near Odessa, range from 0.002 to 0.006.

Pumpage from basalt aquifers in the study region increased from about 44,000 acre-feet in 1963 to about 149,000 acre-feet in 1968. At least half the increase was in a 1,100-square-mile area near Odessa, where ground-water levels have been declining at rates of 2 to more than 10 feet per year since about 1965. Water-level declines predicted for deeper aquifers in the Odessa area, for the period 1967-77, range from 8 to 18 feet per year, if annual pumpage is maintained at the 1967 rate of about 53,000 acre-feet.

In wells tapping basalt aquifers in the immediate vicinity of Pullman, water levels have declined progressively as much as 100 feet since 1913. Annual rates of decline, averaging about 2 feet for many years, have increased to about 3 feet during 1965-69. The accelerated decline at Pullman probably is due not only to increased pumpage at Pullman, but also to pumping from deep basalt aquifers at nearby Moscow, Idaho. Based on historical water-level trends, the net projected decline in artesian head at Pullman may total 30 feet or more during 1970-80.

In most other parts of the study region where there is sizable pumpage from the basalt, water-level declines have begun, but long-term trends are not defined. In areas of intensive pumping, varying water-level declines and well interference are anticipated, depending on the local geohydrologic conditions.

Conditions that have led to depletion of ground water in basalt aquifers of the region include: (1) high rates of pumping withdrawal for consumptive use; (2) dense well spacing; (3) the small storage capacity and low vertical permeability of the basalt; (4) little recharge from precipitation; (5) leakage through uncased well bores; and (6) the presence of impermeable hydraulic boundaries. Early evaluation of the local aquifer systems and determination of optimum sustained yields are necessary for effective management of the ground water in the basalt.

INTRODUCTION

Purpose and Scope

Since about 1963 there has been a continuing increase in the pumping of ground water from basalt aquifers in the 8,400-square-mile region of east-central Washington, which is bounded generally by Roosevelt Lake and the Spokane River on the north, the Idaho border on the east, the Snake River on the south, and the Columbia Basin Irrigation Project area on the west (fig. 1). Although irrigated acreage constitutes only a small percentage of this predominately semiarid and dryland-wheat-farming region, localized areas of water-level decline related to irrigation pumping were detected near Odessa as early as 1964 (Garrett, 1968, p. 14). Declines had been documented even earlier in the Pullman area (fig. 1), where municipal pumping from basalt aquifers has caused progressive lowering of water levels since about 1934 (Foxworthy and Washburn, 1963, p. 2; Walters and Glancy, 1969, p. 14).

A continued increase in ground-water pumpage may accelerate the lowering of water levels and enlarge the areas effected—perhaps creating a condition in a few years wherein the cost of pumping water from increased depths would exceed the additional income from improved crop yield. In addition, certain of the shallower zones tapped by many existing wells are expected ultimately to be largely drained.

The primary goals of this study are to determine (1) the hydraulic characteristics of the basalt aquifers and (2) the effects of present and projected pumpage on the long-term ground-water supply. Although a few well-yield and water-quality problems have arisen in the study region, the major concern of this study was to determine the effects of projected pumpage on the lowering of water levels beyond depths of economically feasible pumping. According to Van Denburgh and Santos (1965, p. 22-29) the quality of the ground water is generally excellent for most uses without treatment; therefore, water-quality variations other than temperature (here used as an interpretive guide) were not considered in this study.

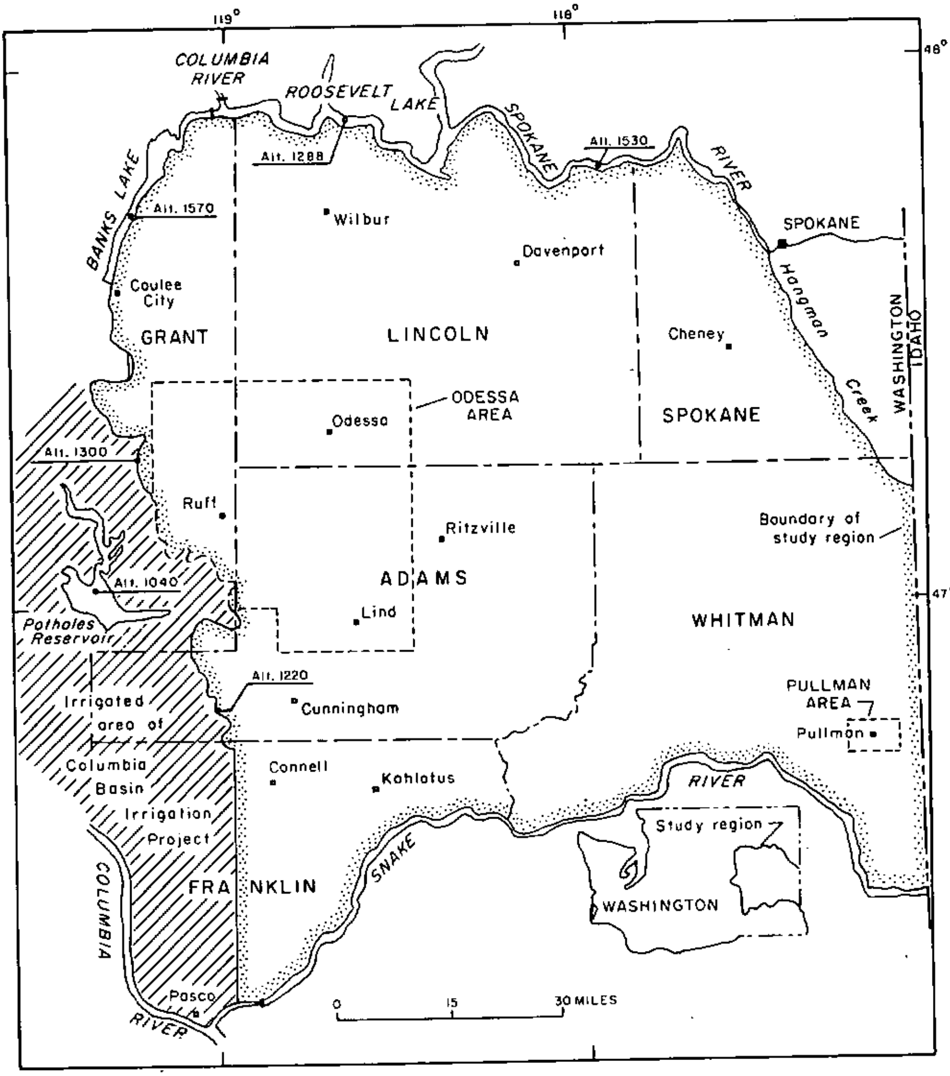

FIGURE 1.–Index map showing boundary of study region and locations of Odessa and Pullman areas.

A general appraisal of the ground-water situation in the Odessa area during 1964 and 1965 (Garrett, 1968) revealed the need for a comprehensive study. The study was intensified through 1969, resulting in a preliminary report (Luzier and others, 1968), and expansion of the coverage to the area discussed in this report. Here, the Odessa and Pullman areas are described in more detail than is the rest of the study region because they have had the most intensive ground-water development and, consequently, have yielded the most data. This study was conducted by the U.S. Geological Survey in cooperation with the Washington Department of Ecology and the former Department of Water Resources.

Acknowledgments

This report was prepared under the supervision of L.B. Laird, district chief in charge of the U.S. Geological Survey's water-resources investigations in the State of Washington. Contributions to the study were made by other hydrologists of the project staff—J.W. Bingham, R.A. Barker, H.E. Pearson, and C.J. Londquist. This report also benefitted from technical reviews of the manuscript by colleagues D.O. Gregg and E.R. Hampton.

The writers extend their gratitude to the farmers and ranchers in east-central Washington who have made their wells available for periodic observations, borehole surveys, and discharge measurements. Also acknowledged are well drillers for supplying their records of wells and power-company officials for making available their power-consumption records.

REGIONAL HYDROLOGIC SETTING

The principal ground-water reservoir of east-central Washington occurs within a thick series of lava flows which constitute the basalt of the Columbia River Group. The basalt was laid down in widespread sheets that underlie a roughly circular area of about 55,000 square miles in eastern Washington, northeastern Oregon, and west-central Idaho.

Underlying the basalt are chiefly granitic and metamorphic rocks which are exposed in an arcuate pattern of resistant knobs along the northern and eastern margins of the study region, from Grand Coulee to Pullman (pl. 1). These generally impermeable older rocks constitute a major hydrologic boundary along the northern margin of the regional ground-water reservoir. The basalt increases in thickness from a few feet near the knobs of the older rocks to more than 4,400 feet near Odessa (oil-test well 21/31-10M1, about 11 miles west of Odessa; see appendix for well-numbering system), and the sequence of volcanic rocks is more than 10,000 feet thick at the Rattlesnake Hills oil test well northwest of Pasco (Raymond and Tillson, 1968, p. 3-5).

The basalt surface forms a broad rolling plateau that slopes gradually to the southwest, from altitudes of more than 2,500 feet along the northern margins of the plateau to about 400 feet in the extreme southwest corner of the area near Pasco. The general dip of the basalt flows is about the same as the slope of the plateau surface, although gentle flexures in the basalt layers occur in the southern and southeastern parts of the region.

The general southwestward slope of the basalt surface and corresponding dip of the flow layers have had significant influence on the landforms and hydrology of the region. First, glacial melt-water floods of enormous volume swept across the gently sloping plateau surface during the Pleistocene Epoch, scouring away much of a preexisting mantle of loess (wind-deposited silt), eroding the present drainageways, and exposing wide belts of basalt today known as the "channeled scablands" (Bretz, 1959). The resultant distribution of surficial materials and the precipitation pattern in the region largely control ground-water recharge.

The basalt is recharged mainly by infiltration of precipitation water, both at the basalt surface and in storm-runoff channels crossing the basalt. Precipitation varies throughout the region according to the general pattern of land-surface altitudes: it is lowest in the southwest and highest to the northeast and east. From a low of about 8 inches between Potholes Reservoir and Pasco (pl. 1), the average annual precipitation increases gradually to about 16 inches near Davenport and about 22 inches along the Washington-Idaho border (Phillips, 1965, fig. 2). Most of the precipitation falls during the cooler seasons, when loss of water to evaporation and plant growth is relatively small, and opportunity for infiltration of the precipitation, therefore, is enhanced. The thin rocky soils of the sparsely vegetated scablands (pl. 1) allow more rapid infiltration of precipitation than does the thicker loess soil of the interchannel "islands." Recharge of the ground water from precipitation is not limited to the rocky areas; it probably occurs throughout the study region simply because much of the annual precipitation occurs in the winter when evapotranspiration loss is small.

The channels of the intermittent or seasonal streams apparently are important avenues of recharge to the basalt in the scabland areas. Two extensive stream systems, those of Crab Creek and the Palouse River, drain most of the study region. Crab Creek and its tributaries drain the northern part of the region, carrying the water westward into the Columbia Basin Irrigation Project area. The Palouse River and its tributaries drain most of the eastern part of the region, carrying the water to the Snake River. In both of these systems, but especially in large parts of the Crab Creek basin, streamflow occurs only during periods of snowmelt and storm runoff. Where the stream levels are higher than the local ground-water levels, recharge to the basalt is greater. In the lower parts of both these drainage systems, the streams are perennial and function as drainageways rather than recharge sources, being maintained by seepage from the ground water in those reaches.

The southwestern part of the study region has few perennial streams, and rarely has surface runoff. Because of the small amount of normal precipitation (less than 10 inches per year), appreciable recharge to the basalt in this part of the region may occur only during years of unusually heavy precipitation.

The regional movement of ground water in the basalt is generally to the southwest, toward discharge areas along the Columbia and Snake rivers. At any point in the regional system, however, the lateral movement of the ground water may be to or from a stream channel or toward a discharging well. Plate 2 shows the generalized patterns of (1) water-level altitudes in deep wells of the region and (2) water-level depths in the wells. The general direction of ground-water movement can be estimated from the water-level contours shown on the plate. In any part of the region, movement is roughly perpendicular to the contours, from higher to lower altitudes.

Crab Creek and the Palouse River have noticeable drainage effects on the ground-water reservoir near Odessa and Hooper, respectively, as indicated by the bending of the water-level contours upstream. In the case of Crab Creek, a shallow westward-trending syncline may be partly responsible for the shape of the contours.

A considerable southward displacement of the water-level contours along the East Low Canal between Warden and Pasco reflects a buildup of water levels. This is due to recharge from the canal and from areas to the west that have been irrigated since 1952.

BASALT AQUIFERS

Physical Description and Correlation

Layer upon layer of basalt can be followed visually for miles along the walls of deep coulees of the region. Thin indentations in the walls mark the flow-contact zones (chiefly rubbly basalt, ash, and cinders) between the thicker and denser parts of the flow layers. The permeable flow-contact zones (fig. 2), sheetlike reservoirs and conduits for ground water where saturated, generally extend laterally for miles between the less permeable central parts of the basalt layers. Although a patch of vegetation, a seep, or perhaps a spring near the base of a coulee wall suggests the presence of water, the wasteland appearance of the coulees and scabland gives no hint of the volumes of water stored in these aquifer zones.

Beneath adjacent rolling wheatlands, the same basalt flows exposed in the coulee walls, or lying below the coulee floors, are penetrated by deep uncased wells. The well bores interconnect the various aquifer zones, some of which are capable of yielding as much as 2,000 gpm (gallons per minute) to deep, large-diameter (12-16 in.) wells.

Borehole geophysical logs of 72 deep wells were made during this study to correlate and identify aquifer zones and determine the extent of interaquifer leakage through uncased wells. Because the flow-contact zones are usually less resistant to drilling than are the dense interiors of the flows, the less resistant material of these zones tends to break out, and the borehole is enlarged, whereas the denser parts of the flows tend to maintain a smaller diameter. Logging of the hole diameter (caliper logging) of such wells produces a trace similar to the cross

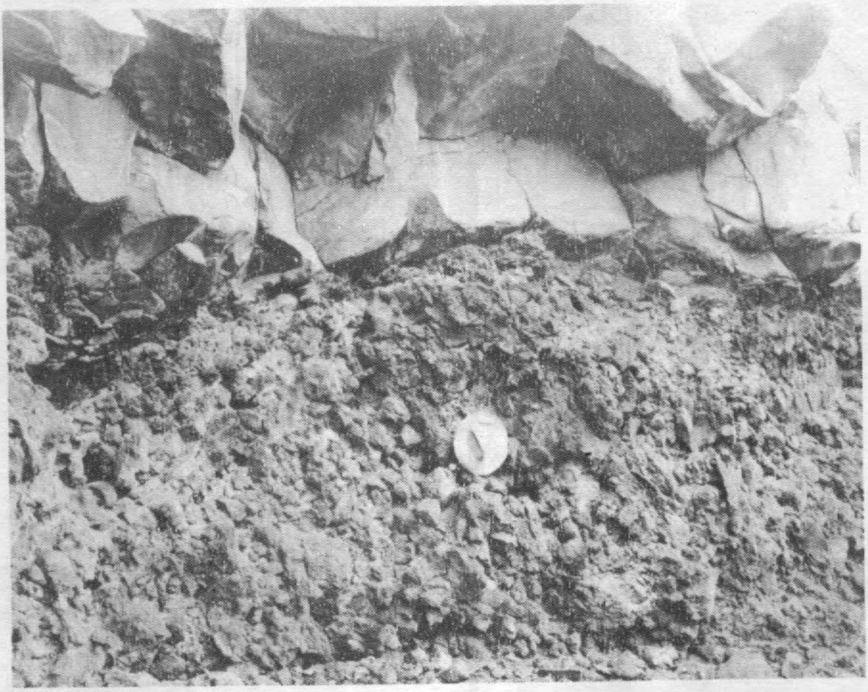

FIGURE 2.–Rubbly flow-contact zone overlain by dense basalt. Photograph from U.S. Bureau of Reclamation.

section of a coulee wall (fig. 3); the zones of hole enlargement in the well, like the indentations on the coulee walls, mark contact zones and possible aquifer materials.

Caliper logs, used in conjunction with fluid-resistivity, fluid-temperature, gamma-radiation, and flowmeter logs, have played an important role in developing an understanding of this multiaquifer flow system. For example, the 72 borehole logs made during this study, mostly of wells in the western part of the study region and to depths of about 1,000 feet, indicate that the thickness of the basalt layers between identifiable contact zones ranges from about 40 to 200 feet and averages about 100 feet. On the average, the contact zones indicated by substantial hole enlargements constitute about 30 percent of the saturated thickness of the basalt penetrated by the wells.

Head Relationships

Hydrostatic heads in the basalt, which are represented by the levels at which water stands in wells, differ both in various aquifer zones and in various parts of the region. The areal and vertical distributions of heads in the basalt aquifers are controlled by (1) the structure of the flow layers, (2) the areal distribution of recharge, (3) lateral changes in the permeability of the aquifer zones, and (4) the altitudes of recharge areas and of the discharge areas for the various basalt aquifers.

The regional pattern of heads in deep basalt aquifers (pl. 2) shows a gradient (decline of head) toward the southwest to the Snake River, the apparent "base level" in the regional ground-water system. The average gradient, which is slightly steeper than the regional dip of the basalt, is partly controlled by the southwestward dip of the rock. However, the gradient is due also to the greater availability of water for recharge in the northern and eastern parts of the region.

In most parts of the region, the hydraulic heads are highest in the shallowest aquifer zones in the basalt and are progressively lower in the deeper zones. During the drilling of a deep well in the basalt, the water level in the well commonly drops several feet, or several tens of feet, as deeper aquifer zones are penetrated. In some areas, the drop in water level may be 100 feet or more. Such large changes in head usually occur only once during the drilling of a well, commonly within the first 500 to 600 feet of drilling. Additional smaller changes in head, are likely to occur with continued drilling. The differences in head reflect the very low permeability of the intervening dense basalt, and largely represent the energy loss as the ground water slowly migrates downward across these layers. Low vertical permeability of individual basalt flows partly accounts for the extremely high position of water levels adjacent to parts of Roosevelt Lake along the northern margin of the project area (pl. 2). For example, water levels in deep irrigation wells at Wilbur and Davenport are 900 to 1,100 feet higher than the altitude of Roosevelt Lake.

Some of the largest head reductions in successively deeper basalt aquifers occur in the Odessa area, but major head declines are not restricted to that area.

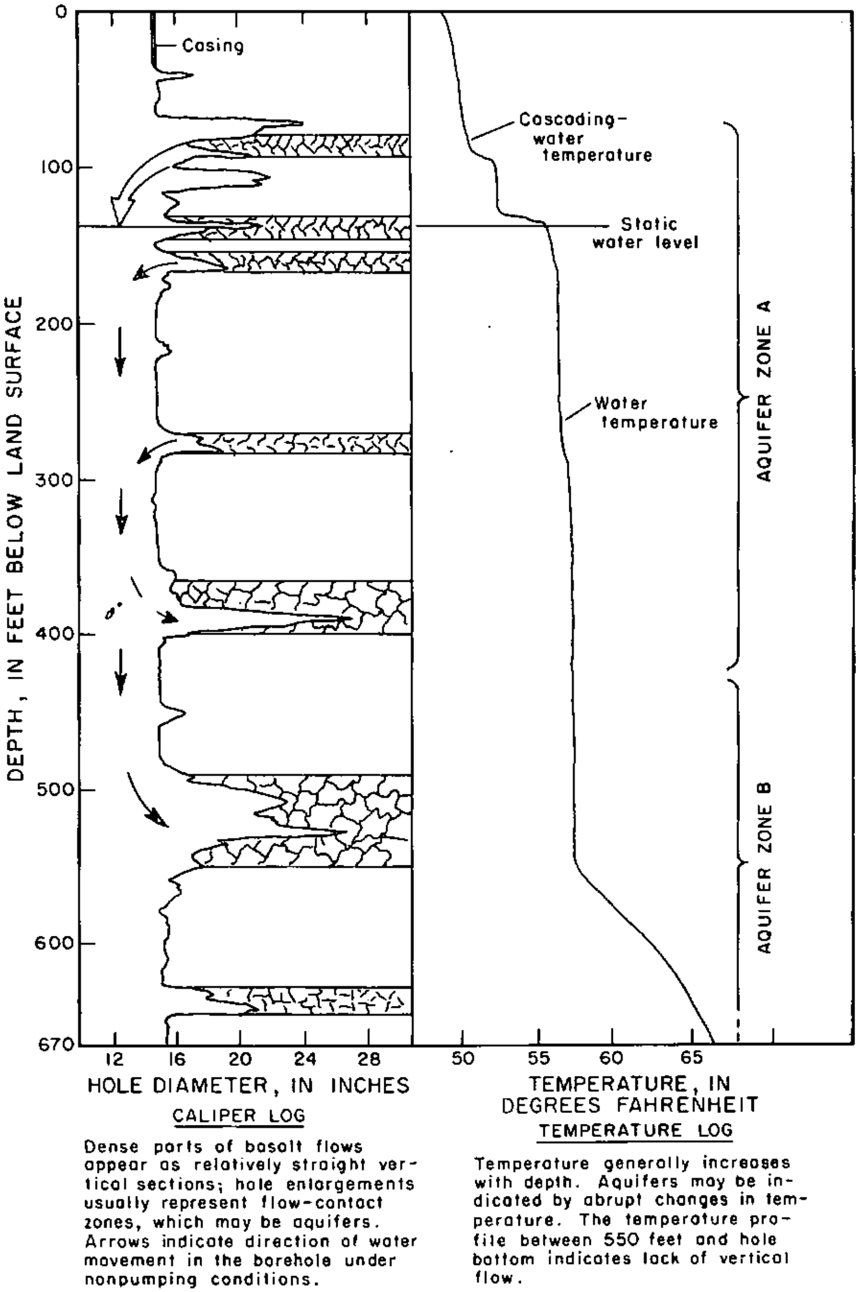

FIGURE 3.–Typical caliper and temperature logs from an irrigation well drilled in basalt of the Columbia River Group.

Borehole geophysical logs of about 29 basalt wells in other parts of the study region show downhole flows. Outside the Odessa area, the largest known head difference occurs in the Cheney-Airway Heights area of Spokane County, where wells less than 200 feet deep commonly have static water levels 200 to 300 feet higher than those of deeper nearby wells. To the south, in most parts of Whitman County, shallower aquifers commonly have heads as much as 100 feet or so higher than those of deeper aquifers. In the northern and eastern half of Lincoln County, near Wilbur and Davenport, and in the eastern half of Adams County, near Ritzville, the shallower aquifers usually have heads less than 50 feet higher than those of deeper aquifers. The depth-to-water map (pl. 2), which is based on data from the deepest existing wells, can be used as a rough guide to the potential for head differences. For instance, a much smaller head difference would be expected in areas where heads in deep aquifers are within 100 feet of land surface than in areas where heads in the deep aquifers are 400 feet or more below the surface.

The only parts of the region where heads in the basalt increase with depth are (1) in the immediate vicinity of perennial streams that are receiving ground-water discharge and (2) in areas where there are gentle flexures of the basalt layers. Most of the latter areas are in Whitman County. There are several flowing artesian wells in both Lincoln and Whitman counties (Molenaar, 1961).

Nearly all water-level data used in this study are from wells that are largely uncased and open to more than one aquifer zone in the basalt. Therefore, most are composite water levels, influenced by the head in each zone, and the data for most of the region are inadequate to delineate heads in any one horizon or depth interval over an extensive area. For this reason, the water-level contours in plate 2 must be considered very generalized because they are based on composite heads from wells having a significant depth range. Deep wells were too widely spaced to allow detailed mapping of potentiometric surfaces[1] throughout the region, even though some areas were becoming significant ground-water pumping centers by 1968.

Odessa Area

In the Odessa area, sufficient head-distribution data were obtained to allow delineation in the basalt of two depth intervals that have somewhat different aquifer characteristics. They are herein designated aquifer zone A and aquifer zone B. The delineation has been based chiefly on (1) distinct differences in static water levels and (2) response or lack of response to large head changes induced by deep-well pumping.

Recurrent water-level measurements in wells tapping aquifer zones A and B, under pumping and nonpumping conditions, were used to help identify each well according to the zone that its water level represented. Well-bottom altitudes and well depths also were used to help define the aquifers. Each aquifer zone

[1] An imaginary surface that everywhere coincides with the hydraulic heads in the aquifer.

may include more than one water-yielding unit, but the heads within the respective zones are similar (fig. 3).

In a large part of the Odessa area the bottoms of most wells that tap only zone A range in altitude (corresponding to the regional dip) from about 1,200 feet along the western and southwestern margins of the study region to about 1,500 feet near Sylvan Lake. However, in T.19 N., Rs. 29 and 30 E., some wells drilled to an altitude of about 900 feet apparently reflect heads in zone A. In general, wells that tap zone A are less than 400 feet deep, are used for domestic and stock supplies, and have a higher water level than wells in zone B.

Conversely, wells used for control in zone B are generally deeper (400 to 1,000 ft deep), have lower water levels, and are used chiefly for irrigation. The bottoms of most of the deeper wells tapping zone B range in altitude from about 650 feet near the East Low Canal to about 1,100 feet near Sylvan Lake.

As elsewhere in the study region, nearly all wells in the Odessa area (particularly wells penetrating zone B) are uncased and, therefore, have a composite water level that is influenced by the head and permeability of each saturated zone penetrated. Because the heads for zone A are higher than those for zone B, water leaks from zone A into zone B through the uncased well bores (fig. 3). The water in both zones is generally confined, except in small areas where water levels in zone A are within permeable intervals. In most of the Odessa area, permeabilities in zone A are relatively low; this keeps the leakage small while the higher permeability of zone B allows that zone to absorb the leakage with little increase in head. Therefore, the composite water level of a well that penetrates both zones, and in which leakage has occurred over a long period of time, probably is about the same as the level of a well tapping only zone B. Accordingly, the water-level measurements of wells that penetrate zone B have been used to define a potentiometric-surface map for that zone (fig. 4). As discussed subsequently, the fluctuations of that potentiometric surface in response to seasonal pumping have been the basis for evaluating ground-water depletion in the Odessa area and also for defining the regional ground-water flow system and estimating the storage characteristics of the basalt. A similar map has been prepared showing the potentiometric surface for zone A (fig. 5).

The potentiometric-surface map for aquifer zone B (fig. 4) shows an abrupt steepening of the hydraulic gradient in a band trending northwest for a distance of more than 20 miles. Deep wells of similar depths on either side of the band, and only 1 to 2 miles apart, have static water levels offset by 150 to 200 feet, those on the north side standing at the higher level. The band also marks a significant change in the regional ground-water gradient, from less than 5 feet per mile on the south side to about 25 feet per mile on the north side. The abrupt change in gradient and the offset in water levels are interpreted as occurring at a low-permeability boundary (natural ground-water dam) that significantly restricts ground-water flow from the northeast to the southwest within zone B. Its effect on zone A is unknown because of insufficient geologic and potentiometric data. The exact nature of the ground-water dam is unknown because it has no apparent surface expression or outcrop.

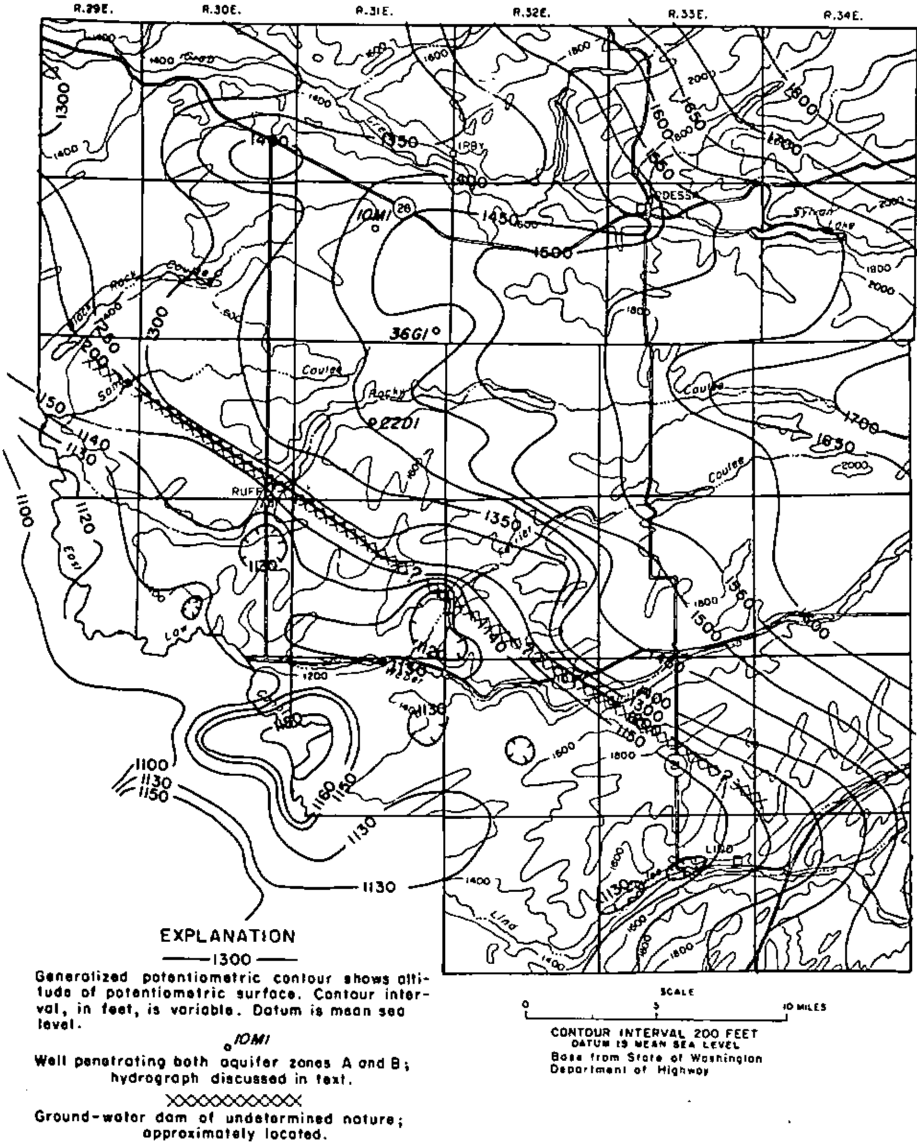

FIGURE 4.—Potentiometric surface of aquifer zone B (lower zone), Odessa area, spring 1967.

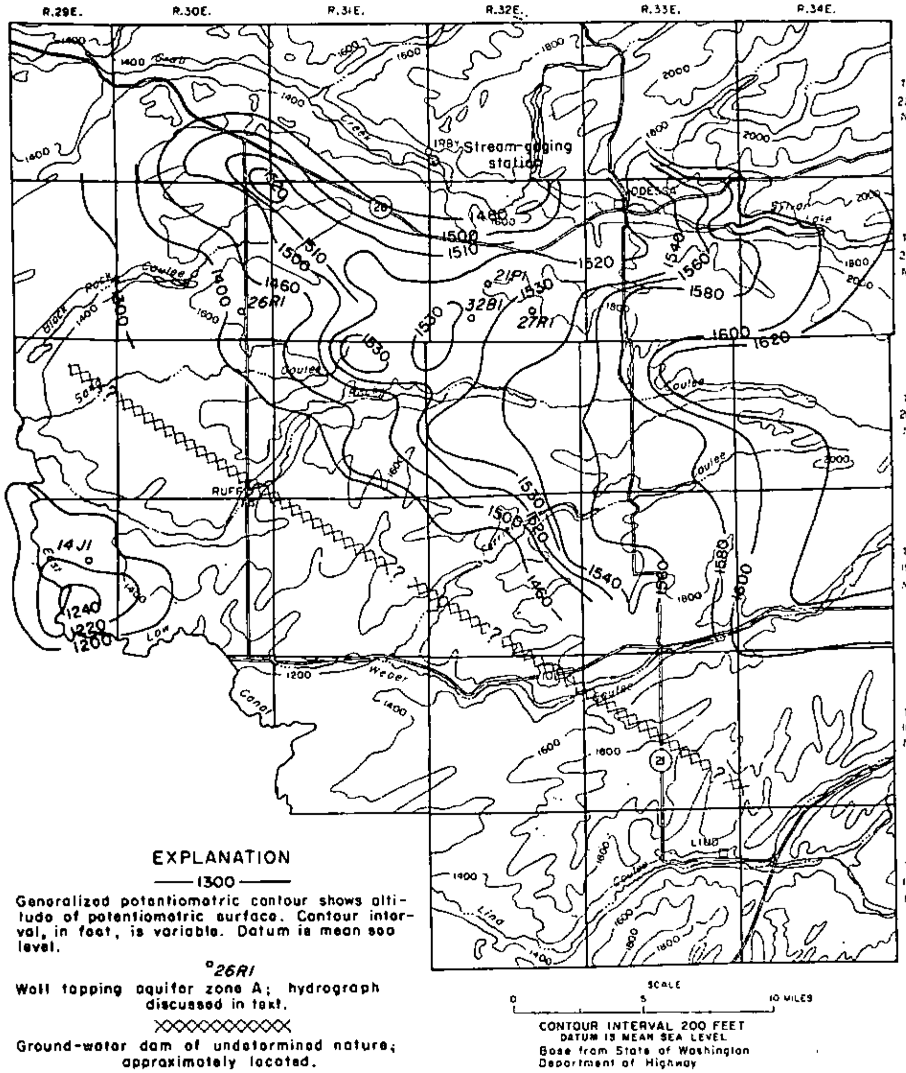

FIGURE 5.–Potentiometric surface of aquifer zone A (upper zone), Odessa area, spring 1967.

Possible explanations for the ground-water dam include (1) a natural thinning or decreased permeability of one or more of the deeper water-bearing zones, unrelated to deformation of the basalt; (2) sharp folding which compacted and decreased permeabilities in the flow-contact zones; (3) a dike of dense intrusive rock cutting across the flow layers; and (4) a fault disrupting the permeability by displacement of flow-contact zones opposite impermeable layers, or producing crushed, impermeable rock material in the fault zone itself.

The most likely explanation is a fault or dike, singly or in combination, cutting across the older and deeper basalt layers, but predating the younger basalt flows which have buried and hidden it. If thinning of a flow-contact zone or sharp folding was the cause, the ground-water dam probably would not be as straight or as long. Newcomb (1961, 1969) has described numerous examples of subsurface ground-water dams, including strike-slip faults more than 20 miles long, in other parts of the Columbia Plateau.

Selected hydrographs of water levels in wells of the Odessa area are included in figure 6 to illustrate the head relationships between zones A and B and the response of both aquifer zones to pumping from zone B. The upper five hydrographs on that figure reflect water-level changes in zone A. The lower three hydrographs represent wells open to both aquifer zones but they reflect changes predominantly in the heavily pumped lower zone B.

As early as the spring of 1965, there has been a declining trend in water levels in all of the zone A wells represented in figure 6, even in well 19/29-14J1 where a dramatic rise in level occurred during the 1950's. Further, the beginning of springtime declines in those wells coincides with the beginning of the annual intensive pumping of zone B, which also is reflected in the fluctuations in the zone B observation wells (fig. 6). Clearly, the heads in both zones A and B are responding to the intensive pumping from the lower zone.

Early in the 1965 pumping season (fig. 6), the water levels in wells 21/32-21P1, 27R1, and 32B1, which tap only zone A, dropped almost simultaneously. A much larger decline occurred in zone B, as shown by the hydrographs of wells 21/31-10M1, 20/31-22D1, and 21/31-36G1. Those three zone A wells are at least 1 to 1½ miles from the nearest irrigation wells, in a part of the area where pumping from zone A is slight. Wells 21/31-10M1 and 20/31-22D1, tapping zone B, are at least 1½ to 3 miles from the nearest irrigation wells (which also tap zone B) that might have an influence reflected on the hydrographs. Thus, the decline in all these wells is reflecting a widespread drawdown caused by pumping of zone B, rather than local effects of nearby pumping. The nearly simultaneous long-distance drawdown of water levels in wells of zone A in the spring, coincident with the start of pumping, is best explained as response to changes in pressure in a confined aquifer zone, rather than to widespread drainage of the upper zone.

The relatively poor natural hydraulic connection between zone A and zone B is shown by the large difference in the magnitude of drawdowns in the two zones that are caused by the seasonal pumping of wells in zone B. For example, as shown by the hydrographs of figure 6, wells tapping only zone A had drawdowns of about 5-7 feet in 1965 and 1966, whereas the wells penetrating zone B had drawdowns of about 30 feet or more.

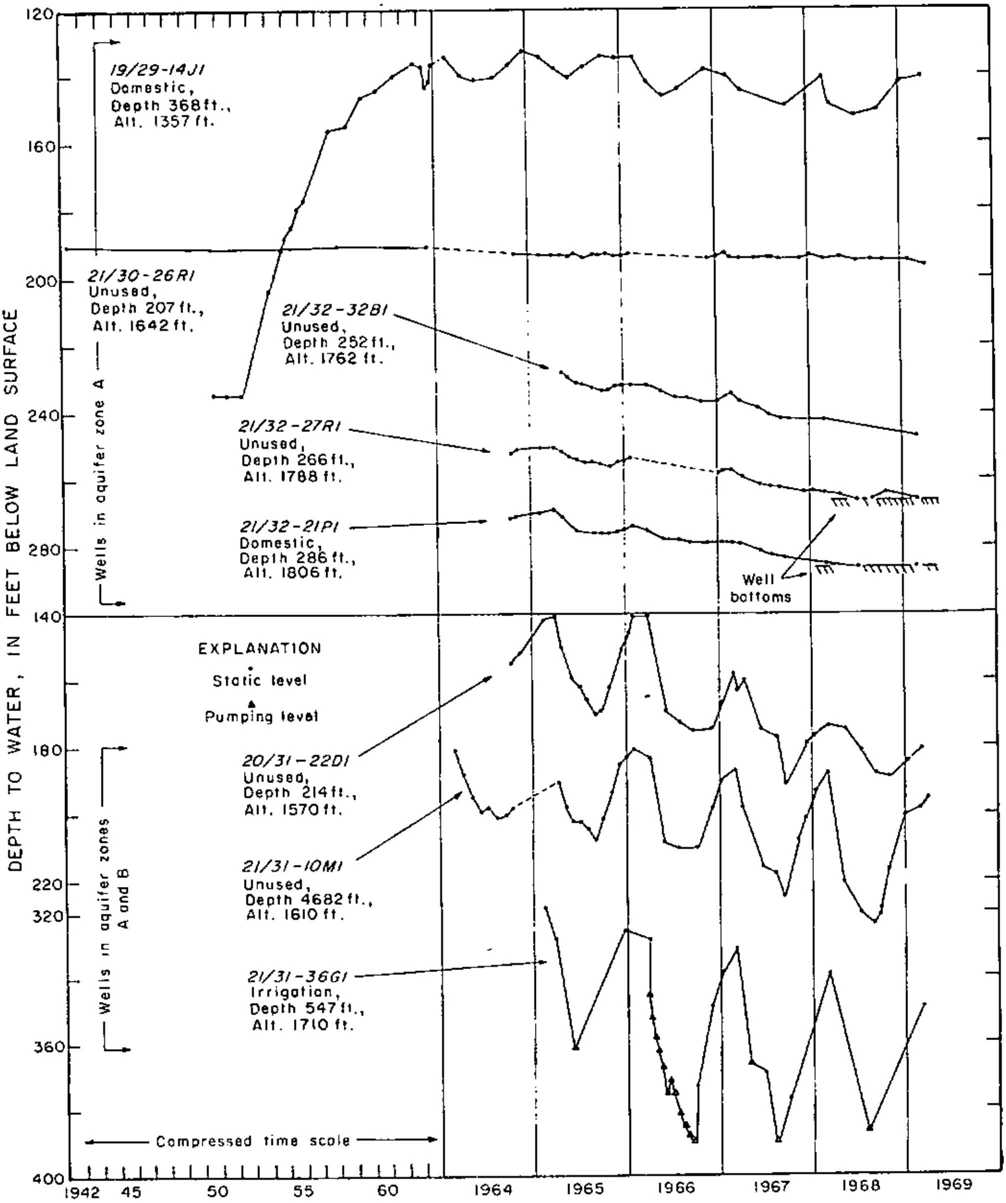

FIGURE 6.—Hydrographs of selected wells, showing water-level trends in Odessa area, 1950-69.

Although some natural hydraulic connection existed and some leakage occurred between the two aquifer zones prior to the drilling of wells in the Odessa area, the uncased deep wells constitute a major increase in the hydraulic connection, or a "short circuit" between zones A and B. In the Odessa area, this short-circuiting effect has been confirmed by borehole logs of about 42 deep wells. In many other wells, it is evident from the sound of cascading ground water in the well bore. Consequently, ground water in zone A throughout much of the Odessa area is being drained almost continuously by deep wells open to aquifers of lower head in zone B. The rate of drainage through a well bore increases rapidly as the head in zone B drops in response to the start of pumping. The rate reaches a maximum when the water level in a well drops below zone A, and all the aquifers of zone A are freely discharging into the well bore. The rate of downhole drainage then remains constant, even after the pumping has stopped, until the head in zone B recovers to the level of the lowermost zone A aquifers. Slower rates of downhole flow then result, as continued recovery reduces the head difference between zones A and B.

The lowering of zone A water levels as a consequence of the pumping of zone B is shown in the hydrographs of wells 21/32-21P1, 27R1, and 32B1 (fig. 6). At the end of the irrigation season late in September 1965, water levels in zone A continued to decline until sometime in November, despite the earlier start of recovery in zone B. Furthermore, the hydrographs of these wells show that, following a slight recovery in zone A during winter 1966-67, a downward trend in zone A water levels apparently persisted until the summer of 1968, despite a sizable recovery of heads in zone B during fall 1967 and winter 1967-68. Those zone A wells are in an area (fig. 5) where the spring-high water levels prior to 1967 were nearly identical in both aquifer zones, thus allowing zone A water levels to recover to levels equal to those of zone B. Because of continued annual decline due to large withdrawals in zone B, the heads in that zone by spring 1968 were reduced to a position below those of the corresponding heads in zone A. This reduction in head resulted in continuous and accelerated drainage of zone A, as is apparent from the hydrographs.

The contours shown in figure 5 reflect a large mound in the potentiometric surface of aquifer zone A in T.19 N., R.29 E. This mound has formed since 1952, when surface water was first delivered by canal to the Columbia Basin Irrigation Project area to the west. The hydrograph of well 19/29-14J1 (fig. 6), which is on the north side of the mound, shows that the rise in head was about 100 feet by 1962, after which water levels generally stabilized before starting a slight downward trend in 1966. The downward trend probably can be attributed to the drilling of seven open-bore irrigation wells since 1965 between well 19/29-14J1 and the canal to the west. The new wells are about 700 feet deep and in the spring of 1967 their water levels stood at an altitude of about 1,120 feet (fig. 4)—a full 100 feet below the water levels in the overlying zone A mound. The uncased wells are draining the recharge mound in zone A causing declining water levels in zone A wells (fig. 11; fig. 6, well 19/29-14J1) and rising water levels in zone B wells (fig. 12). The formation of the recharge mound in aquifer zone A since 1952, without corresponding mounding in zone B, exemplifies the poor vertical permeability and very slow crossbed leakage between the two aquifer zones.

The contours shown in figure 4 reflect a mound in aquifer zone B centered in the western part of T.18 N., R.31 E., in a part of the area where the East Low Canal and smaller canals extending westward from it are unlined. The mound apparently represents an unusual amount of recharge to zone B from the canals, due to leakage through several deep unlined wells in the vicinity. Also, there has been intensive heavy pumping for years from deep wells immediately northeast of Weber Coulee; possibly the depression of zone B heads by pumping in that area has accentuated the potentiometric mound near the canal. The distribution of wells that reflect heads only in zone A was not dense enough to indicate whether there is a corresponding mound in the potentiometric surface of the upper zone in the same area.

Pullman Area

Information on head relationships in the Pullman area has been recorded since before 1900 (Russell, 1897, p. 80). Wells drilled years ago on the flood plain of the South Fork Palouse River, and tapping shallow artesian zones in the basalt sequence, once flowed above land surface. Heads progressively declined, however, and none of the wells were flowing by 1935, when the U.S. Geological Survey began periodic measurements of water levels in the area.

Data from this and previous studies in the Pullman area (Foxworthy and Washburn, 1963) indicate that, as in the Odessa area, the upper part of the basalt contains aquifer zones of relatively small yield and high heads. At greater depths the heads in the basalt aquifers are somewhat lower and the yields from these aquifers are much greater. The water level in 954-foot Pullman city well No. 4 (15/42-32N2) is very near the levels in nearby wells between 200 and 300 feet deep, suggesting that the heads do not change much from zone to zone below moderate depths in the basalt of that area.

The partly inferred potentiometric surface of the principal basalt aquifers in the Pullman area in spring 1969 (fig. 13) has declined to a position a few tens of feet lower than the stream channels in the area. Therefore, the possibility exists for recharge of the basalt aquifers by water from these streams.

Capacity to Transmit and Store Ground Water

Specific Capacity of Wells

Specific capacity (the rate of discharge of a well, in gallons per minute, divided by the drawdown of water level, in feet) was used as a measure of the ability of basalt aquifers to transmit water. Many factors can affect specific-capacity values, such as the well diameter, the degree to which the well bore is open to the aquifer, the extent of penetration, the drilling method, and the degree of cleaning and development of the well. Nearly all irrigation wells in the study region are uncased large-diameter wells (12 to 16 inches), drilled in basalt by the cable-tool method. By this method, the aquifer materials are left fully open to the well bore, often caving and spalling throughout the drilling process, which results in hole enlargements as much as 3 feet or more in diameter. The enlargements at the aquifer interface and the general method of drilling tend to result in very efficient wells. Specific-capacity data determined for such wells are therefore considered to be a fairly valid guide to transmissivity.

The specific-capacity values used in this study were obtained from three types of data. For 35 wells, all but one of which are in the Odessa area, values were obtained from aquifer tests run by the Geological Survey; for about 130 wells, values were determined from short-term aquifer tests reported by well drillers and pump companies; and all other specific-capacity values were estimated by an indirect method developed from the measurements in the Odessa area. By this method, specific capacity was derived from data developed for estimates of pumpage—as determined from rated horsepower and estimated efficiency of each pump—measured or estimated water levels in the well, and pressure in the discharge pipeline. All specific-capacity values used in this study are summarized in table 1. The measured and indirectly derived values are based on long pumping periods and are lower than the values reported from the short-term aquifer tests.

Values based on field measurements were obtained during the intensive study in the Odessa area. At that time the discharges of 25 randomly selected irrigation wells were measured using a portable propeller-type meter, and the discharges of 10 other wells were determined periodically using permanently-installed flowmeters. Water levels were measured directly with steel tapes, electric water-level sounders, air lines, and pressure gages. Specific-capacity values determined from these measurements are presented in figure 7. The first point of each curve in the figure represents a pumping period of only a few hours or less. In general, the specific capacities decreased during the pumping season; such a decrease is to be expected because drawdown in a constantly pumped well normally continues, at a progressively smaller rate, for long periods of time. However, in the Odessa area the drawdown in some wells may be intensified by the pumping of other wells.

The average of the median specific-capacity values (table 1) for 342 wells in the study region is about 12 gpm per foot. For the large-yield irrigation wells in the Odessa area, a comparison of specific capacity (measured and estimated) with well depth showed no apparent relationship, although increases in specific capacity would seem likely as additional aquifers are penetrated by the deeper wells.

Storage Coefficient

The storage coefficient is defined as the volume of water released from or taken into storage in an aquifer per unit change of head within a unit surface area. For example, to arrive at storage coefficients for the basalt in the Odessa area, where withdrawals are large (pl. 3), a volumetric analysis was made of the water pumped versus the resulting water-level changes in the aquifers.

The irrigation season near Odessa lasts from March to October. Most of the irrigation wells are pumped continuously from March until the wheat is

TABLE 1.—Specific capacity of multiaquifer basalt wells in east-central Washington

Area, and source of specific-capacity data	Number of wells	Specific capacity (gpm/ft drawdown) Range	Median
ODESSA AREA (refer to fig. 7):			
North of low-permeability boundary:			
Determined from direct measurements	25	2-53	6
Derived from pump hp-head data*	23	2-168	17
Derived from short-term tests reported by driller	17	<1-198	18
South of low-permeability boundary:			
Determined from direct measurements	9	2-59	13
Derived from pump hp-head data*	20	2-63	10
Derived from short-term tests reported by driller	24	2-360	27
REMAINDER OF PROJECT AREA:			
Grant and Lincoln Counties (excluding Odessa area):			
Determined from direct measurements	—	—	—
Derived from pump hp-head data*	46	<1-80	8
Derived from short-term tests reported by driller	42	<1-120	4
Spokane County:			
Determined from direct measurements	—	—	—
Derived from pump hp-head data*	9	1-80	15
Derived from short-term tests reported by driller	6	3-44	15
Whitman County:			
Determined from direct measurements	1	54	—
Derived from pump hp-head data*	21	<1-33	4
Derived from short-term tests reported by driller	11	1-1440	11
Adams and Franklin Counties (excluding Odessa area):			
Determined from direct measurements	—	—	—
Derived from pump hp-head data*	59	1-270	8
Derived from short-term tests reported by driller	29	<1-100	7
Total number of wells: 342			
Average of the median values of specific capacity: 12			

*Based on measurements in the Odessa area; efficiencies used throughout the region were 49 percent for turbine pumps of less than 100 horsepower, 67 percent for pumps of 100 to 199 horsepower, and 74 percent for pumps of 200 horsepower or more.

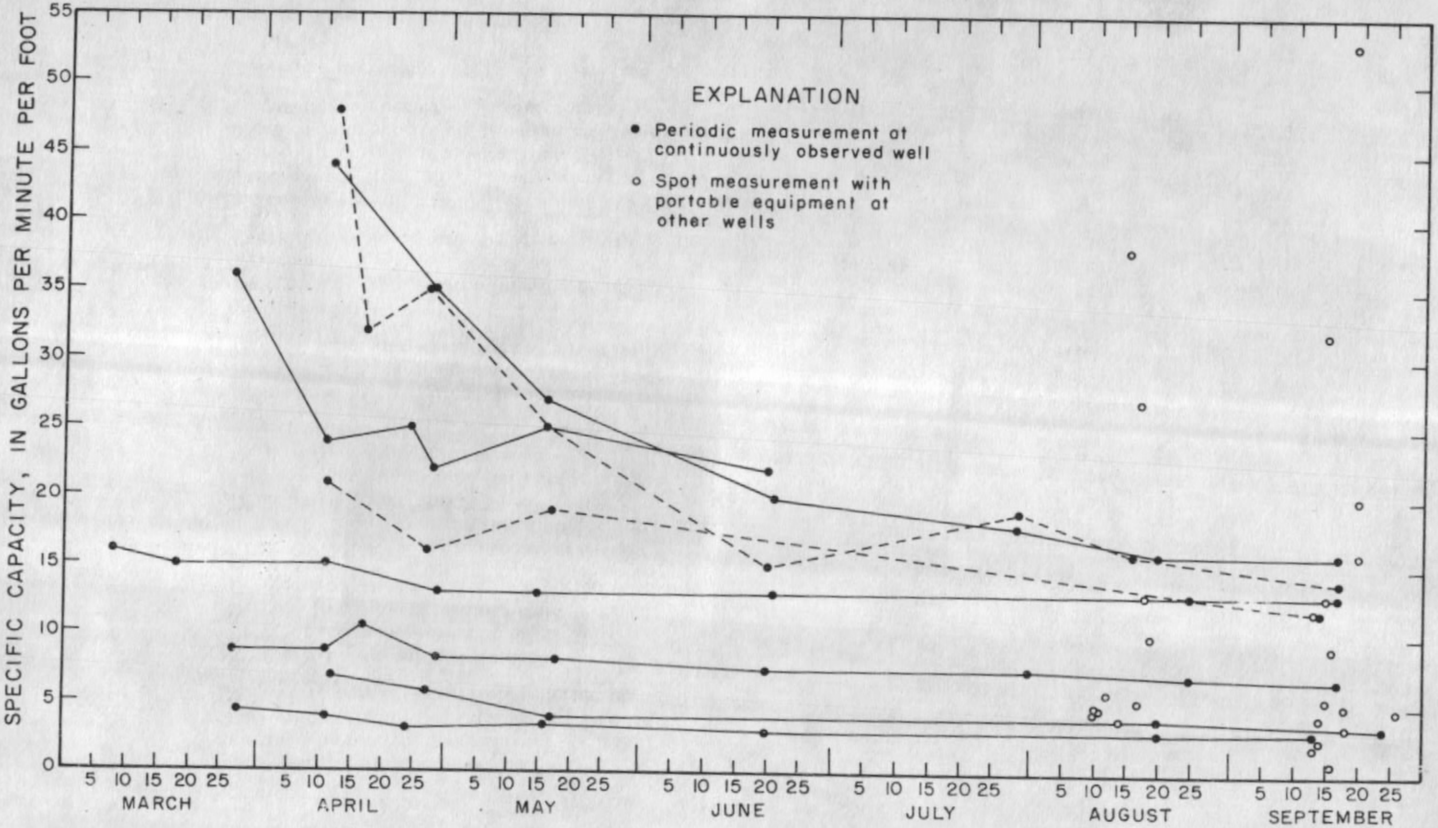

FIGURE 7.–Specific capacities of multiaquifer irrigation wells tapping basalt in the Odessa area, 1967.

harvested in late June or early July, after which the pumping is resumed in preparation for seeding. During the brief pause in pumping, water levels in the wells tapping zone B recover slightly and then, upon resumption of pumping, the levels continue the previously established downward trend until early October. The slight recovery during harvest is reflected in the summertime water-level measurements for well 21/31-10M1, an unused well at least 1.6 miles from the nearest pumped well, and for well 21/31-36G1, a regularly used irrigation well (fig. 6). The pumping during the 1966 season caused a head reduction in zone B (measured a few days after pumping stopped) amounting to 28 feet at well 10M1 and about 45 feet in the vicinity of well 36G1. Similar evidence from other wells suggested that several hundred square miles were involved in the head reduction. This widespread head change in zone B during each pumping season afforded an excellent opportunity for a broad-scale determination of storage coefficients. All available wells in the area were measured in early March 1967, just prior to the start of irrigation pumping, and again late in September and early in October, shortly after the irrigation pumping was stopped. The change in water level was plotted (fig. 8), and pumpage from each irrigation well was determined by conversion of power records (see beyond).

In the volumetric analysis, the area utilized was that within which the contours were considered most reliable (darkened area in fig. 8), and where the lateral inflow was minimal and uniform. Thus, declines in this area would best represent water taken directly from storage in aquifer zone B. The areas of decline on each side of the ground-water dam during the 1967 pumping season were assumed to be (1) the large area enclosed by the single 20-foot line northeast of the ground-water dam, and (2) the area enclosed by the 10-foot line southwest of the dam (fig. 8). The shaded areas of the map were measured by planimeter and multiplied by the appropriate head decline to determine the volume of rock through which the pressure reduction occurred. As shown by the data used in the two computations (table 2), the calculated values of the storage coefficient are 0.0025 for the decline area northeast of the ground-water dam and 0.0065 for the decline area southwest of the dam.

TABLE 2.—Data used in computation of storage coefficients in aquifer zone B, Odessa area

Part of map shown in figure 8	Area (sq mi)	Head-decline volume (acre-ft)	Pumpage from aquifer zone B (acre-ft)	Storage coefficient (S)
Northeast side of ground-water dam .... (shaded area enclosed by 20-foot contour)	276	6,700,000	17,000	0.0025
Southwest side of ground-water dam .... (shaded area enclosed by 10-foot contour)	102	2,000,000	13,000	.0065

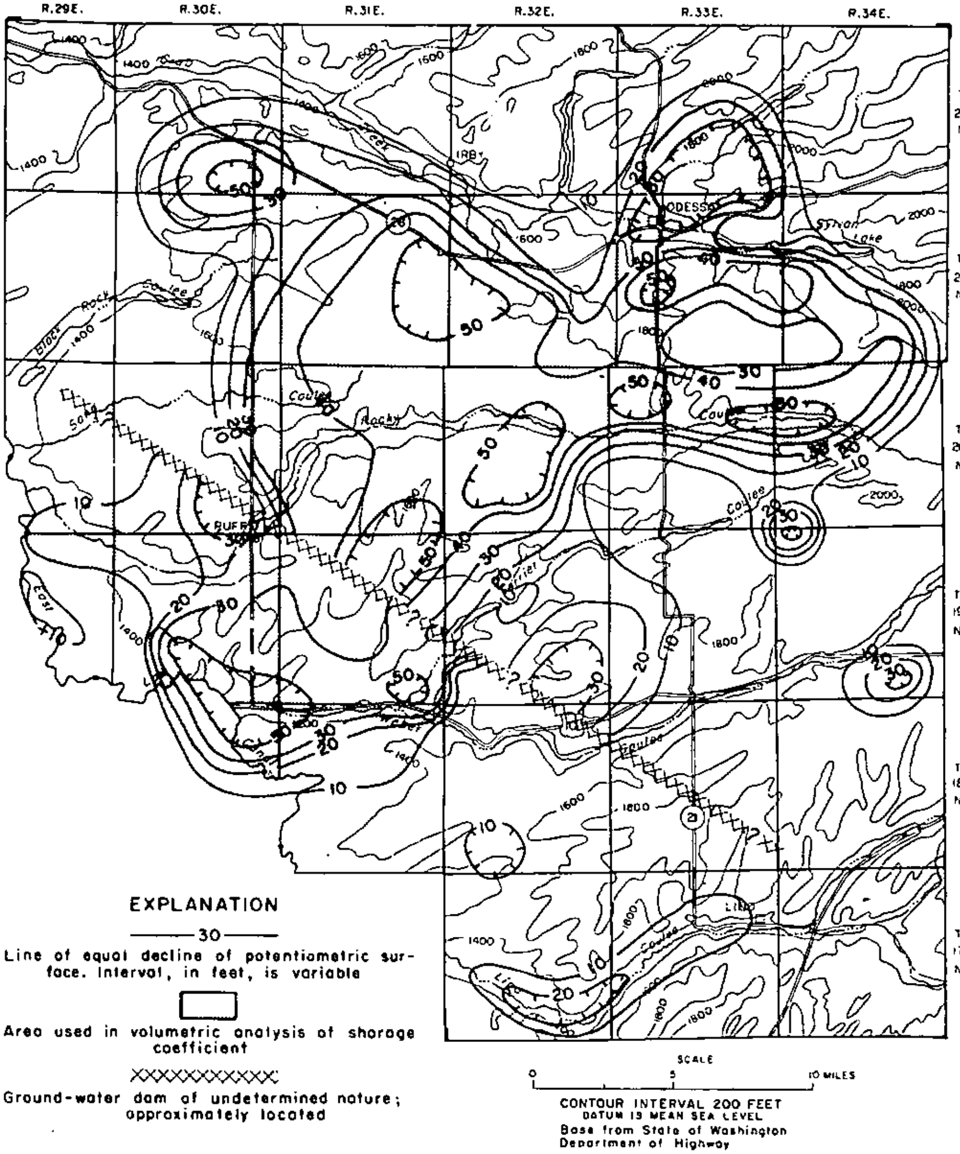

FIGURE 8.–Generalized change in potentiometric surface of aquifer zone B near Odessa, March-October, 1967.

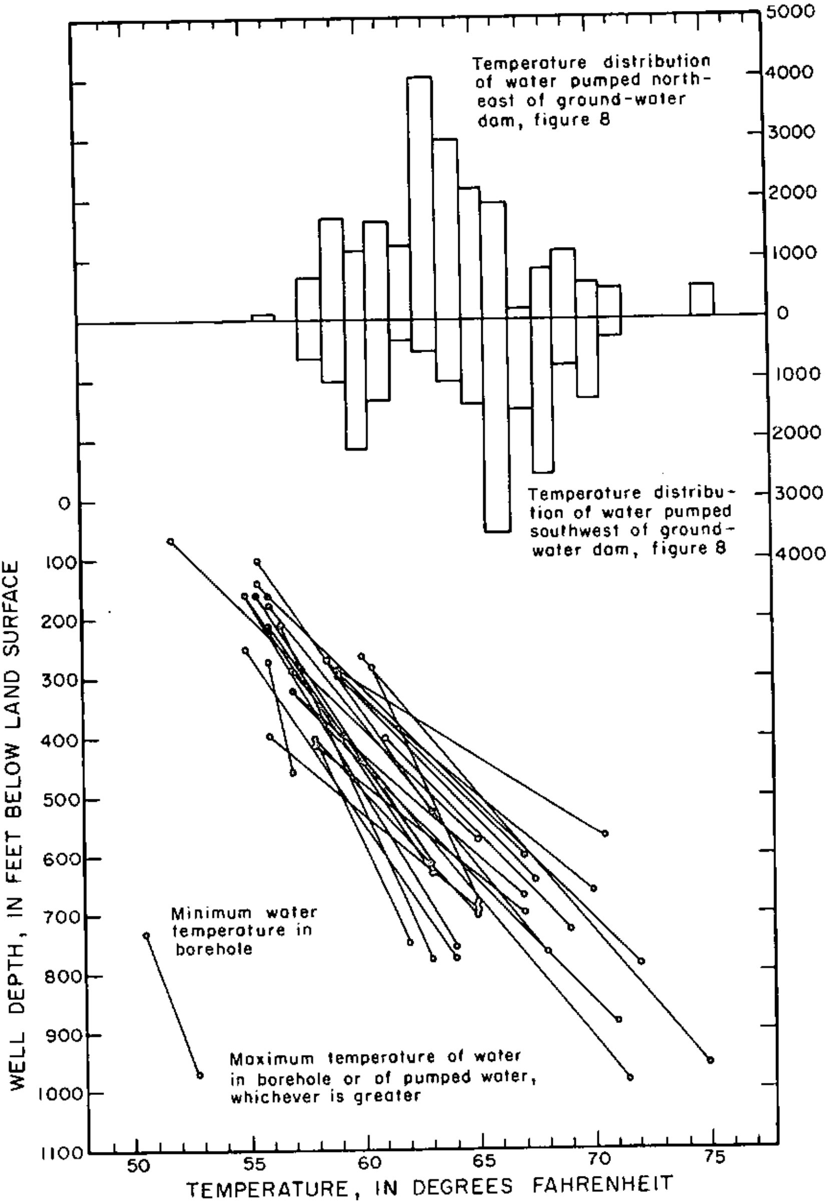

FIGURE 9.–Temperature distribution of water pumped and temperature ranges in deep wells near Odessa, 1967.

In this analysis, the assumption was made that recharge within the area was negligible during the period of large withdrawals, and that the reduction in head was a direct measure of change in storage. However, some recharge to aquifer zone B does occur in the form of cross-bed leakage from higher aquifers, largely by drainage from zone A aquifers through the uncased well bores. If the cross-bed leakage to zone B did not occur, the storage coefficients would be much smaller, and the head decline for the same volume of pumpage would be much greater.

Because ground-water temperatures increase with aquifer depth, the general magnitude of downward leakage during the irrigation season can be estimated by analyzing the distribution of temperatures of the pumped ground water. The bar graph in figure 9 shows the temperature distribution of about 73 percent (38,700 acre-ft) of the water withdrawn from wells drilled in the intensively pumped area. Near Odessa about 12 percent of the water pumped on the northeast side of the ground-water dam (fig. 8) had temperatures lower than 16°C (Celsius), or 60°F, whereas about 9 percent of the water pumped on the southwest side of the dam was lower than 16°C (60°F).

As suggested by the temperature gradients in boreholes (lower half of fig. 9), the pumped water having a temperature lower than 16°C (60°F) is largely from aquifers less than 400 feet below land surface (zone A). Of course, some part of the cooler pumped water is from zone B and cooled to below 16°C (60°F) by mixing with zone A water. Therefore, the contribution from the cooler, shallower aquifers probably was at least 12 percent of the total pumpage on the northeast side and 9 percent of the pumpage on the southwest side of the ground-water dam. In other words, for the 30,000 acre-feet of pumpage involved in the volumetric analysis (table 2), the contribution from aquifer zone A probably was at least 2,000 acre-feet in the part of the Odessa area northeast of the ground-water dam, and 1,200 acre-feet southwest of the dam. Evidently, the cool water pumped from the deep wells was mainly leakage from aquifer zone A. Therefore, the calculated storage coefficients for aquifer zone B have been rounded to 0.002 and 0.006, respectively, for the areas northeast and southwest of the ground-water dam.

Storage coefficients in other areas of east-central Washington have not been determined. Volumetric analyses are not feasible in lightly pumped areas, and the cost of pumping tests suitable to determine storage coefficients over such a large area is prohibitive.

Transmissivity

Transmissivity of the basalt aquifers, a measure of the relative ability of these aquifers to transmit ground water, is a key parameter in the quantitative evaluation of the ground-water system. Transmissivity data needed for this study were estimated from specific-capacity values of the basalt wells, in the manner described by Theis and others (1963, p. 331-341). The transmissivity of the basalt aquifers (in feet squared per day) is roughly equivalent to the specific capacity in gpm per foot of drawdown multiplied by 270.

Based on regional data from 342 wells summarized in table 1, the median specific-capacity values multiplied by 270 indicate an average transmissivity of basalt aquifers of about 3,200 feet squared per day (24,000 gallons per day per foot). Accordingly, transmissivity estimated for various parts of the region are:

	Estimated transmissivity	
	(ft^2/day)	(gpd/ft)
Odessa area	4,000	30,000
Grant and Lincoln Counties, exclusive of Odessa area	1,600	12,000
Spokane County	4,000	30,000
Whitman County	2,000	15,000
Adams and Franklin Counties, exclusive of Odessa area	2,000	15,000

The above values suggest that the average transmissivity of basalt aquifers in east-central Washington, within the depth range penetrated by the large-yield wells, is remarkably uniform over broad areas. On a more localized scale, however, transmissivity may vary over a wide range.

PUMPING WITHDRAWALS AND RESPONSE OF THE GROUND-WATER RESERVOIR

Ground water in east-central Washington is pumped mainly for irrigation. The amount of ground water pumped for public supply—most of which is in the Pullman area—is a small fraction of the amount pumped for irrigation. Thus, pumpage for public supplies is not tabulated or discussed separately.

Derivation of Pumpage from Electrical-Power-Consumption Records

In this study, pumpage was estimated from electrical-power consumption on the basis that pump-power input is related to water discharge. Power-consumption records for 1963-68 were obtained from electrical-power suppliers for nearly all wells in the region with pumps of more than 10 horsepower.

In order to measure pumpage accurately, and to determine the seasonal variation of power input and water discharge, 11 flowmeters were installed at selected irrigation wells. In addition, a portable flowmeter was used to make spot measurements at 25 other selected irrigation wells. Variations in line pressure of the sprinkler-irrigation systems, as well as the gradual decline in pumping levels during the irrigation season, caused variations in the relation of power input to water discharge for a given well. Most wells near Odessa were measured several different times so that the average total head (depth to pumping level plus discharge-line head) could be determined. Irrigation wells in other parts of the project area were measured less frequently and, in some instances, estimates of total head had to be based only on fragmentary information. The total head for each well was multiplied by a kilowatt-hour-consumption factor based on horsepower groupings (table 3), giving the conversion factor that was used in the pumpage compilation. For a description of formulas used and a more detailed discussion of pumpage computation, the reader is referred to Sandberg (1966, p. 114-117).

In the study of power input versus water discharge, the large-yield wells were considered most reliable (table 3). Only 9 percent of the wells having pump motors of less than 100 horsepower were included because this group accounts for only a small proportion of the total pumpage. Pumps of less than 100 horsepower also have the lowest average efficiency, probably in part because they are the oldest in the study area. Most of the pumps installed during the past few years are in the range of 200-400 hp (horsepower) and have the highest average efficiencies. Because the average efficiency of pumps in the middle group (100-199 hp) is only slightly lower than that of the largest horsepower group, the two groups were combined for determination of kilowatt hours per acre-foot per foot of lift (table 3).

TABLE 3.—Power-input data for turbine pumps in the Odessa area, 1967

	Group Classification		
	Pumps of less than 100 hp	Pumps of 100-199 hp	Pumps of 200 hp or more
Number of wells used in power-pumpage analysis	75	54	38
Percentage of group sampled	9	44	40
Average pump efficiency, in percent	49	67	74
Kilowatt hours required to lift 1 acre-foot of water 1 foot	2.3		1.7

Annual Pumpage

Distribution of pumpage throughout the study region during the period 1963-68 is shown in plate 3. As the plate shows, ground-water development in the region has been most intense in and adjacent to the Odessa area. Pumpage in that area has increased from 16,000 acre-feet (85 wells) in 1963, to about 74,000 acre-feet (169 wells) in 1968 (fig. 10). Total pumpage from large-yield wells in the entire study region for the same period rose from 44,000 acre-feet (292 wells) to 149,000 acre-feet (479 wells). Pumpage in the Pullman area (fig. 14) was about one-third greater in 1968 than in 1963.

A comparison of pumpage distribution (plate 3) with ground-water withdrawals (plate 1) shows that pumpage has become concentrated in the western part of east-central Washington within loess-covered areas between the scabland areas. These localities of the more intensive pumping generally are higher in altitude than adjacent scablands and, therefore, pumping lifts are somewhat greater. Ground-water pumping on the higher farmlands, as well as pumping from increasingly greater depths, is a trend that probably will become more pronounced as irrigation development continues to spread toward the north and east.

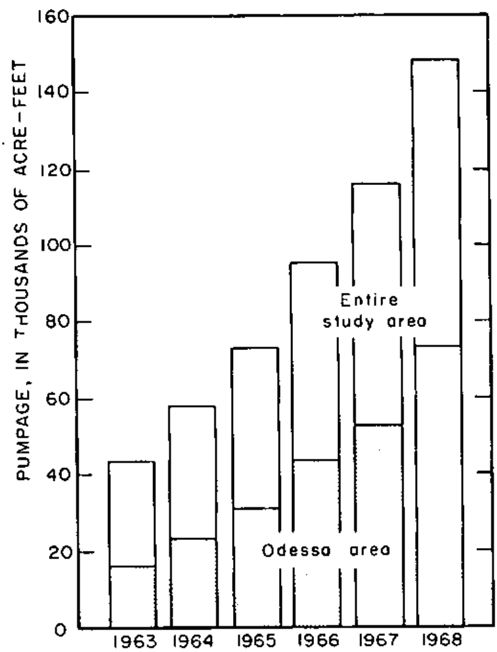

FIGURE 10.—Annual pumpage of ground water, 1963-68.

Water-Level Changes Related to Pumping

In order to observe water-level changes, an extensive network of observation wells has been maintained in the Odessa area since 1963, and in other parts of the project area since autumn of 1966. In addition, long-term water-level data were also obtained from several observation wells in the Pullman area. For the Odessa and Pullman areas, hydrographs of observation wells (figs. 6 and 14, respectively) show declines that are closely related to pumping. In most parts of the study region, however, the number of observation wells and length of record are insufficient to define water-level trends that are clearly related to pumping. Hydrographs of wells near Coulee City, Wilbur, Davenport, Ritzville, Cunningham, and in the Cheney-Airway Heights, Cannawai Creek, and Connell-Kahlotus areas are presented in figures 15-22 to show typical ranges of water level and short-term trends.

Odessa Area

For the Odessa area, water-level changes in both aquifer zones A and B, in response to pumping from zone B, have been described in detail in the section on head relationships, and only the overall effects of the pumping need to be summarized here.

In the Odessa area, distinct year-to-year water-level declines apparently started in 1964-65, and have averaged about 2 to 5 feet per year in aquifer zone A from about 1965 to 1969 (fig. 11). Declines in aquifer zone B are generally greater and have averaged about 5 feet or more per year for the same period (fig. 12). Generally greater rates of decline (6 to 12 feet or more) occurred in zone B during 1967-69, as might be expected, considering the increased rates of withdrawal (pl. 3).

Pullman Area

Basalt aquifers in the immediate vicinity of Pullman have undergone a progressive water-level decline since at least 1913, when some wells were flowing above land surface. The decline is largely in response to pumping of wells owned by the city and by WSU (Washington State University; fig. 13 and 14). Pumpage from the two well fields shown in figure 13 is about evenly divided and produces a combined total amounting to more than 95 percent of all pumpage in the area. Long-term water-level decline in the Pullman well field was at least 99 feet during 1913-69, and about 73 feet for 1933-69. Decline in the WSU well field for the latter period amounted to about 55 feet. Many of the wells shown in figure 13, with the exception of a few newer wells (Pullman wells 14/45-7H1 and 15/45-32C1, WSU well 15/45-34L1), have had almost identical average rates of decline, ranging from about 1.8 to 2 feet per year during 1953-69. The remarkable similarity in long-term decline rates, even in wells such as 14/45-4H1 and 4N1 (fig. 14) which are far from the pumping centers, suggests that the maximum known decline of 99 feet or more in the Pullman well field since 1913 may be nearly representative of total decline throughout much of the area

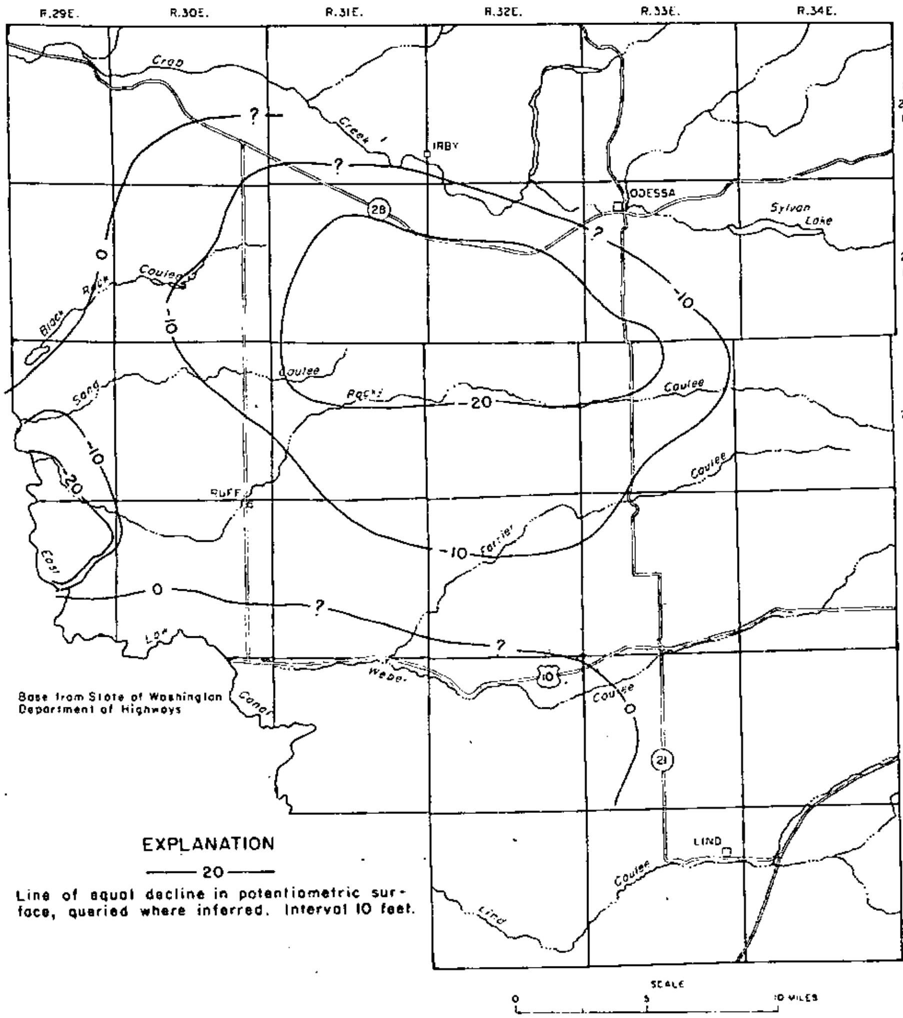

FIGURE 11.–Generalized net change in potentiometric surface of aquifer zone A in Odessa area, spring 1965-spring 1969.

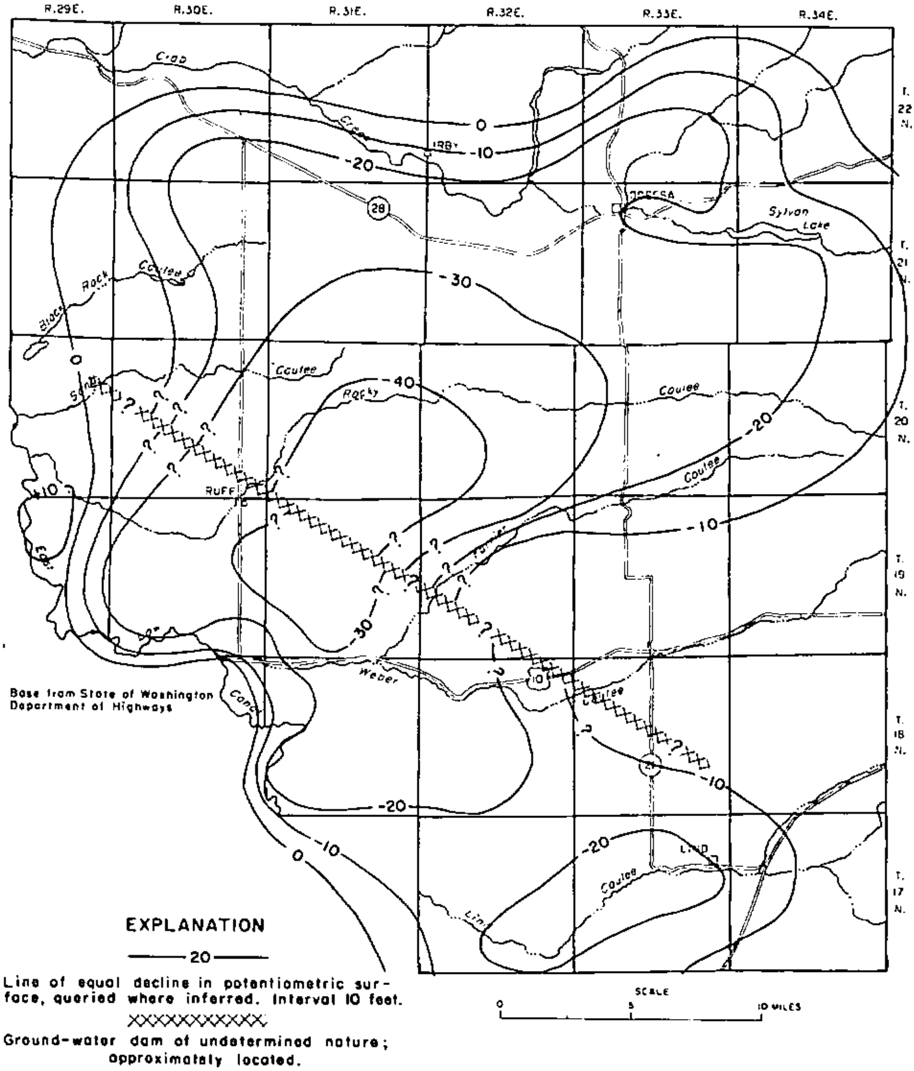

FIGURE 12.—Generalized net change in potentiometric surface of aquifer zone B in Odessa area, spring 1965-spring 1969.

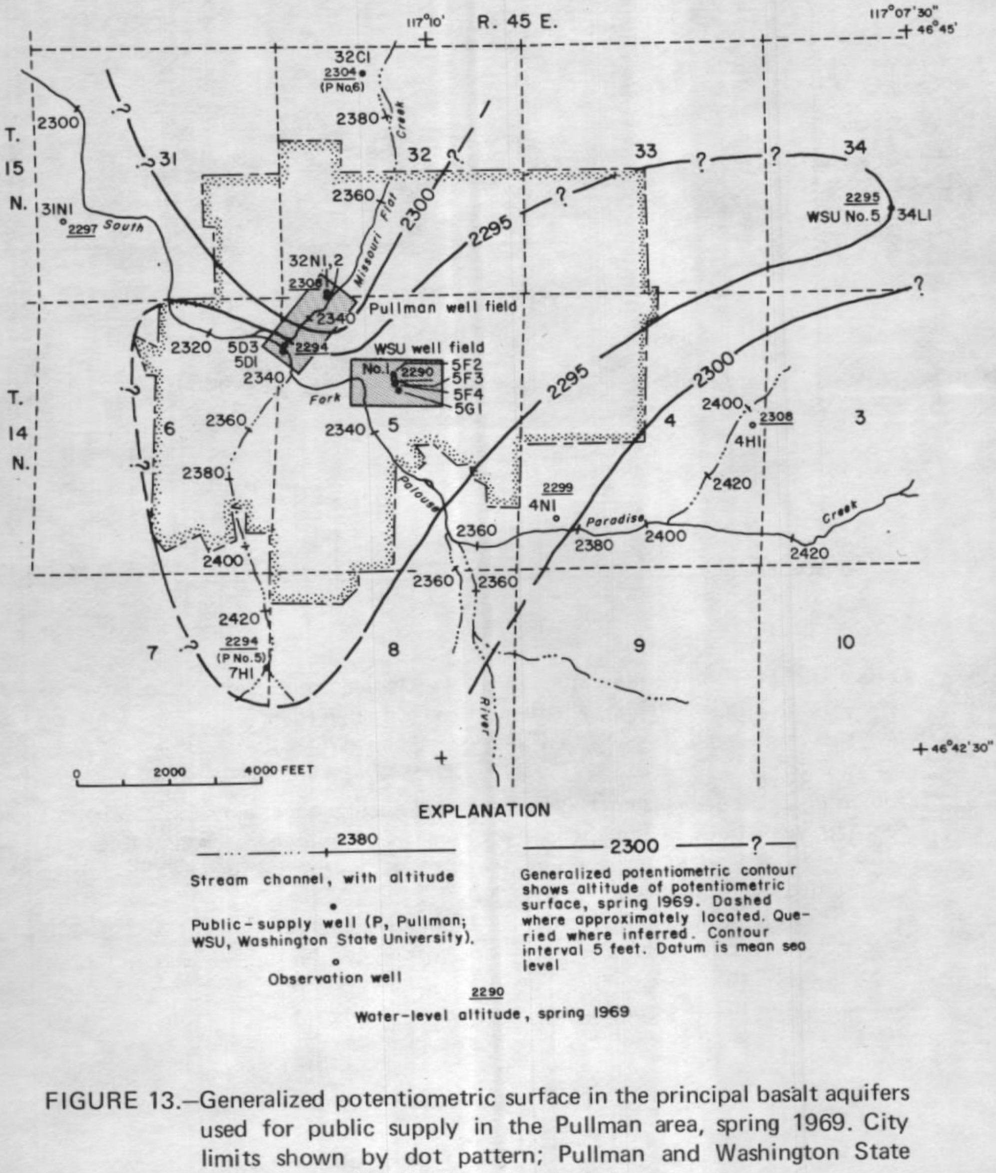

FIGURE 13.—Generalized potentiometric surface in the principal basalt aquifers used for public supply in the Pullman area, spring 1969. City limits shown by dot pattern; Pullman and Washington State University well fields shown by shaded areas.

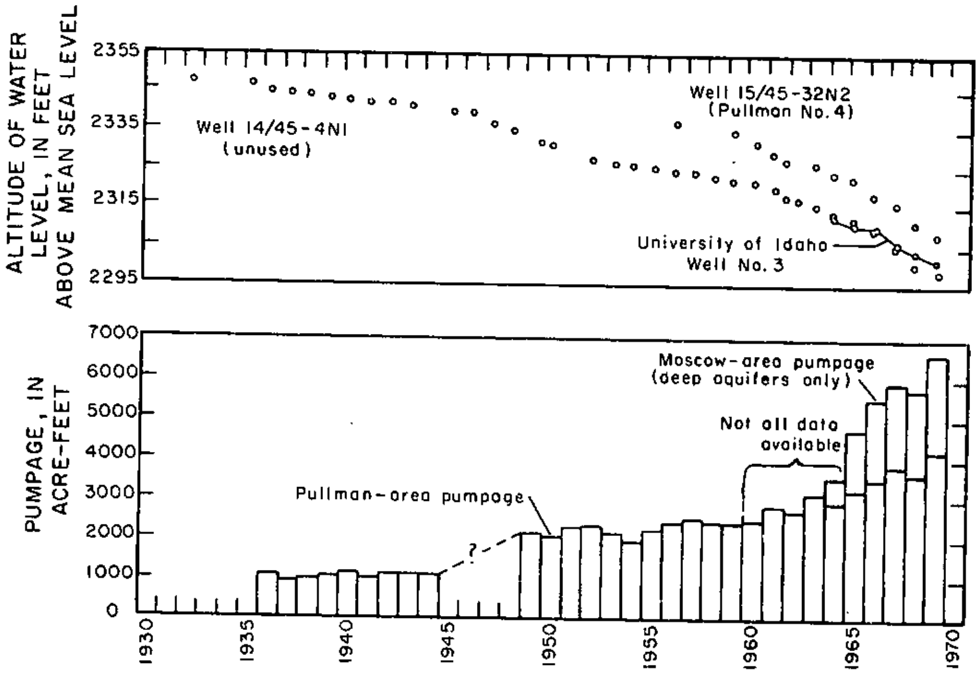

FIGURE 14.—Springtime water levels in selected wells and annual pumpage near Pullman, Washington and Moscow, Idaho.

shown in figure 13. During 1965-69, rates of decline have increased to about 3 feet per year, both in the shallow aquifers, as represented by well 14/45-4N1 (100 ft deep), and in the aquifers at depths between 400 and 1,000 feet, as represented by Pullman well 15/45-32N2.

The ground-water gradients near Pullman are relatively flat (fig. 13) and, according to Foxworthy and Washburn (1963, p. 33), they could not have become much steeper over the years of continued pumping. This would suggest that a relatively flat potentiometric surface extends to near the boundaries of the ground-water reservoir. The boundaries probably are the older granitic and metamorphic rocks (pl. 1), which form a broken rim of hills around the topographic basin that includes Pullman and the city of Moscow, Idaho (8 miles east of Pullman).

Foxworthy and Washburn (1963, p. 14), suggested the existence of a ground-water barrier crossing the basin between the two cities near the Washington-Idaho border. For years Moscow and Pullman have obtained their public-water supplies largely from shallow artesian aquifers in the basalt. Moscow has experienced declining water levels, but the rates of decline there were different than those recorded in Pullman. According to Foxworthy and

Washburn (1963, p. 42), the differing rates of decline, the significant differences in altitudes of the potentiometric surfaces, and the differences in chemical composition of the ground water suggested that the two pumping centers were hydrologically isolated from one another. Since the study by Foxworthy and Washburn (1963), nearly all pumping for public supply in the Moscow area has shifted to three new deep wells (Jones and Ross, 1969, p. 2), two of which fully penetrate the basalt sequence and reach granitic rock at depths of about 1,300 to 1,400 feet. Water levels in the latter two wells (Moscow no. 8 and Univ. Idaho no. 3, locations not shown) stand at an altitude of about 2,300 feet, considerably below the water levels in the upper aquifers of the Moscow area and at about the same altitude as the potentiometric surface at Pullman (fig. 14). This fact was recognized by Chang-Lu Lin (1967, p. 75), who suggested the possibility that the two potentiometric surfaces are correlative. Also, according to Ross (1965, p. 60-65), the chemical character of water from the deeper confined aquifers tapped by the University of Idaho well no. 3 resembles more closely the character of water in the wells at Pullman (Foxworthy and Washburn, 1963, p. 30) than that of the water from the formerly pumped upper aquifers at Moscow.

Water levels in wells tapping the upper aquifers at Moscow declined about 100 feet (from altitude 2,550 to 2,450 ft) during 1900-60. Since the shift to withdrawals from deeper aquifers during 1960-65, heads in the upper aquifers have risen and by April, 1969, had reached an altitude of 2,497 feet, achieving overall recovery of 47 feet (Jones and Ross, 1969, p. 2). The effect of this recovery is not evident in the hydrographs for wells at Pullman (fig. 14), which show an accelerated rate of decline during 1960-69. The decline of heads in the deeper confined aquifers at Moscow since 1965, has been a little more than 2 feet per year (fig. 14, Univ. Idaho well no. 3), or just slightly less than the 3-feet-per-year rate of decline at Pullman for the same period.

The above evidence strongly suggests that (1) prior to 1960, pumpage and water-level declines at Pullman and Moscow were occurring in aquifers vertically and hydraulically separated from one another, those at Moscow being at a higher level; and (2) the newly tapped deeper aquifers at Moscow are probably correlative with and hydraulically connected with aquifers used for public supply at Pullman. Therefore, accelerated rates of decline at Pullman may be due in part to pumpage in the Moscow area as well as increased pumping at Pullman. The combined total pumpage from both areas in recent years has averaged about 6,000 acre-feet (fig. 14).

An important factor contributing to the decline in the Pullman area is the small areal extent of basalt underlying the Pullman-Moscow basin. The area probably is less than 130 square miles, of which an area of about 16 square miles is in Idaho. The lateral extent of head decline caused by the many years of pumping at Pullman is not known; however, the relatively flat gradients would suggest that a substantial area of the Pullman-Moscow basin is involved.

Coulee City Area

Hydrographs of wells in the Coulee City area (fig. 15) reveal no evidence of long-term decline, even though the pumpage has averaged about 3,500 acre-feet during the past several years. Possibly Banks Lake is an effective source of recharge to basalt aquifers in that area.

Wilbur Area

Well 26/32-11G1 near Wilbur (fig. 16) had a spring-to-spring rise in water level of about 5 feet during 1967-69. However, the well is shallow and is in a coulee that carries runoff during parts of the year, and therefore it tends to respond rapidly to recharge. Well 26/33-34P1, on a plateau and tapping the deeper basalt aquifers, had a water-level decline of about 4 feet during the same period. Pumping withdrawal near Wilbur is mainly within about a township-size area and has increased from about 1,100 acre-feet in 1966 to 2,300 acre-feet in 1968.

Davenport Area

Wells 25/36-21J1, 27Q1, and 25/37-20P2 near Davenport (fig. 17) had net water-level declines ranging from 5 to 17 feet during 1967-69, or about 2 to 6 feet per year. The decline apparently is in response to pumping, which increased slightly from 2,100 acre-feet in 1966 to 2,500 acre-feet in 1968, and which was mainly from wells in three townships (pl. 3). Most of the pumpage is from an area about the size of one township.

Cheney-Airway Heights Area

Hydrographs of wells in the Cheney-Airway Heights area (fig. 18) show gradual spring-to-spring declines of water level in localities of intensive pumping (wells 23/41-19R1 and 25/42-30A1) but no discernible decline in levels in a locality of lesser pumping (24/42-6J1). Net declines during 1967-69 have ranged from 4 to 8 feet, or about 2 to 4 feet per year. Pumpage during 1967 and 1968 averaged about 1,000 to 1,100 acre-feet per year in each of the three townships (T.23 N., R.41 E.; T.24 N., R.41 E.; T.25 N., R.42 E.) where most of the withdrawals occurred (pl. 3).

Canniwai Creek Area

To the north of the Odessa area, and lying partly within the drainage basin of Canniwai Creek, is an area where pumpage for irrigation increased from about 1,100 acre-feet in 1963 to 6,300 acre-feet in 1968. Most of the pumpage was from T.23 N., R.32 E., and T.24 N., R.32 E. (pl. 3). The number of irrigation wells increased during that period from 4 to 15. Hydrographs of two wells in the area (fig. 19), 180 and 712 feet deep, for 1967-69, show a definite spring-to-spring downward trend, amounting to about 17 feet in the shallower well and 13 feet in the deeper well.

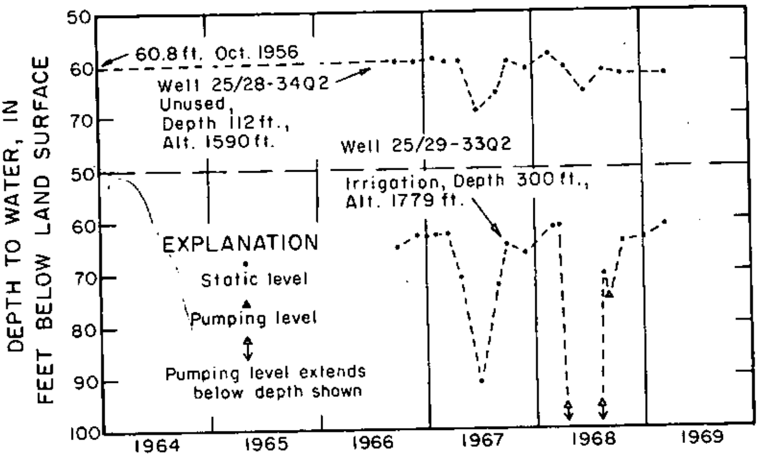

FIGURE 15.—Hydrographs of selected wells near Coulee City, 1956-69.

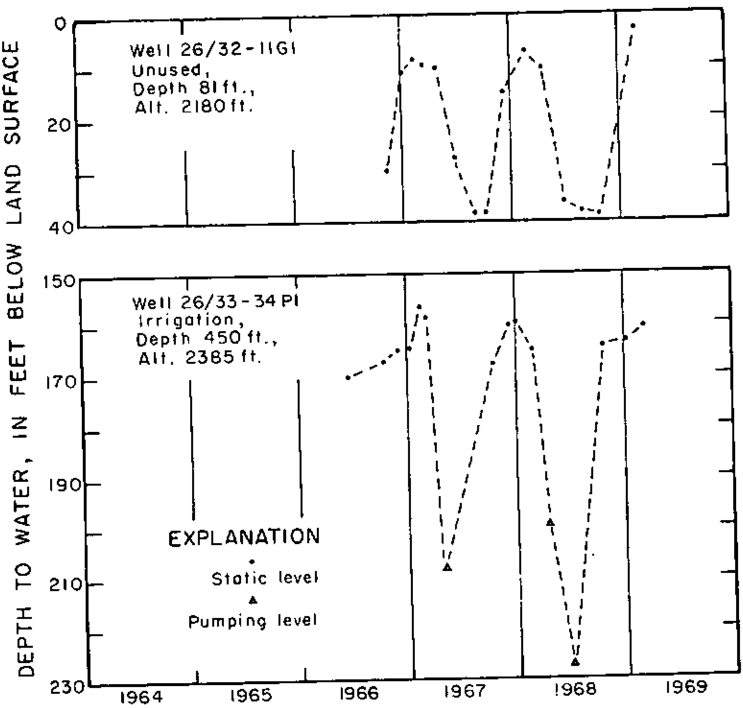

FIGURE 16.—Hydrographs of selected wells near Wilbur, 1966-69.

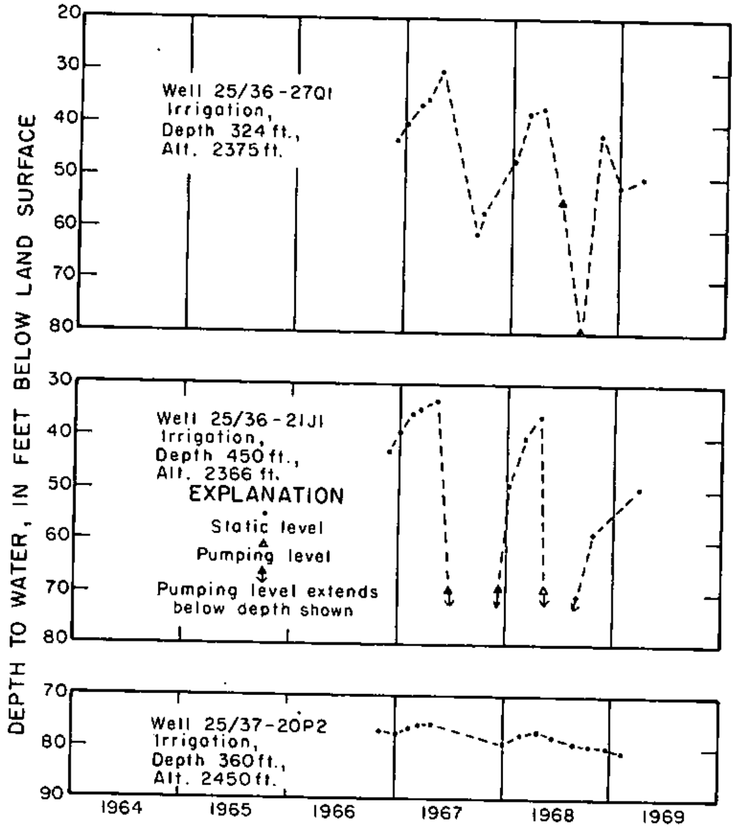

FIGURE 17.—Hydrographs of selected wells in Davenport area, 1966-69.

Ritzville Area

Hydrographs of wells in the Ritzville area (fig. 20) generally showed only minor year-to-year water-level changes through the spring of 1969. However, measurements of well 19/36-20H1 showed an apparent net decline in water level of about 15 feet during 1966-69 or an average of 5 feet per year. Pumpage from the three townships in which the observation wells near Ritzville are located actually is from an area less than a township in size centered just southeast of Ritzville (pl. 3). Total pumpage in the township-size area increased from about 1,500 acre-feet in 1965 to about 4,000 acre-feet in 1968.

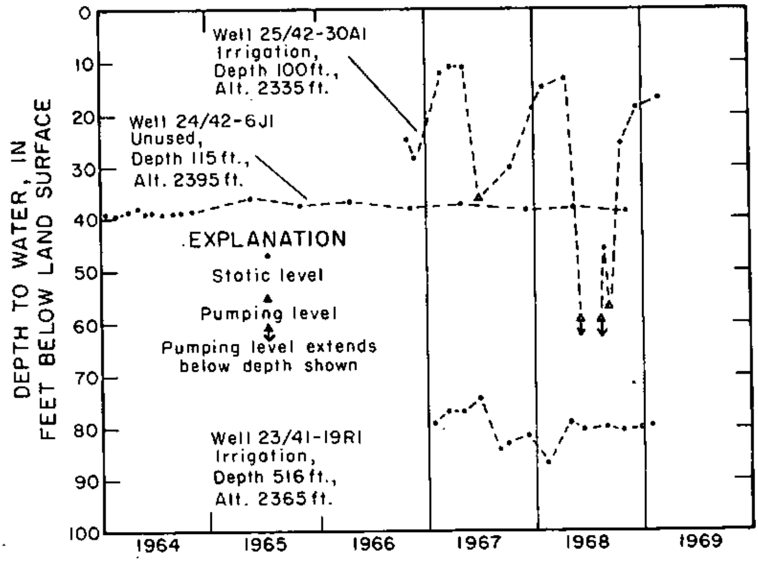

FIGURE 18.—Hydrographs of selected wells in Cheney-Airway Heights area, 1964-69.

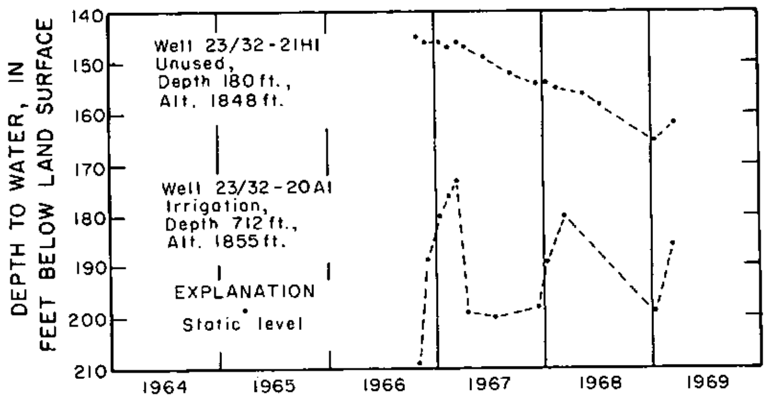

FIGURE 19.—Hydrographs of selected wells in Canniwai Creek area, 1966-69.

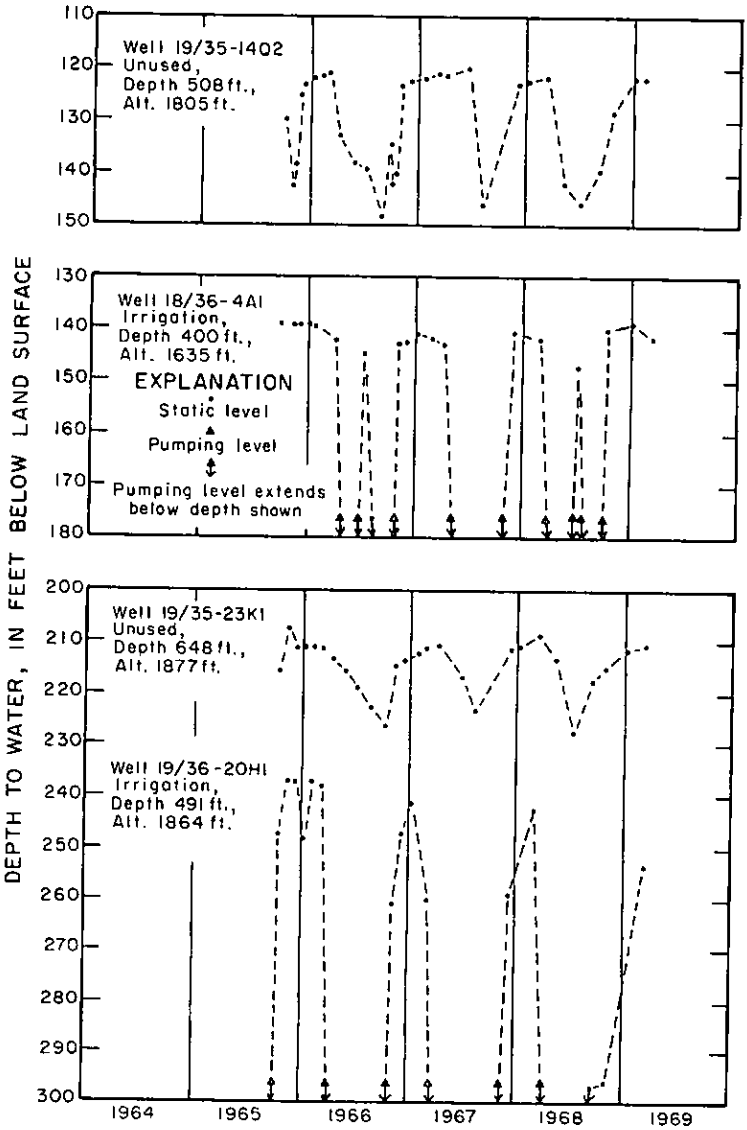

FIGURE 20.—Hydrographs of selected wells in Ritzville area, 1965-69.

Cunningham Area

Most of the pumpage in the Cunningham area is from townships lying north, west, and southwest of the town (pl. 3). Pumpage in the area increased from about 3,100 acre-feet in 1963 to 15,600 acre-feet in 1968. During that period the number of irrigation wells in the area increased from seven to 20.

The greatest effect of pumping in the area on water levels is near Providence Coulee, about 4 miles northeast of Cunningham. There, water levels declined a maximum of about 13 feet from spring 1967 to spring 1969 (fig. 21, well 16/32-14A1). The hydrograph of well 16/33-26J1 (Pl. 3) indicates that the declining trend extends farther east. By 1969, a declining trend was not evident in the townships to the west and southwest of Cunningham (fig. 21, well 16/31-28Q1), even though more than half the pumpage in the general area was from those townships. It is possible that water percolating downward from the East Low Canal, and from irrigated lands served by the canal, was supplying enough recharge to the pumped aquifers to partly offset the pumping decline.

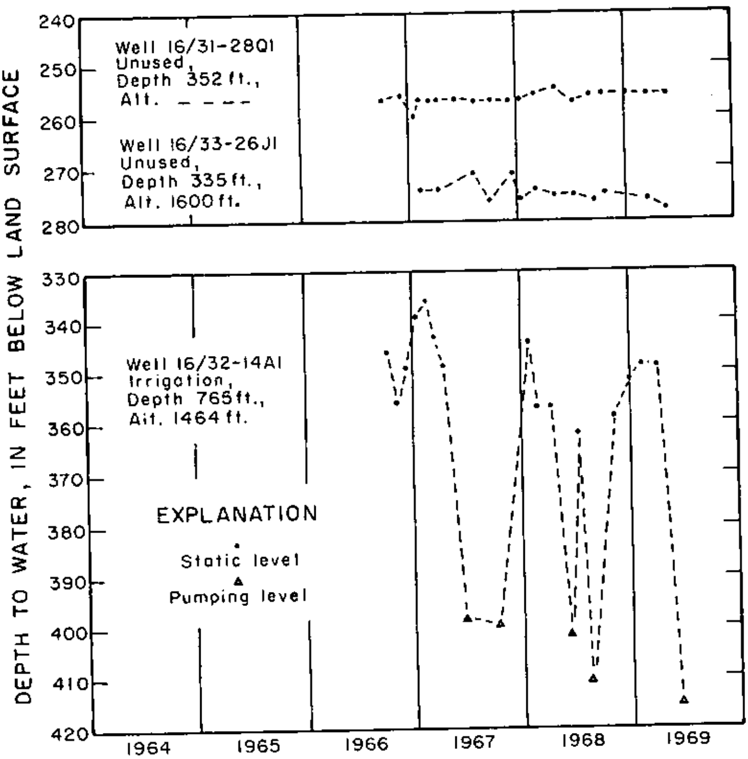

FIGURE 21.—Hydrographs of selected wells in Cunningham area, 1966-69.

Connell-Kahlotus Area

Hydrographs of wells in Washtucna Coulee (fig. 22) near Connell and Kahlotus show no evidence of a year-to-year water-level decline. Water is withdrawn from wells distributed along the coulee floor from Connell to an area northeast of Kahlotus (pl. 3). Pumpage in the lower part of the coulee near well 13/32-1F1 increased from about 1,500 acre-feet in 1966 to about 2,600 acre-feet in 1968, whereas pumpage in the part of the coulee northeast of Kahlotus averaged only about 500 acre-feet, somewhat lower than in previous years (pl. 3).

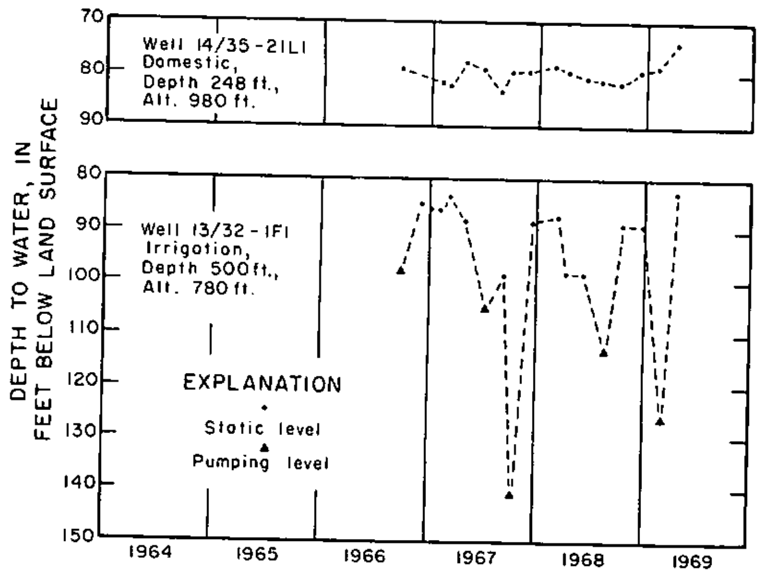

FIGURE 22.—Hydrographs of selected wells in Connell-Kahlotus areas, 1966-69.

PREDICTION OF AQUIFER RESPONSE TO FUTURE PUMPING

Aquifer Zone B near Odessa

If the hydraulic properties of an aquifer or series of aquifers are known, their response to pumping can be predicted. The reliability of the prediction is dependent upon how closely the aquifer system fits the rigorous assumptions defined for a theoretical ground-water-flow system and, of course, upon the accuracy of the data and interpretations used in the analysis. For aquifer zone B near Odessa, an estimate of the storage coefficient, one of the most significant of the hydraulic parameters in these predictions, was derived on the basis of a broad-scale aquifer test of about 7-months duration, as discussed previously. Similarly, estimates of transmissivity were based largely on lengthy specific-capacity tests. Because of the long-term basis for their derivation, these hydraulic parameters for the Odessa area should be especially suitable for making predictions. Basalt aquifers doubtless are complex in detail but, when considered over a large area, their response to an intense pumping development, such as that in the Odessa area, appears to be fairly uniform. Therefore, it is assumed that the interpretations and hydraulic properties as determined for aquifer zone B near Odessa are fairly representative of actual conditions, and can be used to predict the magnitude of the water-level decline that may occur there.

A graphical technique described in detail by Conover and Reeder (1963, p. C38-C44) for the prediction of drawdown in heavily pumped areas was used by the writers to estimate water-level declines in the Odessa area for 1967-77. The technique involves the preparation of a special drawdown scale that reflects the hydraulic properties of the aquifer zone, the length of time the well is pumped, and the quantity pumped. For this study, a scribed plastic scale was constructed from each of two curves (fig. 23) which gives the solution of the Theis nonequilibrium formula (Ferris and others, 1962, p. 92-98). Each scale, one for each side of the ground-water dam, represents the drawdown, at various distances, caused by a single well pumping at a uniform rate of 100 acre-feet per year. To ascertain the expected drawdown at a given point on a map, preferably one not immediately adjacent to pumped wells, the scale is rotated about the point, and the accumulated drawdowns caused by all pumped wells in the area are tabulated to predict net drawdown at the point.

This method assumes the following: (1) Transmissivity and storage properties, as calculated, are uniform on either side of the ground-water dam (fig. 4); (2) the ground-water dam is an impermeable boundary along its entire length; (3) Crab Creek is not a significant recharge boundary; (4) the East Low Canal and its laterals, which supply irrigation water to the west, are not significant recharge sources; (5) recharge from precipitation and irrigation-return flow, or from aquifer zone A, is not significant during the prediction period; (6) each well is pumped continuously and uniformly for the entire 10-year period at the 1967 annual rate; and (7) no new deep wells are drilled, and pumpage in the area is held at the 1967 rate.

The most significant hydraulic boundary in the area is the ground-water dam. Because it is assumed that no flow occurs across the boundary, the drawdowns induced by real pumped wells on each side were reflected across the boundary once, and the image effects (Ferris and others, 1962, p. 144-166) were added to the total predicted drawdown at the selected points. The individual points of drawdown throughout the area were then used as control for preparing a map showing lines of equal water-level decline (fig. 24).

Although the map of predicted water-level decline (fig. 24) is not suitable for accurate prediction of the water levels at specific sites, a comparison of the predicted decline with recent water-level trends indicates the analysis is generally reasonable. The map indicates rates of decline as much as 8 to 18 feet per year.

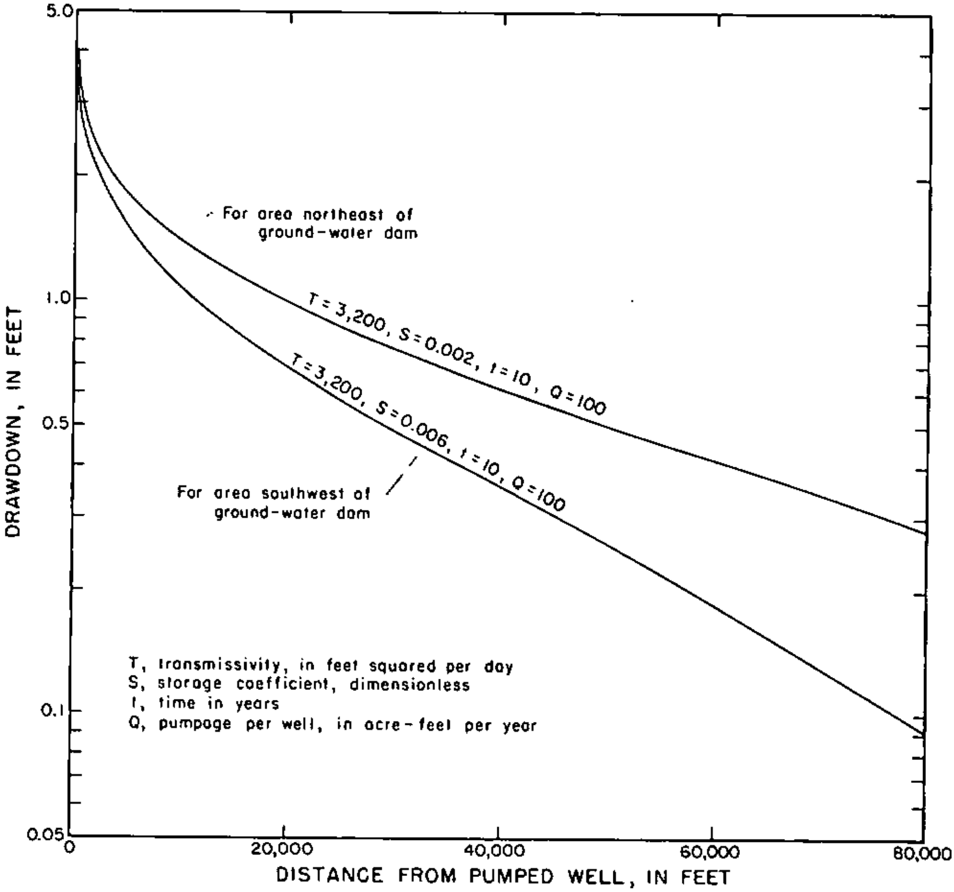

FIGURE 23.—Distance-drawdown curves used for scaling drawdown in aquifer zone B near Odessa.

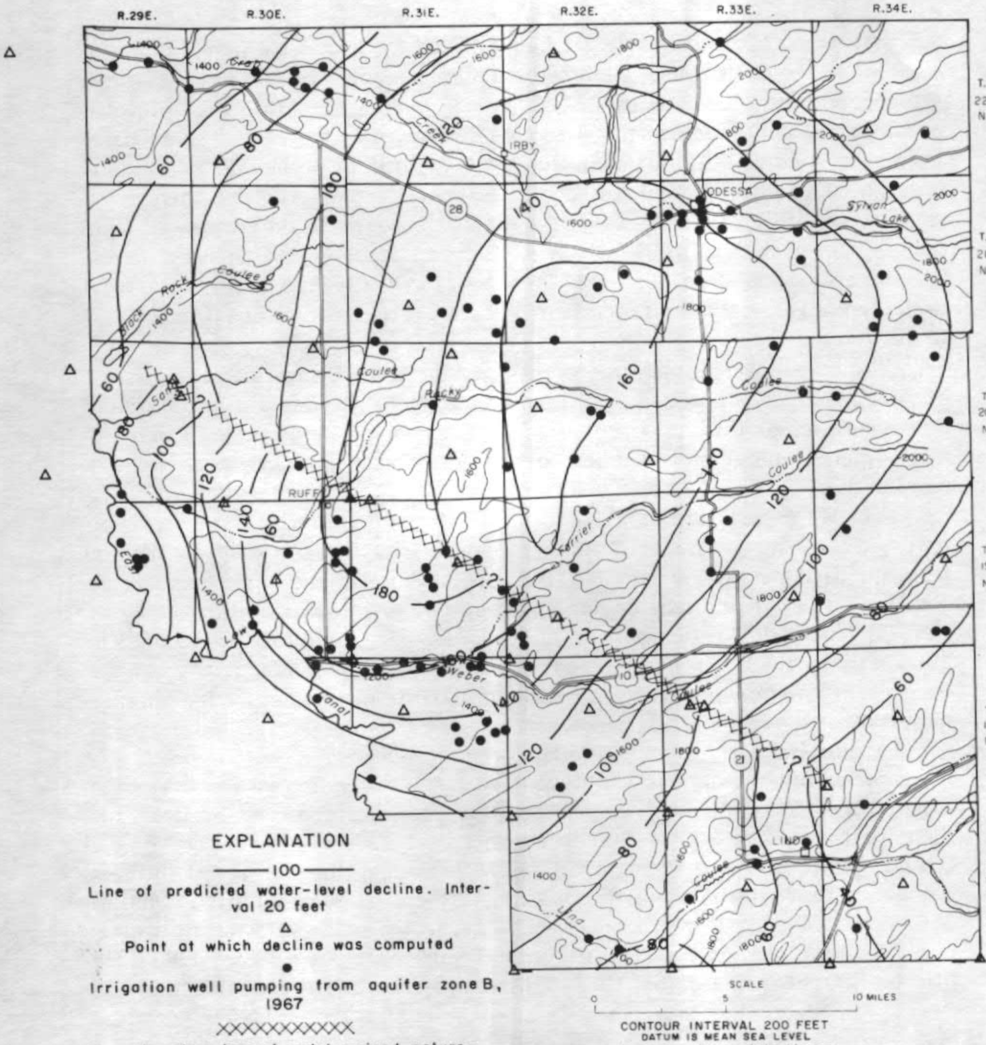

FIGURE 24.–Predicted decline of potentiometric surface of aquifer zone B (lower zone) near Odessa, 1967-77.

Similar rates of decline have already been detected in areas of heaviest withdrawal (fig. 12).

Although additional wells are being drilled for large-scale pumping in and adjacent to the Odessa area, the projected pumpage for 1968 was lower than the actual pumpage. (See discussion of annual pumpage.) Also, the projected water-level declines appear to be too small. However, the effects of recharge from zone A to zone B, not included in this method of projection, would tend to make the projected declines too large. The effect of assuming there is no recharge probably would outweigh the effect of the moderate increase of 1968 pumpage over that of 1967, which is likely to occur in and adjacent to the Odessa area. Therefore, figure 24 may represent the maximum water-level declines more closely than it represents the average declines in zone B from 1967 to 1977.

Prolonged decline of water levels in aquifer zone B may eventually result in widespread reduction of heads in aquifer zone A, and perhaps in the virtual drainage of some of its uppermost aquifers. The problem could be acute in many areas where zone A is the source of water for domestic and stock wells, a number of which already have gone dry.

The water-level decline in each aquifer zone should cause some depletion of dry-season streamflow in Crab Creek above Irby (fig. 5); low-flow records from the gaging station at Irby (fig. 25) suggest that depletion may have started already. The average discharge during the 90-day low-flow period of each year (fig. 25) has gradually diminished from about 8 cfs (cubic feet per second) in 1960 to about 1.5 cfs in 1968. It is not known how much, if any, of the decrease in low flow is a result of below-normal precipitation in the region. (See discussion of the regional hydrologic setting.)

An inevitable effect of continued water-level decline in aquifer zone B will be increased operational costs to the irrigator. Already, pump intakes have been lowered in many wells, and some wells have been deepened. As of 1967, the pumping levels were 300 to 500 feet below land surface in large parts of the Odessa area (Luzier and others, 1968, fig. 7). Including a head of about 150 feet required for pressure in the sprinkler systems, the total pumping lifts are 450 to 650 feet in large parts of the area. According to the predicted rates of decline (fig. 24), large areas northeast of the ground-water dam may have total pumping lifts of 600 to 700 feet by 1977. This is based on the assumption that the

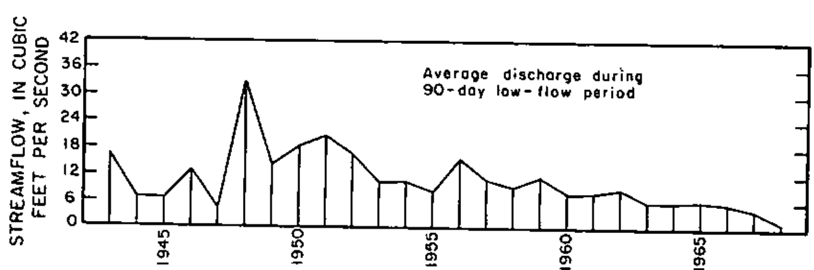

FIGURE 25.—Low flow of Crab Creek at Irby, 1943-68.

irrigator will continue to pump at the 1967 rate. In all probability, pumping rates will decrease in some localities because of uneconomical pumping lifts and, as a result, the water levels may stabilize above the predicted levels.

Aquifers in Pullman Area

The persistent decline of artesian heads in the Pullman area (fig. 14) probably will continue with the increase in combined pumpage from the areas of both Pullman and Moscow, Idaho. The hydraulic properties of the aquifers in the Pullman area are not known in sufficient detail to use the graphical technique for decline prediction, as was done for the Odessa area. However, the long-term hydrographs (fig. 14) show fairly good correlation with the combined volume of pumpage from the Pullman and Moscow areas, and a simple projection of the hydrographs probably would be useful in estimating the additional decline of water level expected by 1980. A straight-line projection of the downward trend in water levels of wells 14/45-4N1 and 15/45-32N2 (fig. 14), for 1964-69, suggests that by 1980 the potentiometric surface in the Pullman area (fig. 13) will be lowered by about 30 feet or more below the 1969 position. This estimate could be inaccurate if there is much change in the future pumping distribution or in the volume of ground-water withdrawal from the Pullman-Moscow basin. Also, the declines at Pullman could accelerate if the effects of pumping in the Moscow area reach westward to Pullman.

Depths to water in the principal public-supply wells in the Pullman area as of 1969 are generally between 50 and 150 feet below land surface. By 1980 this range in depth to water may approach 100 to 200 feet. At least seven of the public-supply wells in use as of 1969 are 164 to 275 feet deep, one is 396 feet deep, and two are more than 500 feet deep. By 1980, some of the shallower wells probably will have to be abandoned or deepened because of declining water levels. In addition to those wells, there are a number of small-yield industrial and private wells less than 300 feet deep that are likely to be similarly affected.

Potential Problems Elsewhere in the Study Area

Ground-water depletion and associated problems that have occurred in the Odessa and Pullman areas undoubtedly will be repeated elsewhere in the study region where intensive withdrawals from the basalt continue. Under intensive pumping, water levels will continue to decline except where surface water (lakes, streams, canals) can recharge the basalt in amounts equal to ground-water discharge. This cause-and-effect relation has been noted previously in areas of large-scale pumping from basalt of the Columbia River Group, not only in Washington (Taylor, 1948, p. 42; Price, 1960, p. 11), but also in Oregon, as in the areas of The Dalles (Foxworthy and Bryant, 1967, p. 12) and Salem (Foxworthy, 1970, p. 14).

In areas of present (1969) intensive pumpage from deep aquifers, drainage of shallower aquifers generally will be accelerated as the heads in the deeper zones decline. As seen in the Odessa area, a significant part of that downward leakage will be localized in the unlined bores of existing wells. In the future, the severity of well interference can be decreased by spacing large-yield wells as widely as possible, Also, the rate of decline in the upper zones can be minimized by casing these zones in the deeper wells.

Near the northern and eastern margins of the basalt, there are places where the flow layers are thin and overlie impermeable bedrock, There, the total volume of water stored in the basalt is relatively small. In the marginal areas of the lava flows intensive pumping may ultimately eliminate the basalt as an economic water source by dewatering all the productive aquifer zones. Natural recharge in those parts of the region may be so small that many decades would be required for replenishment of the aquifers.

For the general areas of major pumping withdrawals indicated by the patterns on plate 3, the outlook is briefly outlined below. In the following discussion, water-level declines refer to spring-to-spring declines in the water levels in wells penetrating large-yield basalt aquifers (generally deep or moderately deep). Predictions of future declines are based generally on short-range effects of present (1969) pumpage or anticipated increases in pumpage based on recent trends.

Coulee City Area

Continued pumping at about the same rate in the Coulee City area probably will not cause major decline of water levels unless there is an increase in pumpage from adjacent areas. Areas of fairly thick loessal soils northeast and east of Coulee City are suitable for farming, and the need for ground-water supplies for irrigation could affect local water levels there.

Wilbur Area

Pumpage from basalt aquifers in the Wilbur area more than doubled during 1966-68 (pl. 3), and is expected to increase further. The presence of relatively thick loessal soil (pl. 1) is favorable for irrigation farming, and the increased production from irrigation in nearby areas probably will encourage greater withdrawals from the basalt near Wilbur. The decline in water levels due to major pumping is expected to be high in this area for two reasons: (1) the drawdown resulting from the intensive pumping in the Odessa and Cannawai Creek areas can be expected to spread toward the Wilbur area, and (2) the area is near the northern boundary of the basalt plateau (pl. 1), where the basalt is thinner than it is farther south and the granitic and metamorphic rocks greatly limit the movement of ground water from the north and east.

Davenport Area

Decline of water levels related to pumping from basalt aquifers apparently has been greater, in relation to the amount pumped, in the Davenport area than in most other parts of east-central Washington. This may be due partly to the underlying granitic and metamorphic rocks, which are extensively exposed about 7 to 12 miles north, east, and southeast of Davenport. Because these rocks serve as a virtually impermeable hydraulic boundary, any sizable increases in pumping in the Davenport area probably will cause an acceleration in the rates of water-level decline in the area. However, pumping in adjacent areas probably will have little effect on water levels in the Davenport area. Pumpage has been small in adjoining areas to the south and west and is not expected to increase greatly, because vast areas of land in these directions are underlain by scabland basalt without arable soil.

Cheney-Airway Heights Area

The basalt aquifers in the Cheney-Airway Heights area are relatively isolated hydraulically from the rest of the basalt plateau by intervening knobs and ridges of the granitic and metamorphic rocks (pl. 1). In much of the area the basalt is only a few hundred feet thick or less, and is underlain by or interlayered with silt and clay (Latah Formation) of low permeability. Although the rate of water-level decline in the area has not been generally high, it may increase sharply if pumpage becomes intensive. Where the basalt is thin and includes only one or a few permeable flow-contact zones, there is a risk that water-level declines will result in actual dewatering of the only aquifer zones locally available.

Canniwai Creek Area

Water-level declines will continue in the Canniwai Creek area if the present (1969) pattern of pumping continues; also, the recent rates of decline are likely to increase. As the lines in figure 24 show, declines caused by pumping in the Odessa area are predicted to spread northward into the Canniwai Creek area and by 1977, the total decline in this area probably will amount to a few tens of feet.

Ritzville Area

Water-level declines in the Ritzville area will remain moderate unless pumpage increases considerably. However, declines resulting from continued pumping in the adjacent Odessa area (fig. 24) are predicted to extend into this area and, if the present (1969) pattern of pumping continues, the total decline of levels in the Ritzville area may amount to several tens of feet by 1977. Pumpage probably will not increase greatly east, northeast, and southeast of the Ritzville area, where extensive scabland areas are not suitable for irrigation farming.

Cunningham Area

In the Cunningham area, pumpage is more concentrated and increased more during 1963-68 than in any other part of the region except the Odessa area to the north (pl. 3). Therefore, sizable water-level declines are anticipated, even though they were not apparent in 1969 measurements (fig. 21). Water pumped from storage in the basalt aquifers may be partly recharged by downward percolation from the East Low Canal and irrigated lands served by the canal; however, it is unlikely that this vertical leakage can keep pace with the pumpage from the deep basalt aquifers. Therefore, the water-level declines are expected not only to continue and to increase yearly, but also to spread to the east and west beyond the Cunningham area.

Connell-Kahlotus Area

Water levels in the Connell-Kahlotus area appear to be relatively stable at the present rate of pumping. If pumpage increases significantly, declines probably will be greater in the western part of the area, near Connell, because the pumpage has been greater there than it has been farther east.

SUMMARY AND CONCLUSIONS

Ground water in the basalt is the only available source of large quantities of good-quality water in much of east-central Washington. The water occurs within a thick sequence of lava flows—the basalt of the Columbia River Group—and is derived mainly from sheetlike permeable flow-contact zones between thicker, less permeable parts of the basalt layers. The overall movement of ground water in the basalt underlying the region is in a southwesterly direction, corresponding with (1) the slight regional dip of the basalt and (2) the difference in altitudes between the main ground-water recharge areas in the northern and eastern parts of the region and the main discharge area (the hydraulic base level) at the Snake River along the southern margin of the area.

In some parts of the region, the ground water in the basalt is being depleted by large-scale pumping, notably in the Odessa and Pullman areas. Conditions which foster this depletion are summarized as follows:

1. Although the basalt is capable of yielding large quantities of water to wells, it contains relatively small volumes of ground water per unit volume of rock. The average of the median specific-capacity values for 342 multi-aquifer irrigation wells in the 8,400-square-mile study region is about 12 gpm per foot of drawdown. Storage coefficients, computed by volumetric analyses of seasonal pumping drawdowns for two areas near Odessa totaling about 400 square miles, are about 0.002 and 0.006—in the range commonly attributed to "leaky artesian" conditions.

2. Pumpage of ground water from basalt aquifers in the study region, as calculated from electrical power consumption, increased from about 44,000 acre-feet in 1963 to about 149,000 acre-feet in 1968. At least half the total pumpage in 1968 was from a 1,100-square-mile area near Odessa.

3. Water in the permeable flow-contact zones is confined generally between the adjacent less permeable parts of the basalt layers. Under such confined conditions, the drawdown resulting from pumping is widespread, and interference between two or more nearby pumping wells in an area commonly increases the decline of ground water levels at each of the wells.

4. Precipitation, the only basic source of recharge in most of the region, is generally meager. Although there is some vertical movement of ground water through joints and fractures in the dense parts of the basalt layers, the cross-bed percolation of the ground water is very slow. Because of these two conditions—the small amount of precipitation available for recharge and the slow cross-bed leakage—the natural recharge to the most productive basalt aquifers normally cannot keep pace with large-scale withdrawals.

5. Except in a few areas of the region, the hydraulic heads decrease progressively from one aquifer zone to another with increased depth. Because most wells in the region are not cased through most of the basalt they penetrate, the deep wells generally act as conduits between shallow and deep aquifers. The condition of decreasing head with depth results in continuous down-hole flow from shallow aquifers to deeper aquifers of lower head. This situation has contributed to the significant drainage of upper aquifers used for domestic supply, particularly in the intensively pumped Odessa area.

6. Although most aquifer zones are areally extensive, some individual aquifers pinch out laterally, and the area in which they are conduits for ground water is thereby limited. Also, there are internal barriers to ground-water movement, such as the buried ground-water dam near Odessa. Some aquifers near the margins of the basalt plateau terminate against hills and ridges of impermeable granitic and metamorphic rocks. The effects of these hydraulic boundaries often are not apparent during short-term pumping withdrawals but, over a long period of time, they are reflected by increased rates of water-level decline.

In the Odessa area, ground-water levels have been declining at rates ranging from 2 to more than 10 feet per year since about 1965. Declines of water levels in wells tapping deep aquifers (aquifer zone B) near Odessa during 1967-77 may be as much as 8 to 18 feet per year, if annual pumpage is maintained at the 1967 rate of about 53,000 acre-feet.

Persistent, long-term declines at Pullman have continued at increasing rates and, by 1969, were averaging about 3 feet per year. The increased rate of decline probably is due not only to increased pumpage in the Pullman area, but also to pumping from deep aquifers at nearby Moscow, Idaho. Projection of existing rates of decline suggest that the potentiometric surface in the Pullman area may be lowered about 30 feet or more during 1970-80.

For most other areas of east-central Washington, water-level trends and their relation to pumpage are not yet (1969) adequately defined. However, throughout broad areas of the region the basalt aquifers apparently are capable of yielding water at large rates but they have a generally poor capacity for ground-water storage. Also, the short-circuiting effect of deep wells is the rule rather than the exception. Together, these conditions lead to the general conclusion that well interference and water-level decline can be expected to occur fairly early in the development of ground water from the basalt aquifers.

Local geohydrologic conditions will determine the potential for, and extent of, water-level declines resulting from pumping from the basalt aquifers. In some areas where current or anticipated ground-water withdrawal is large, the effects of intensive pumping in adjacent areas will tend to accelerate the year-to-year decline of ground-water levels. Examples are the Cunningham and Cannawai Creek areas, adjacent to the intensively pumped Odessa area. In areas near the margins of the basalt plateau, such as the Pullman and Cheney-Airway Heights areas, the proximity of impermeable boundaries can be expected to cause relatively rapid water-level declines in response to pumping from the basalt. In such areas where the basalt is thin and the aquifer zones few, water-level declines may result in dewatering of the available ground-water reservoir. Conversely, in areas where there is a potential for additional recharge water, decline of water levels may be slowed. Such a possibility exists in the Coulee City area adjacent to Banks Lake, in the Cunningham area adjacent to the East Low Canal, and in the irrigated lands served by the canal.

The ability of the basalt to yield water readily to wells, despite its low storage coefficient and relatively low annual recharge, fosters overdevelopment and depletion of the water it contains. Generally, within a few years after the discovery and early development of high-yield aquifers in an area, the communities, irrigators, and industries become committed to and dependent upon this ground-water resource before feeling the long-term effects of overpumping. Thus, there is an immediate need to establish an early evaluation of the local aquifer system and to determine its optimum yield and pattern of development, particularly in areas where large supplies of water from alternate sources are not economically available.

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Well-Numbering System

In this report wells are designated by numbers and letters that indicate their locations according to the official rectangular public-land survey of the United States. For example, in the symbol 21/32-21P1, the part preceding the hyphen indicates successively the township and range (T.21 N., R.32 E.) north and east of the Willamette base line and meridian. Because the report region lies entirely north and east of the Willamette base line and meridian, the letters indicating the directions north and east are omitted. The first number following the hyphen indicates the section (sec.21), and the letter "P" indicates the 40-acre subdivision of the section, as shown in the figure below. The numeral "1" indicates that this well is the first one listed within the subdivision. Where well numbers are shown on the maps, owing to space limitations and to avoid clutter, the township and range designations are omitted.

D	C	B	A
E	F	G	H
M	L	K	J
N	P	Q	R