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Calvin G. Clyde

Christopher J. Duffy

Edward P. Fisk

Daniel H. Hoggan

David E. Hansen

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MANAGEMENT OF GROUNDWATER RECHARGE AREAS IN THE MOUTH OF WEBER CANYON

by

Calvin G. Clyde, Christopher J. Duffy,
Edward P. Fisk, Daniel H. Hoggan,
and David E. Hansen

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Utah Water Research Laboratory
Utah State University
Logan, Utah 84322

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ABSTRACT

Proper management of surface and groundwater resources is important for their prolonged and beneficial use. Within the Weber Delta area there has existed a continual decline in the piezometric surface of the deep confined aquifer over the last 40 years. This decline ranges from approximately 20 feet along the eastern shore of the Great Salt Lake to 50 feet in the vicinity of Hill Air Force Base. Declines in the piezometric surface are undesirable because of increased well installation costs, increased pumping costs, decreased aquifer storage, increased risk of salt water intrusion, and the possibility of land subsidence. Declines in the piezometric surface can be prevented or reduced by utilizing artificial groundwater recharge.

The purpose of this study was to develop and operate a basin groundwater model with stochastic recharge inputs to determine the feasibility of utilizing available Weber River water for the improvement of the groundwater availability. This was accomplished by preparing auxiliary computer models which generated statistically similar river flows from which river water rights were subtracted. The feasibility of utilizing this type of recharge input was examined by comparing the economic benefit gained by reducing areawide pumping lifts through artificial recharge with the costs of the recharge operations. Institutions for implementing a recharge program were examined.

Through this process a greater understanding of the geohydrologic conditions of the area was obtained. Piezometric surface contour maps, geologic profiles, calibrated values for geologic and hydrologic variables, as well as system response to change were quantified.

ACKNOWLEDGMENTS

Funding of this project by the Utah Water Research Laboratory is gratefully recognized. The writers appreciate the ready cooperation and assistance given by federal, state, and county agencies, the Weber Basin Water Conservancy District, and private individuals.

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INTRODUCTION

Problem Description and Opportunity

Water availability and economics are of primary concern when contemplating further development of any area. Sufficient water supplies have been available in the past to accommodate the needs of the growing population along the Wasatch Front. The water easiest to obtain was utilized first. As these easy sources became fully appropriated, or as expansion increased into areas not supplied by surface water, groundwater became an important alternate supply.

Weber and Davis Counties, Utah, have typically been areas where subsurface water has been utilized to augment the surface water supply. During the early to mid 1900s the major use of groundwater was for agriculture. Within the last 20 years industrial and municipal water uses have greatly increased. In some locations, including the Weber Delta subdistrict of the East Shore area, this extraction has continued at a higher rate than the natural recharge to the area, and has resulted in a net depletion in groundwater storage. In the Weber Delta region, overdraft of the groundwater supply not only has increased pumping lifts and hence operational costs, but could also initiate land subsidence. Moreover, some potential exists for salt water intrusion from the Great Salt Lake.

Artificial groundwater recharge is a technique of introducing water into a groundwater system to enhance groundwater quality, reduce pumping lifts, store water, or salvage storm runoff or waste waters. Groundwater aquifers, just like surface reservoirs, can be used as storage facilities. In any reservoir the quantity of water stored and the amount available for use is reduced by losses from the system. In surface reservoirs these losses result from infiltration into the ground and from evaporation. The loss due to evaporation may be a significant quantity of water.

System losses in groundwater reservoirs can consist of water moving out of the system in any direction and in shallow aquifers by evapotranspiration. In groundwater systems water movement occurs very slowly compared to surface water movement. This allows groundwater systems to be used as storage reservoirs wherein evaporation is usually negligible.

Artificial groundwater recharge could be an important means, not only to stop, but also to reverse the long term downward trend in groundwater pumping levels. Artificially introducing water into the ground can be accomplished by surface spreading, ponding, or injection into wells. The area considered herein appears to be ideally suited to recharge through ponding due to the extremely porous alluvial materials found near the mountain front. Beginning a short distance west of the mountain front at the mouth of Weber Canyon, a confined aquifer system extends westward throughout the region. Many water users pump from this confined groundwater system and would benefit from the decrease in pumping lifts caused by artificial recharge.

Need for Artificial Recharge

Water level records have been obtained for selected wells in the East

Shore area starting in 1937 and water level contour maps have been prepared for specific years since that time. It appears that since the mid-1950s there has been a gradual trend towards declining groundwater levels. From the changes which have occurred in selected wells over the 1937-1980 period, a map was developed to show the areas of major drawdown in the principal artesian aquifer. Figure 1 shows the change in piezometric surface between 1937 and 1980 as well as other salient features of the area.

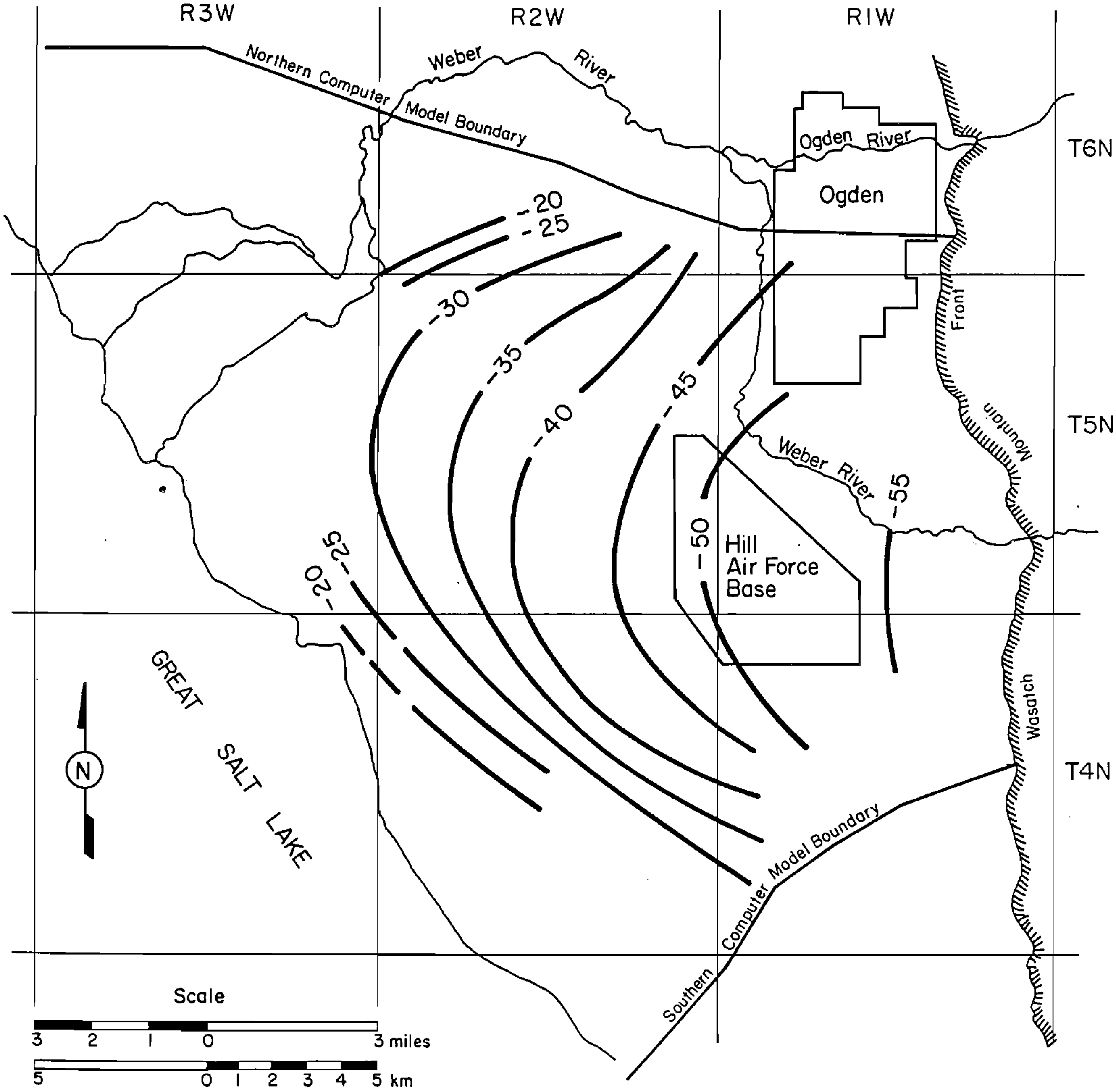

Figure 1. Change in piezometric surface for the Delta Aquifer between 1937 and 1980. Contours are lines of equal change in feet.

Since 1940 the groundwater reservoir in the confined Delta Aquifer system has declined by more than 50 ft (15 m) in the vicinity of Hill Air Force Base. If allowed to continue, the decline will result in increasing energy costs and at the same time will reduce the storage and recovery potential of the groundwater aquifer. This long term downward groundwater trend shows that an imbalance between the natural recharge and groundwater usage has caused a depletion of aquifer storage. However, there has been no appreciable change in piezometric surface on the outer fringes of the map of Figure 1. If artificial recharge could reverse the downward trend in water levels, economic benefits would accrue to present and future users of this groundwater resource.

Past Recharge Studies

Past artificial groundwater recharge studies completed within the State of Utah are centralized along the highly populated areas of the Wasatch Front. Studies have been completed in Utah Valley, Salt Lake Valley, and in Davis, Weber, and Box Elder Counties.

The first study for the Salt Lake area was done by A. J. Lazenby (1936). Two tests were performed within an area of approximately 5 m^2 (13 km^2) located along the east side of Salt Lake City. The general conclusions of these recharge tests were that groundwater recharge should be implemented to improve the capacity of groundwater withdrawal and to prevent mining of the groundwater reservoir.

Water spreading via canals was adopted by the City of Bountiful, Utah, in 1941 (Thomas 1949). The original intent of the spreading operation was to supply water to an artesian aquifer system during nonirrigation periods so that it might later be reclaimed for use. Unfortunately the spreading sites were not in direct hydraulic communication with the aquifer. Although the spreading project continued for approximately 7 years only a small portion of the applied water reached the confined aquifer system through a more pervious zone west of the recharge area. Perhaps the most important conclusion was that water spreading techniques are not universally applicable along the Wasatch Front, and extreme care should be taken to insure that the recharge waters can effectively reach the artesian aquifers.

The most thorough study of artificial groundwater recharge in Utah was conducted by the United States Bureau of Reclamation (Feth et al. 1966). Extensive drilling, research, and testing were completed in the Weber Delta area near the mouth of Weber Canyon during the early 1950s.

Four recharge experiments were conducted between 1953 and 1958 to test the response of the deep artesian Delta Aquifer system to artificial recharge. Recharge waters were diverted from the Weber River into an abandoned gravel pit approximately 0.25 mi (0.40 km) west of the canyon mouth. The first two experiments diverted an average of 7 cfs/ac (490 l/sec/ha) into the gravel pit during February and March of 1953. After 3 days from the start of recharge, an observation well 0.25 mi (0.40 km) west of the recharge pit started responding to the recharge waters and rose a total of 34 ft (10 m) during the experiment. Water levels in other wells being monitored from 3 to 6 mi (5 to 10 km) west of the recharge pit rose within a month.

The third recharge experiment was conducted from December 1954 to March 1955. Exceptionally cold weather and turbid water reduced the effectiveness of the test, but the response times and effects were similar to experiments 1 and 2.

The fourth recharge experiment was conducted from November 1957 to February 1958. The results showed an average of 3.5 ft (1.1 m) of increased head within the confined aquifer system after the groundwater mound in the recharge area had dissipated. The U.S. Bureau of Reclamation concluded that recharge water can be infiltrated successfully in the experiment area and that it does reach the principal aquifer as demonstrated by the increase of water levels in observation wells up to 6 miles west of the recharge point (Feth 1966).

Land surface infiltration of water is feasible for the Weber Delta area due to the high vertical hydraulic conductivities at the recharge site. In contrast, conditions at the Bountiful site were not suitable for surface spreading due to low vertical hydraulic conductivities. However, artificial recharge through injection wells might be possible at Bountiful if the horizontal conductivities prove to be adequate.

The Utah Geological and Mineral Survey conducted a recharge related study in the Mount Olympus Cove area of Salt Lake City in the fall of 1974 which dealt with the physical terrain and the factors relating to urban growth and also discussed methods whereby runoff water could be introduced into the subsurface environment. The study concluded that artificial groundwater recharge could be introduced through the use of injection wells.

The 1977 State Legislature directed the Utah Division of Water Rights to evaluate the feasibility and cost of diverting excess and surplus water to increase the recharge to aquifers along the Wasatch Front. Nielsen, Maxwell & Wangsgard completed a feasibility study under the direction of the State Engineer in which geology, water supply, and specific sites in Utah County were considered (Carpenter 1978). Six major recharge areas were chosen and a brief evaluation of each site was documented including discussion of the location, water sources, required facilities, costs, and other considerations. The conclusions reached by the study are that the water is already fully appropriated and any recharged water would have to be purchased, and that a recharge project is not needed. None of the potential problems of decreasing water levels, increased aquifer demands, land subsidence, or maintenance of water quality exist in Utah County.

Hansen (1978) completed a study in Salt Lake County for the Utah Division of Water Rights under the same legislative mandate. Included in his report are brief reviews of two previous studies conducted in the Salt Lake Valley. Four potential recharge sites were chosen and brief feasibility analyses were completed on them. Recommendations made by Hansen were:

1. The state should purchase the property needed for future artificial recharge.

2. Purchased recharge areas could be temporarily leased as sand and gravel operations where appropriate. With proper supervision these areas could be so excavated as to become future recharge pits.

3. Exhausted gravel pits not immediately needed for recharge should be developed as parks, thus allowing later conversion into recharge areas as needed.

4. Appropriate sites could be converted into golf courses with certain low-lying areas utilized for recharge as required.

5. Test and observation wells should be completed to observe if the water will enter the proper aquifer system.

6. The use of the proposed countywide storm drain and reservoir system as a possible source of recharge water should be studied.

The final study for the Utah Division of Water Rights was completed by Valley Engineering (1978) and included Davis, Weber, and Box Elder Counties. Fifteen recharge sites were identified, and brief descriptions as to location, ownership, geology, water source, water diversion point, existing local wells, possibilities of success, and estimated costs were given. Of all the recharge sites considered, the one which was chosen as having the most promise of success is the one proposed in this investigation near the mouth of Weber Canyon.

Previous Studies and Data Sources

The most complete report pertaining to the East Shore area of Weber County was prepared by the U.S. Geological Survey in cooperation with the Utah Department of Natural Resources (Bolke and Waddell 1972). The report describes the area, well construction, aquifer discharges, water level fluctuations, changes in storage, and chemical quality.

Extensive data are available on geologic and water conditions in the Weber Delta area. Much of the geologic research was done by the U.S. Bureau of Reclamation (USBR) during the 1950s. The data taken up to that time were summarized in the U.S. Geological Survey, Professional Paper 518 (Feth et al. 1966). The USBR (1982) generously provided old unpublished records and data pertaining to the study area.

Another source of information titled "Groundwater Conditions in Utah" is published by the Utah Department of Natural Resources, Division of Water Resources (1964-81) and the U.S. Geological Survey in the spring of each year. Especially relevant from these reports are the contour maps of groundwater level changes for the East Shore area.

Water well level records extend back to the mid 1930s, but only a few are continuous or complete. Additional water related records have been obtained from U.S. Geological Survey, Water-Supply Papers, Utah Basic Data Report No. 1 (Smith 1961), and from personal communications with the U.S. Geological Survey (Herbert et al. 1982).

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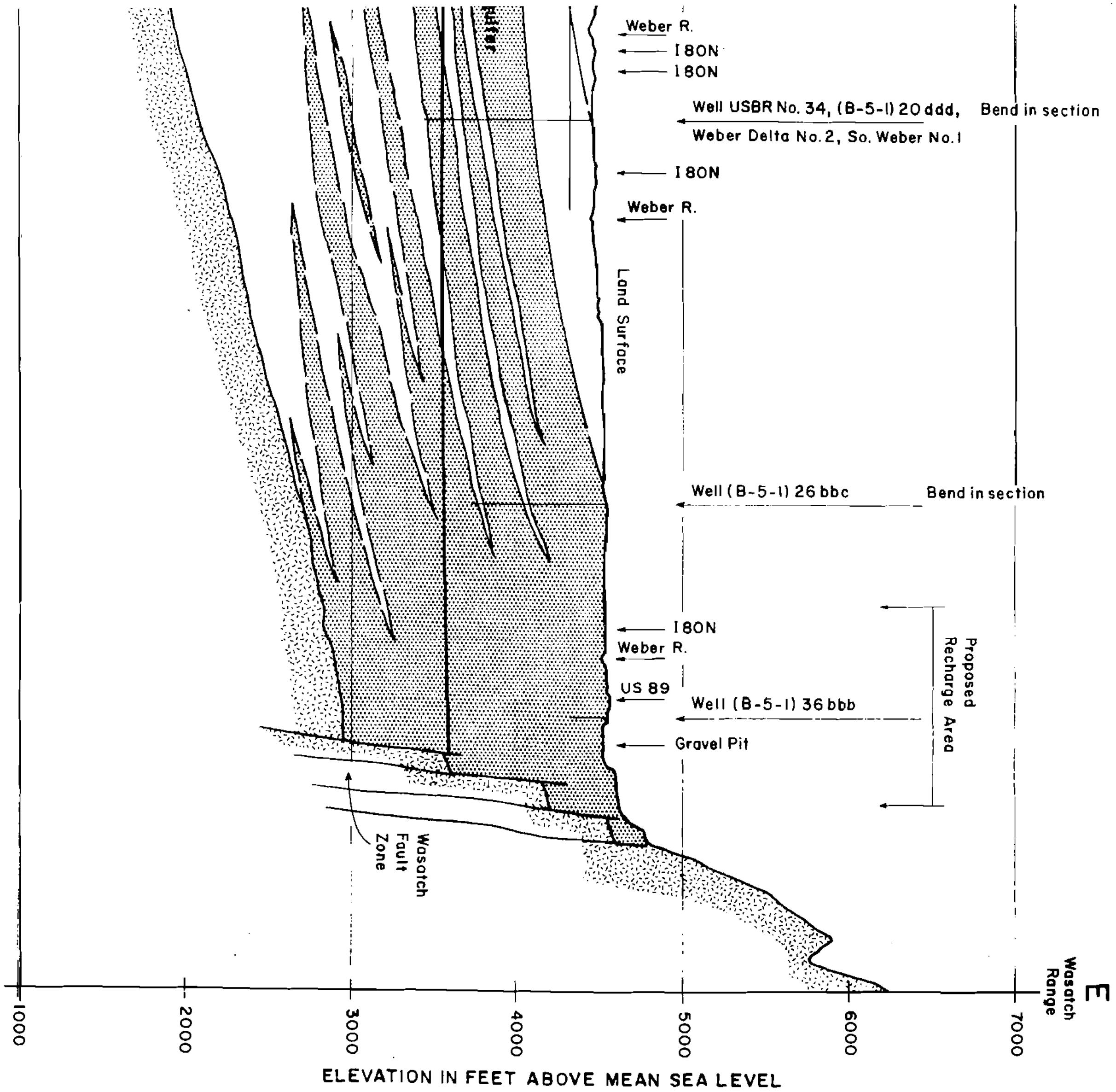

Weber R.
I 80N
I 80N
Well USBR No. 34, (B-5-1) 20 ddd,
Weber Delta No. 2, So. Weber No. 1
Bend in section
I 80N
Weber R.
Land Surface
Well (B-5-1) 26 bbc
Bend in section
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Weber R.
US 89
Well (B-5-1) 36 bbb
Gravel Pit
Proposed Recharge Area
Wasatch Fault Zone
E
Wasatch Range
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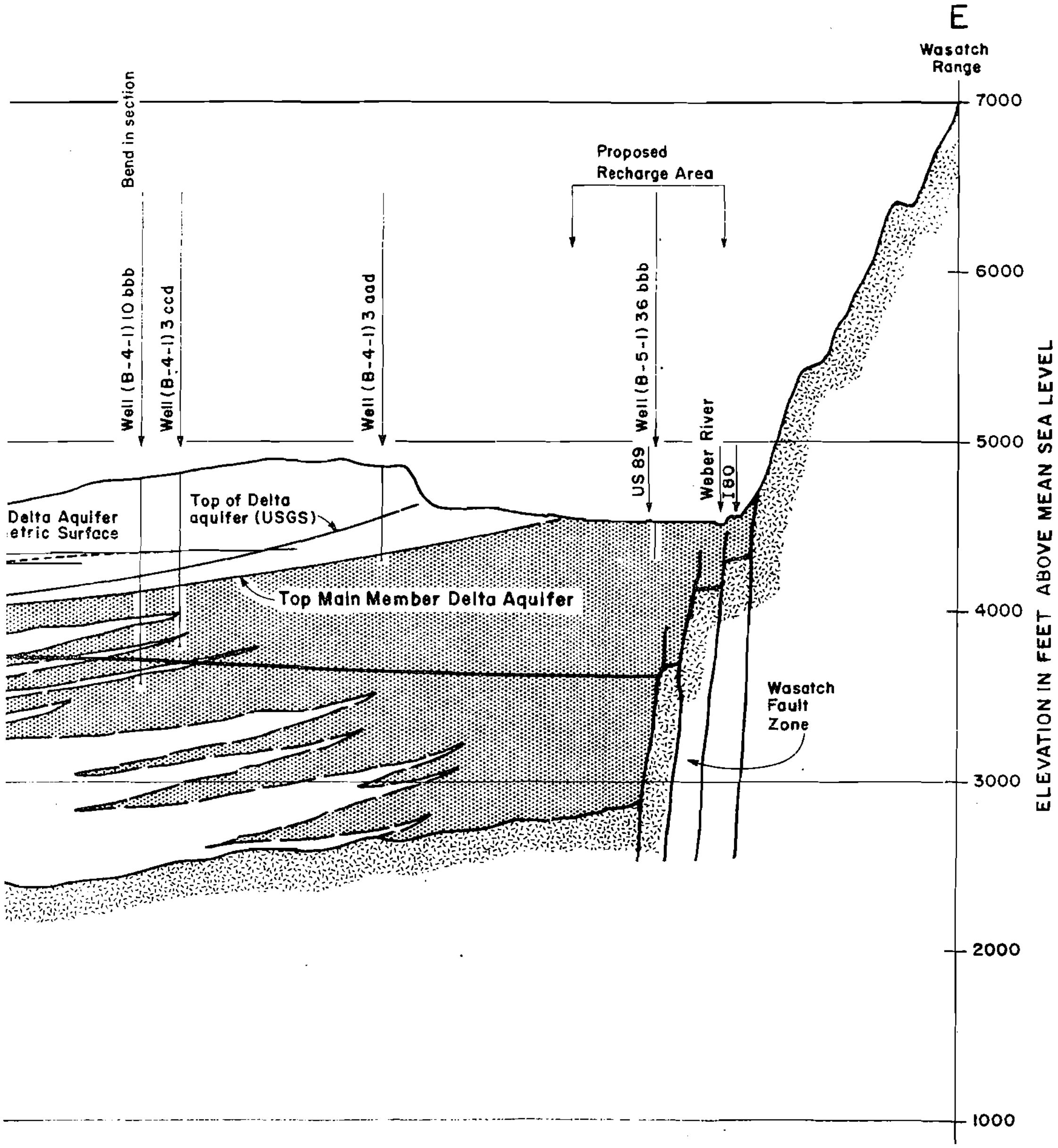
5000
6000
7000
ELEVATION IN FEET ABOVE MEAN SEA LEVEL


E
Wasatch Range
7000
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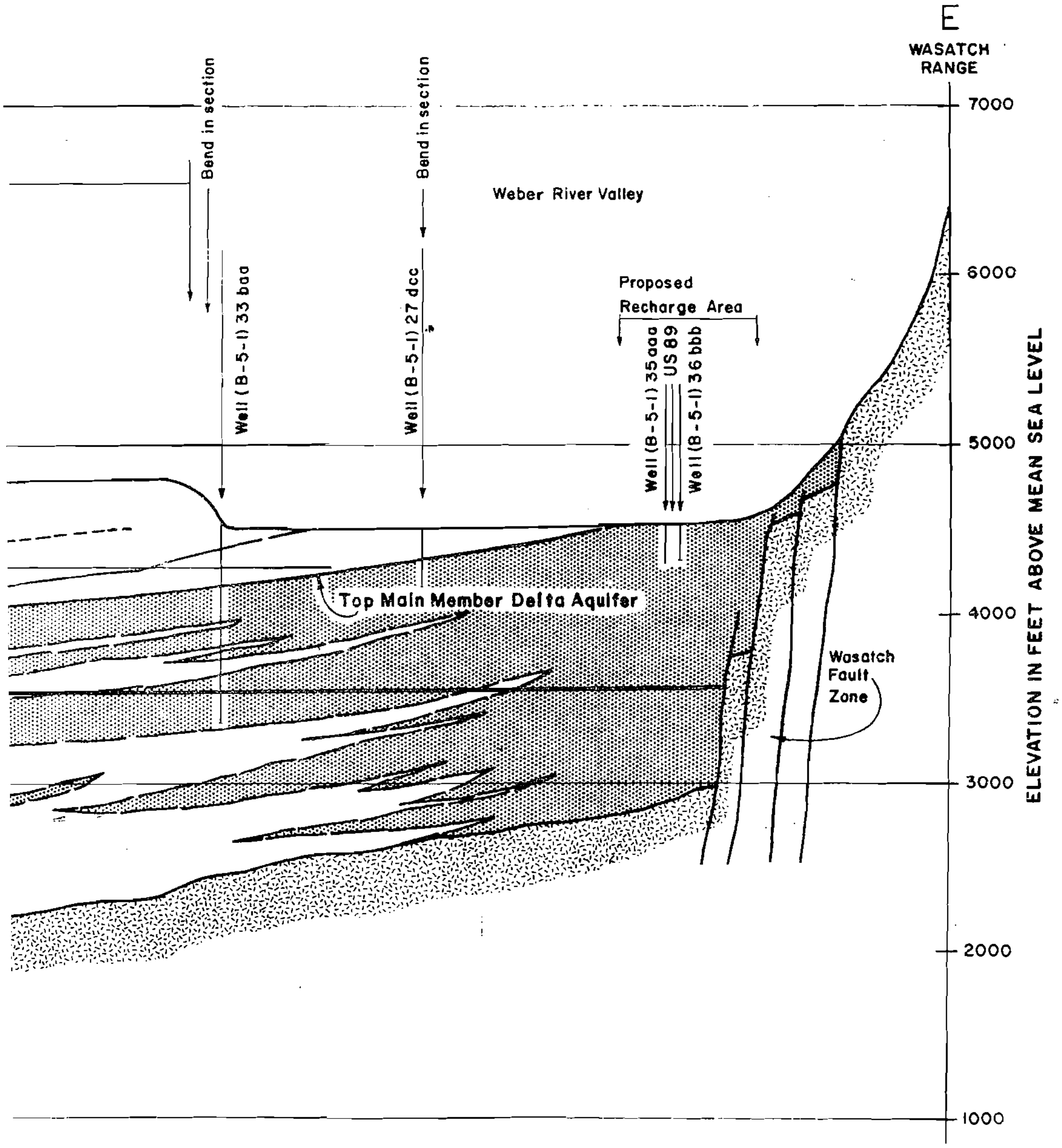
ELEVATION IN FEET ABOVE MEAN SEA LEVEL
Bend in section
Well (B-4-1) 10 bbb
Well (B-4-1) 3 ccd
Well (B-4-1) 3 aad
Proposed Recharge Area
Well (B-5-1) 36 bbb
US 89
Weber River
I 80
Delta Aquifer
etric Surface
Top of Delta aquifer (USGS)
Top Main Member Delta Aquifer
Wasatch Fault Zone

ke, Utah.


E
WASATCH RANGE
Bend in section
Bend in section
Weber River Valley
Well (B-5-1) 33 baa
Well (B-5-1) 27 dcc
Proposed
Recharge Area
Well (B-5-1) 35 aaa
US 89
Well (B-5-1) 36 bbb
Top Main Member Delta Aquifer
Wasatch Fault Zone
7000
6000
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3000
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1000
ELEVATION IN FEET ABOVE MEAN SEA LEVEL

Utah.

and some adjoining areas. It is composed mainly of coarse-grained sands and gravels with thin interfingering layers of clay, silt, and sand. Much of it is described in drillers' logs as "boulders and clay," thus indicating chaotic conditions of deposition characteristic of mudflows. The Delta Aquifer probably represents a large alluvial fan of mixed mudflow and braided-streamflow origin which has coalesced with minor alluvial fans and colluvium of the Wasatch Front. It evidently formed near the beginning of a pluvial stage of the Pleistocene Epoch as increasing precipitation and runoff dislodged accumulated alluvial and glacial sediments of the upper Weber Valley. The coarse-grained sediments that underlie the Delta Aquifer and which are assumed to be hydraulically interconnected with it could be of Pleistocene or even of upper Tertiary age.

Although the Delta is the principal aquifer of the Weber Delta subdistrict, few wells have fully penetrated it. Therefore, its lower boundary, water-bearing properties, and stratigraphy are not well defined. The exceptionally coarse-grained main section of the Delta Aquifer ranges in thickness from at least 300 ft (90 m) along the Wasatch fault zone to less than 100 ft (30 m) west of the Weber Delta. Similar gravelly aquifers below the Delta Aquifer near the mountain front virtually disappear in the same distance westward. These aquifers may be considered a part of the Delta Aquifer as they are probably in direct hydraulic communication with it along the mountain front.

Formational thinning of the Delta Aquifer is accomplished by both pinching out and by lateral gradation to finer-grained materials westward and radially away from the source of the sediments. Geophysical surveys indicate that coarser sediments predominate in the eastern part of the Weber Delta subdistrict (Wantland 1956). Alluvial fan deposits typically thin out radially away from their apex areas and interfinger with other basin sediments around their peripheries. This is evidently true of the Delta Aquifer.

The uppermost approximately 100 ft (30 m) (not stippled in the geologic profiles) of the Delta Aquifer are particularly more lenticular and are finer grained than the main body of the aquifer below. In the recharge area they are separated from the main body by a clay stratum. It is believed that most of the groundwater of the aquifer is transmitted through the main body of more continuous and coarser-grained sediments. This uppermost portion of the aquifer probably represents interfingering deposits of an encroaching but widely fluctuating lake interrupting the alluvial fan deposition.

Alluvial fans usually make excellent aquifers, especially those of braided-stream deposition and to a lesser extent those of mixed braided-streamflow and mudflow origin. Drillers' logs of wells in the apex area of the Delta Aquifer reveal that very coarse-grained sediments predominate. Although the Delta Aquifer has been covered with hundreds of feet of deltaic and other deposits, the apex of the main Delta Aquifer fan has been reached by the incision of the Weber River at the proposed artificial recharge site where the river debouches from Weber Canyon. The top of the main Delta Aquifer decreases in elevation radially to the west and consequently is covered with an increased thickness of sediments which partially and increasingly confine it hydraulically in that direction.

In its deeply buried position, with its apex or recharge area exposed by erosion, this aquifer is in an excellent situation to receive both natural and artificial recharge. Usually alluvial fan aquifers are situated very close to the land surface and are not recharged by large perennial streams. The main Delta Aquifer has the advantage of being submerged below the regional water table in all of its area except at its apex, where the perennial Weber River now provides a continuous natural source of recharge. The Delta Aquifer is probably fully saturated and confined in all but its apex area. In that area and along the nearby mountain front, natural recharge has been occurring, but it could be increased readily by artificial recharge. A relatively deep water table and apparently high vertical and radially horizontal permeabilities in the Delta and underlying aquifers are prevalent conditions favorable for the success of artificial recharge at the proposed site.

Deposition of the Delta Aquifer obviously predated the overlying Lake Bonneville delta deposits of the Alpine Formation of the Wisconsin stage of the Pleistocene Epoch. Pre-Lake Bonneville deposits are distinguished in the Weber Delta subdistrict beneath an unconformity at the base of the Alpine Formation (Feth et al. 1966). It is believed that the Delta Aquifer is among the uppermost deposits of these inferred pre-Alpine Pleistocene formations.

Lake Bonneville Group

The intervening Sunset Aquifer probably represents a transition period as the encroaching Alpine Lake overlapped both older and contemporaneous alluvial fan deposits of the study area. Thus the Sunset Aquifer could be assigned to either the early Alpine or pre-Alpine stages, but is probably early Alpine. The Alpine Lake-delta deposits form practically all of the Weber Delta. Thickness of the Alpine deltaic deposits ranges up to a few hundred feet (100 m). After formation of the main lake delta during the Alpine stage of deposition, the ancient lake rose from about 5100 ft (1550 m) elevation to its maximum level at about 5200 ft (1580 m), called the Bonneville level. Perhaps the delta was enlarged somewhat during that time, but the lake suddenly was lowered to about 4800 ft (1460 m), called the Provo level, where it remained fairly stationary for some time. The Weber Delta was then planed off to levels below 4800 ft (1460 m) and relatively thin deposits of the Provo Formation were left on the top of the delta and in a few surrounding areas (Feth et al. 1966). The ancient lake generally receded thereafter leaving the Weber River to incise its channel across the delta in late Pleistocene and into Holocene (recent) time.

Recent Sediments

Subsequently the Weber River has greatly diminished in flow but it has continued to deposit its fine-grained sediments, including reworked deltaic deposits, beyond the delta and has deposited its coarse-grained sediments in the floodplain of its incised channel through the delta. There may be silts and clays beneath these coarse-grained sediments in the floodplain, but they are probably absent or are of little consequence in the apex area as observed in gravel pits and wells there. Feth et al. (1966), however, suggest the possibility that impermeable strata capable of impeding recharge may be present in the proposed artificial recharge area.

Groundwater Hydrology

Recharge

Underground formations of the Weber Delta subdistrict are recharged principally by the Weber River, underflow from the Wasatch Front, direct infiltration of precipitation, and probably by some canals and irrigation waters. Most of the soils and subsoils along the mountain front and atop the Weber Delta are very sandy and porous. Precipitation, irrigation waters, and runoff from numerous streamlets along the mountain front seep into these porous materials and recharge groundwater reservoirs. Beyond the delta the soils are relatively impermeable and recharge to the principal aquifers is considered negligible. Furthermore, the principal aquifers there are mainly confined and water is leaking upward from them.

The average annual flow of the Weber River for the 20-year period ending in 1947 was 360,000 ac-ft (44,400 hectare-meters) (Feth et al. 1966). Water available for artificial recharge and long-term flow analysis of the Weber River are addressed in the following chapter of this report. Some measurements have been made of the natural seepage losses from the Weber River in the apex area. The mean value has been estimated to be 14,000 ac-ft (2000 ha-m) annually for the 20-year period ending in 1947 (Feth et al. 1966). Natural recharge probably fluctuates annually in proportion more to the wetted area of the stream bed than to stream discharge.

The shape of the regional piezometric surface of the Delta Aquifer is clear evidence that it is being recharged by sources along the mountain front with a strong component coming from the Weber River itself and/or from fractured substrata in the vicinity of the Weber River near the mountain front. Feth et al. (1966) give some estimates of flows expected from the Weber River and from the mountain front. Furthermore, chemistry of the Delta Aquifer groundwater is sufficiently similar to that of Weber River water to confirm the Weber River as a source of recharge (Feth et al. 1966). Underflow from the mountain front could also be expected to be of similar water chemistry as it would have contact with the same rock types that the Weber River water encounters upstream. The same similarities of water chemistry and piezometric gradients exist with regard to recharge of the Sunset Aquifer. Recharge to the shallower aquifers of the western Weber Delta subdistrict is from various sources including upward leakage from the principal aquifers beneath them.

Feth et al. (1966) report the existence of a clay formation that prevents recharge to the deeper aquifers in the floodplain of the Weber River west of a point about 1.5 mi (2.4 km) from the Wasatch Front. The proposed recharge area is safely east of and stratigraphically below this area where recharge may be prevented by the clay layer. This clay formation is believed to be that member which caps the main Delta Aquifer, thus recharge is accessible to the aquifer stratigraphically only below the clay.

Recharge along the mountain front from subsidiary streams and underflow from basement rocks across the Wasatch fault zone was estimated to be approximately 33,000 ac-ft (4100 ha-m) annually for the entire 30 mi (48 km) of Wasatch Front bordering the Weber Delta groundwater district, according to Feth et al. (1966). Beneath the eastern flank of the Weber Delta alone this may be roughly 10,000 ac-ft (1200 ha-m) or about 8200 ft^3 per lineal ft (770 m^3/m) along the mountain front annually. Feth et al. (1966) further estimate an appreciable amount of water is recharged by direct infiltration of rainfall and seepage from irrigated areas and canals, but probably very little of this actually reaches the Delta Aquifer as most of this inferred recharge takes place in areas where the Delta Aquifer is confined. In fact, so far as the Delta Aquifer is concerned, a small portion of the preceding recharge estimate may not reach that aquifer at all, and, therefore, a value of 8000 ft^3/ft (740 m^3/m) may be a reasonable first estimate of all recharge to the Delta Aquifer along the Wasatch Front in the area of the Weber Delta, exclusive of recharge provided by the Weber River.

Surface Water Hydrology

The Weber River is the prime source of water for the Weber Delta area. Its flow is regulated by several dams upstream and water is diverted mainly for agricultural purposes. Figure 6 shows discharges for the Weber River at Gateway for the years 1920 through 1981. Water available for natural and artificial recharge has been quite variable.

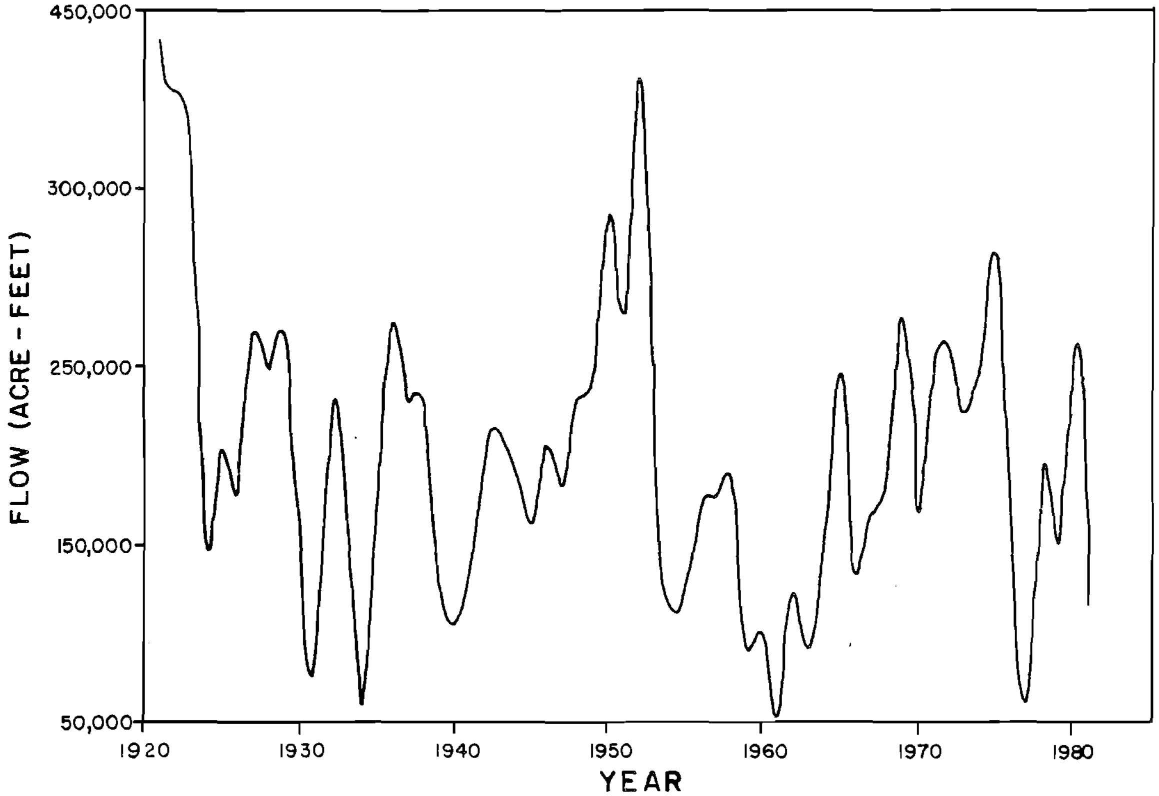


Figure 6. Yearly discharges for the Weber River at Gateway.

Statistical analysis is needed to predict future average supplies that might be available physically for artificial recharge.

The Great Salt Lake is the ultimate sink or discharge level of the East Shore area for both surface waters and groundwaters. Although the lake is a considerable distance from the proposed recharge site, its level does have an indirect effect upon recharge and groundwater flow by controlling downstream piezometric levels and hydraulic gradients. Overdevelopment of the artesian aquifers in the East Shore area could reverse the present lakeward hydraulic gradients and induce salt water intrusion into these valuable aquifers. Fortunately the lake is very shallow and is partially shielded from these aquifers by lake sediments of very low permeability.

Storage

Feth et al. (1966) have estimated that roughly 13 x 10^6 ac-ft (1.6 x 10^6 ha-m) of usable-quality groundwater are stored in the artesian aquifers of the Weber Delta subdistrict. They admit that in a practical sense something between 380,000 ac-ft and 700,000 ac-ft (47,000 ha-m and 86,000 ha-m) may be all that is recoverable if the head in the artesian aquifers were pumped down and the upper 50 ft (15 m) were dewatered in the Weber Delta subdistrict. They estimate that between 80,000 ac-ft and 100,000 ac-ft (10,000 ha-m and 12,000 ha-m) of the foregoing amounts could be readily developed and manipulated as active groundwater storage without dewatering the artesian aquifers. Their estimates appear to be very conservative for they evidently omitted from their calculations the additional water that leakage between aquifers would afford when the aquifers are pumped heavily, and they apparently dealt only with the Delta Aquifer.

Discharge

Under natural conditions groundwater discharge is nearly equal to the recharge in a given basin. The total water in storage normally changes very little in response to climatic fluctuations. Groundwater discharge in the Weber Delta subdistrict occurs naturally by means of seeps and springs, evaporation and transpiration from wetlands, and upward seepage into the Great Salt Lake.

Additional recharge from canal leakage and irrigation return flow as well as increased discharge by wells and drains have upset the natural balance in recent years. Increased use of groundwater is now being made for municipal and domestic purposes in the subdistrict. Piezometric levels have declined in response to increased discharge for these and other uses. The needs of this year-round water demand can be satisfied more effectively by the proposed groundwater basin-management scheme. Feth et al. estimated that in 1952 nearly 145,000 ac-ft (18,000 ha-m) of water were discharged from cattail areas, salt barrens, water surfaces, and leakage to Great Salt Lake in the Weber Delta district. Much of this surface water and groundwater wastage could be salvaged for continued development of the district.

Feth et al. (1966) estimated that about 40,000 ac-ft (5000 ha-m) of groundwater annually flowed through the Weber Delta subdistrict between the land surface and a depth of 1300 ft (400 m). They believed about one-half of this groundwater underflow was lost to the Great Salt Lake and estimated that about 9000 ac-ft (1100 ha-m) were wasted annually by flowing wells put to little or no beneficial use in the district.

Delta Aquifer Water Levels

Piezometric contour maps have been developed for the Delta Aquifer and are shown in Figures 7 through 13 for the years 1937, 1945, 1955, 1964, 1970, 1974, and 1980, respectively. The 1964 map was taken from Arnow et al. (1964); however, alterations were made to their original map. The altered map depicts more of a line source of recharge emanating from the Wasatch Range rather than a stream source emanating from the Weber River. The 1974 map was taken from Stephens et al. (1974) without modifications.

Figures 14 and 15 illustrate the time response of particular piezometric contours within the Delta Aquifer. Figure 14 illustrates that during the period from 1937 to 1955 the 4300-foot piezometric contour fluctuated very little. By 1964 the line had traveled about 6 miles (10 km) to the east, and has held relatively constant since. Figure 15 shows that the 4280-foot contour line went through the same transition between 1974 and 1980 after a steady period from 1937 to 1974. Combined, the two figures show that a 20-foot (6 m) decline in piezometric levels occurred over a span of approximately 15 years.

The drop in piezometric levels in Figures 14 and 15 illustrates that usage from the Delta Aquifer has exceeded the natural recharge. Apparently this condition has accelerated in more recent years and may continue with anticipated population and land development growth.

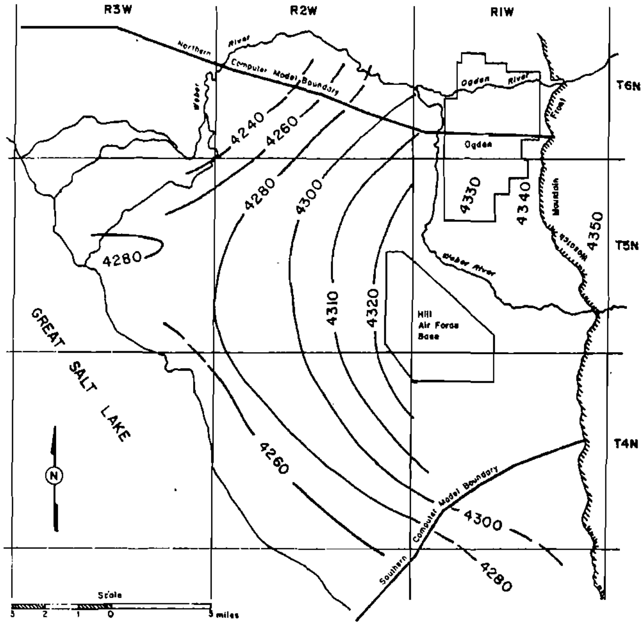


Figure 7. 1937 piezometric contour map for the Delta Aquifer.

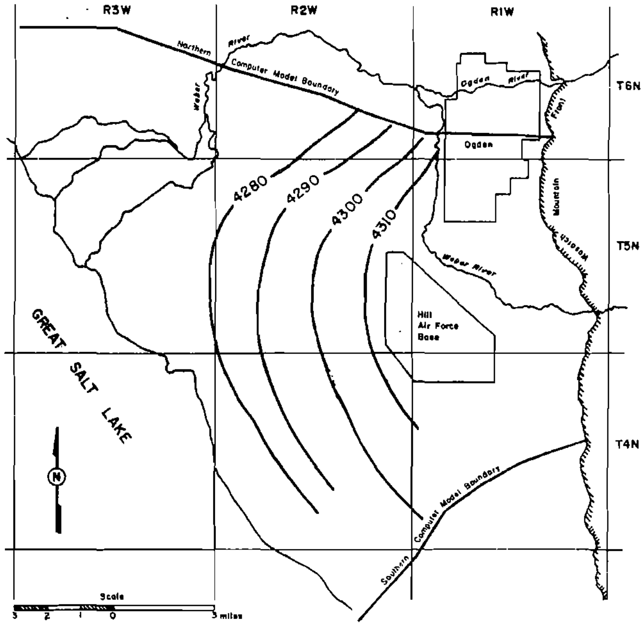


Figure 8. 1945 piezometric contour map for the Delta Aquifer.

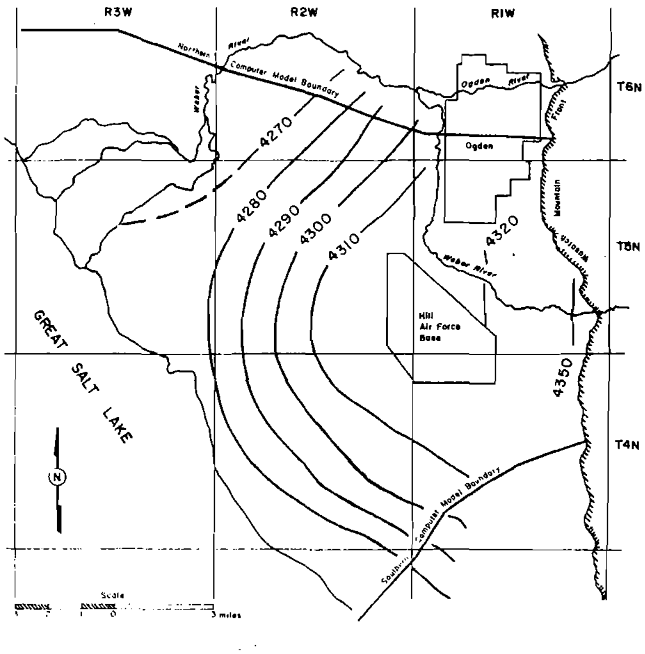


Figure 9. 1955 piezometric contour map for the Delta Aquifer.

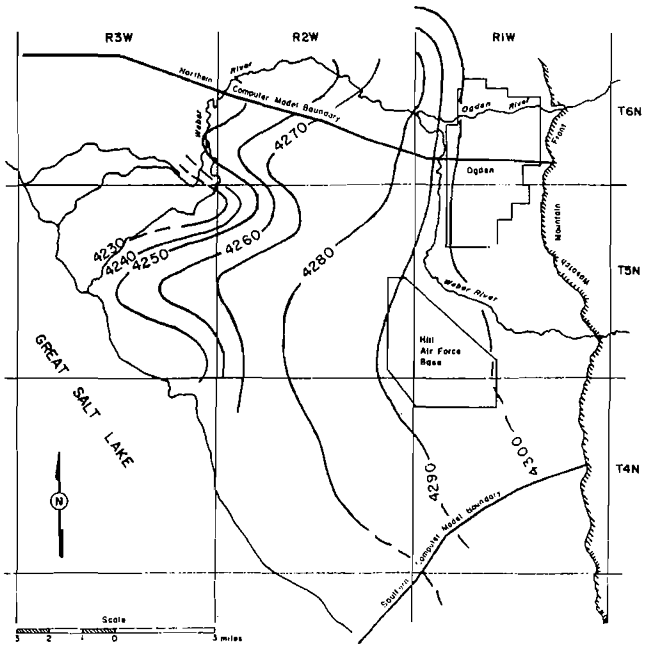


Figure 10. 1964 piezometric contour map for the Delta Aquifer.

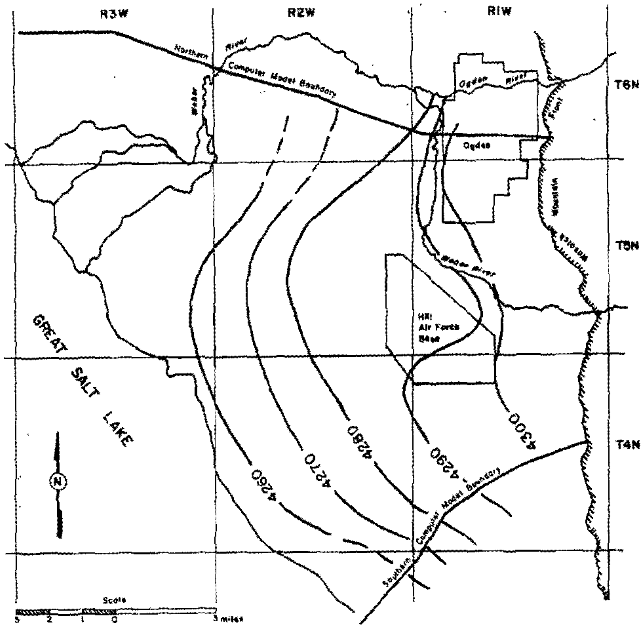


Figure 11. 1970 piezometric contour map for the Delta Aquifer.

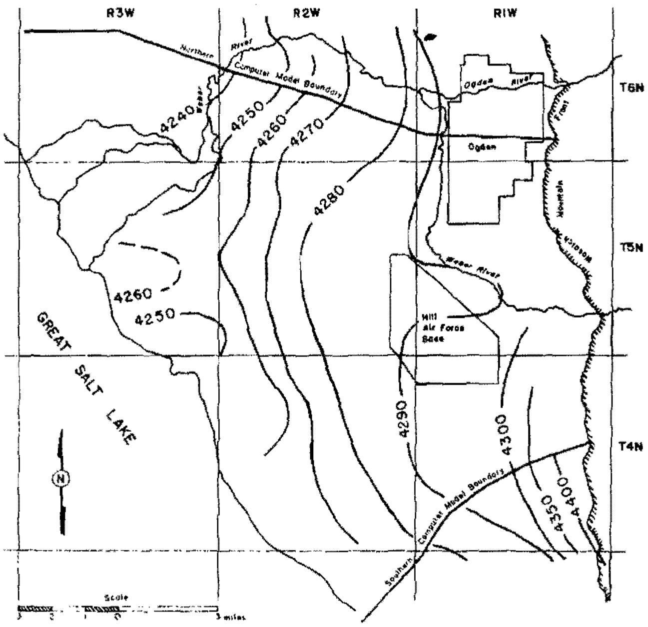


Figure 12. 1974 piezometric contour map for the Delta Aquifer.

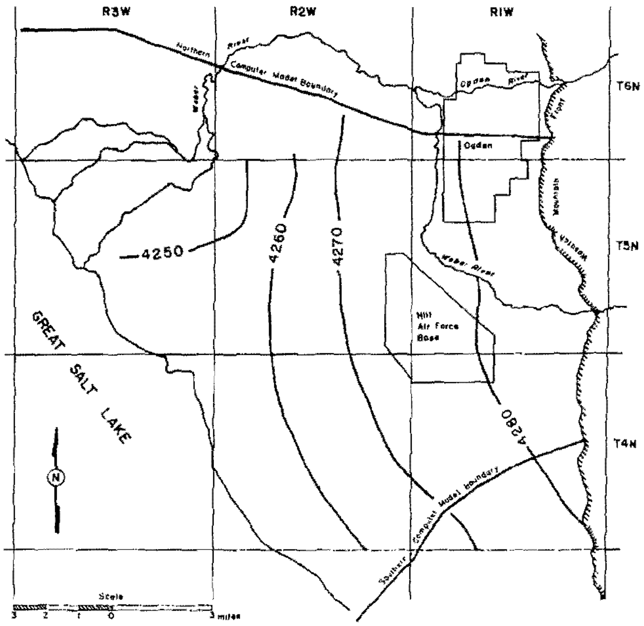


Figure 13. 1980 piezometric contour map for the Delta Aquifer.

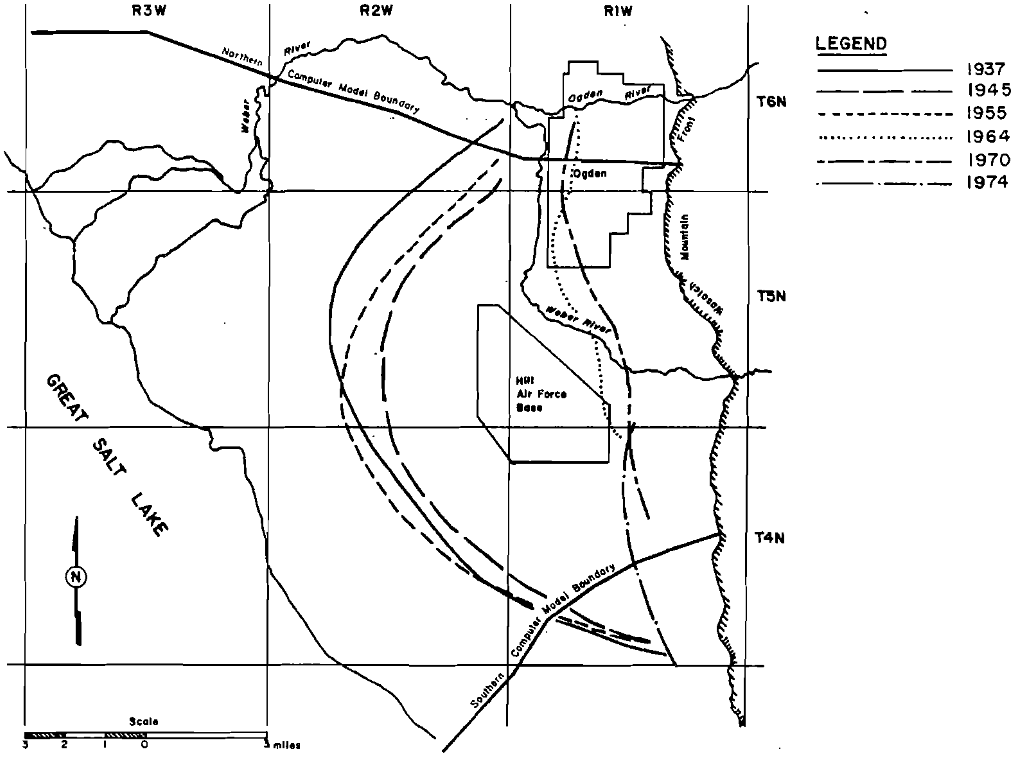


Figure 14. 4300-ft piezometric contour line plotted at advancing time intervals.

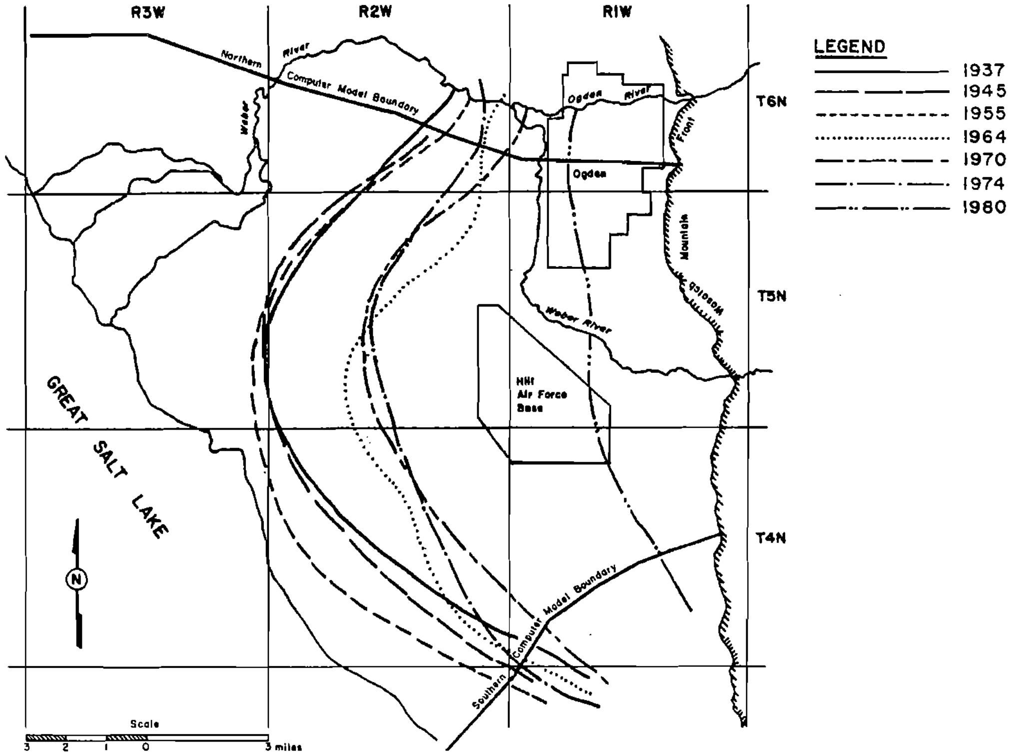


Figure 15. 4280-ft piezometric contour line plotted at advancing time intervals.

Regimen of Flow

The internal structure of an alluvial fan strongly influences the movement of groundwater through it. Alluvial fans typically have buried channels of coarse-grained deposits radiating outward from their apex. These channels are often braided and interconnected as the fan was built by deposits of the parent stream which played across the fan in numerous configurations. Despite the chaotic depositional patterns of alluvial fans when viewed in detail, they tend to conduct groundwater radially outward and slightly downward when viewed from a broad perspective. Apparently this occurs in the Delta Aquifer (see Figures 7 through 13) and a reserve capacity to transmit water radially outward from the apex area still exists. Less extensive alluvial-fan deposits are believed to occur both above and below the main water-bearing member of the Delta Aquifer. They are believed to be in hydraulic communication with one another to various degrees. These alluvial fans and other associated deposits readily conduct groundwater away from the mountain front to points of discharge to the west.

As the coarse-grained materials diminish and permeabilities are reduced westward, the water flow expands horizontally (radially in the horizontal fan deposits) and subsequently moves generally upward. As the bedrock formations become considerably deeper at the middle of the basin, a little water can move downward into the expanding sedimentary sequence, but those deeper formations are less permeable and accommodate little water movement. What water does move downward probably moves very slowly, deteriorates in quality, and eventually may emerge in the Great Salt Lake or from some hot springs in the East Shore area.

The low water table in the recharge area is evidence that recharge could be increased artificially. Hydraulic gradients can be increased and the Delta and other aquifers can transmit more water to areas of heavy groundwater withdrawals along the general paths indicated, but modified somewhat by artificially imposed gradients.

Groundwater Quality

In the Weber Delta subdistrict, groundwater derived from recharge by waters of the Wasatch range is usually of the calcium bicarbonate type, but there is evidence that some deeper Delta Aquifer horizons yield sodium bicarbonate water (Bolke and Waddell 1972). This increased sodium concentration probably is due to natural cation exchange or some other complex reactions underground, and presumably does not render the calcium water incompatible for artificial recharge to these horizons.

Total dissolved solids (residue at 180°C) of the calcium bicarbonate Delta Aquifer well water average between 300 mg/l and 400 mg/l and seldom exceed 500 mg/l. Dissolved solids generally increase with well depth in the Weber Delta area. Furthermore, dissolved solids are slightly lower (less than 250 mg/l) in the groundwater along the mountain front south of and a little north of the Weber River than they are close to the River (Bolke and Waddell 1972, Plate 3) suggesting that recharge from the mountain front may be of slightly better quality than that of the river. Dissolved solids (residue at 180°C) of the Weber River water average between 250 mg/l and 350 mg/l.

ARTIFICIAL RECHARGE

Overview

In recent years our understanding of the geology and hydraulics of groundwater reservoirs has improved significantly. These advances in understanding are closely related to the accelerated groundwater development and exploitation witnessed during the last three decades. Although extensive groundwater supplies exist in Utah, careful management of this resource will be essential for meeting long term needs. In some areas increased groundwater development has led to a series of interrelated problems which have the potential to limit or terminate groundwater usage. Among the most significant of these problems are: the depletion of storage in groundwater reservoirs leading to reduced well yields, increased pumping lifts and costs, settlement and subsidence as a result of decreased pore pressures in fine-grained strata, and water quality deterioration. Consequently, water resource managers are recognizing the need for artificially augmenting and managing groundwater supplies in much the same way as surface waters are managed. The primary difference between surface water and groundwater management is that a new set of rules and decisions are necessary which take into account the physics and chemistry of groundwater flow as well as spatial and temporal variations in storage of groundwater reservoirs.

This report deals first with the remedial benefits of artificial recharge in general terms. Specific objectives include: 1) the conservation and disposal of excess runoff and floodwaters, 2) the augmentation of groundwater storage to maintain or improve present levels of utilization, 3) the stabilization or raising of groundwater levels to reduce pumping lifts and costs, and 4) the investigation of seasonal groundwater augmentation to increase reservoir storage during periods of peak demand.

The second phase of the research description is a compilation and analysis of local geologic and hydrologic conditions in the Weber Delta region. Because of the complex nature of aquifers, implementation of any artificial recharge project requires a thorough and detailed examination of local geologic and hydrologic data to avoid unwanted impacts from the project. This aquifer investigation phase is the first step in the assessment of reservoir potential for artificial recharge. The most important hydrogeologic parameters include the following:

1. Geologic boundaries and lithology of the aquifer(s) and adjacent units.

2. Hydraulic boundaries including depth to water table, aquifer extent, thickness, etc.

3. Available storage capacity of the groundwater reservoir. This will depend on the storage coefficient of the reservoir as well as the thickness of the unsaturated zone above the reservoir.

4. Vertical and horizontal components of hydraulic conductivity or permeability of the groundwater reservoir. Vertical components are especially significant for water spreading or basin ponding methods of artificial recharge. Since groundwater must move vertically to effectively recharge an

aquifer, low vertical permeability even in combination with high horizontal permeability may not be suitable for such recharge as was shown by the early Bountiful experiments (Thomas 1949).

5. Natural recharge mechanisms. In order to be able to quantify the water balance in a particular reservoir, it is essential to understand the natural inputs to the system. Since natural recharge areas are often the most likely sites for artificial recharge, the mechanisms, volumes, and extent of recharge should be well defined.

6. Volume and timing of water available for artificial recharge. Artificial recharge can be implemented to benefit surface water conservation and flood control. Excess runoff may be diverted during flood periods or it may be stored in reservoirs and released slowly depending on the mode of operation at the recharge facility.

7. Geochemical compatibility of the recharge water with the groundwater reservoir.

The third aspect of the research plan involves the assessment of the most effective method of performing artificial recharge in the study area. The most cost-effective practice not only will take into account the cost of the recharge facilities, but also the net regional benefits of the artificial recharge. Three different methods of recharge have been developed to allow recharge under diverse conditions. These methods are water spreading, recharge basins or pits, and injection wells (Walton 1970).

Water Spreading

Water spreading on the land surface is accomplished through the use of feeder ditches and outlets to evenly distribute water over the desired area. This method of recharge is most efficient if the land surface is relatively flat, the vegetative ground cover is left undisturbed, and the soils at the point of application allow a high rate of vertical infiltration (Walton 1970). Another problem, common to all types of recharge methods, is the clogging of soil pores by particulate matter. Whenever recharge water contains significant quantities of suspended material, the sediment must be removed before attempting to recharge the water. Surface spreading of water is the most economical method in terms of land preparation when compared with other spreading options.

Recharge Basins

Recharge basin operating principles are similar to those for water spreading. Recharge basins or pits are excavated or formed by dikes and water is routed or pumped from a nearby source into them. Unfortunately, large amounts of silt were introduced into the recharge basin during the last recharge experiment conducted by the USBR in 1957-58. This resulted in a substantial decrease in the rate of recharge. One method of removing undesirable suspended material is to divert the water through settling ponds prior to the main recharge pits. This method not only protects the infiltration performance of the main pits, but also introduces smaller amounts of recharge water into the subsurface from the settling ponds. Usually, periodic cleaning of the basins is required by scraping the bottom between recharge periods to maintain higher infiltration rates. Since the infiltration rate is directly proportional to the head maintained in the basin, large infiltration rates can be expected under favorable conditions.

Injection Wells

Of all the recharge methods, recharge of the groundwater reservoir through wells encounters the most difficulties of operation. Several potential problems, which directly affect recharge rates, must be addressed before injection wells are operated. These are summarized in two basic categories.

1. Clogging of the aquifer by suspended particles, entrained air, algae, and microorganisms. Any sediment or floating material carried into the well will be filtered out in the aquifer zone surrounding the well. Microorganisms growing within the well and in the surrounding aquifer also reduce the hydraulic transmitting capacity of the aquifer. Entrained air carried into the aquifer effectively reduces the hydraulic conductivity by reducing the available pore space for conveyance of water.

2. Physico-chemical processes which also clog the aquifer. Sometimes the injected water is of such a nature that chemical reactions take place when commingled with the groundwater. Oxidation states, pH, temperatures, solubility levels, and other characteristics may differ to the point that physical and chemical reactions take place forming colloids or precipitates. Chemical reactions on silts and clays may reduce aquifer hydraulic conductivity through ion exchange, flocculation of clays, and other reactions between the aquifer and the recharge water.

These problems are very difficult to correct because they occur deep within the aquifer system. Desilting of a clogged well must be accomplished by reverse pumping or intense development work instead of the easier less expensive method of surface scraping utilized in recharge basins. Biological growth removal would require special procedures. These procedures might include introduction of a killing agent, then reverse pumping and proper disposal to remove the contaminant and microorganic growth.

Operation of recharge wells may have considerably higher costs than either surface spreading or recharge basins but the ability to deliver recharge within an aquifer at any desired location may in some cases override the cost considerations or be the only method physically possible at a given site.

The fourth phase of artificial recharge planning for this research involves the prediction of the effectiveness of the proposed recharge method and its potential impact on groundwater users. This was accomplished by first calibrating a computer model of the groundwater reservoir based on the data compiled in phase 2 of this investigation. The computer model was then used to simulate historical groundwater level behavior and to estimate the spatial and temporal distribution of natural recharge and basin discharge. Alternate artificial recharge practices and their impact on groundwater levels were then examined.

Field Conditions at the Weber Delta Site

In the first section of this report a review of the published geohydrologic data was presented including some interpretation from the present research. It is evident that much information on the geology and hydrology of the Weber Delta subbasin is available and extensive field investigations are not necessary. Feth et al. (1966) describe the zone most favorable for recharge as a strip of land in the Weber River valley about 1.5 miles (2.4 km) in width adjacent to the mountain front. The writers identify this strip as the principal recharge area.

Natural recharge consists of two parts: 1) Channel seepage where the Weber River crosses the principal recharge area (estimated to be 16,000 acre-feet (2,370 ha-m) annually) and 2) mountain front recharge or underflow from the Wasatch Range plus direct recharge from precipitation and irrigation seepage (estimated to be approximately 46,000 acre-feet (5,520 ha-m) annually). The principal recharge zone is characterized as a belt of gravel and sand deposits that will readily absorb the water made available by natural recharge.

Artificial recharge experiments were performed in the principal recharge area in 1953 (Feth et al. 1966) and in subsequent years using surplus flows from the Weber River. Water was diverted into a pit having an area of 3.25 acres (1.32 ha). The experiment demonstrated that a continuous infiltration of 7 cfs/acre (490 ℓ/sec/ha) of pit could produce a temporary increase in a nearby observation well of 34 ft (10.4 m). The initial depth to water is at least 217 ft (66.1 m) which indicates significant storage capacity exists for artificial recharge in the principal aquifers there. These experiments also demonstrated that the verticial hydraulic conductivity in the principal recharge area is relatively large. Horizontal hydraulic conductivities in the water table aquifer of the Weber Delta District have been estimated from pumping tests to be on the order of 30,000 to 40,000 gal/ft^2/day (1,222 to 1,630 m^3/m^2/day) and it is likely that vertical conductivities are nearly as large as this value.

The volume and timing of water available will depend on the availability of surplus water, and will be discussed subsequently.

Discharge Hydrographs and Water Availability

Early settlers in the Ogden area diverted surface water to irrigate the crops required to sustain the lives of the settlers and their animals. Municipal use was very small. As additional settlers arrived, more water was diverted to supply the increased agricultural needs. Eventually, municipal distribution systems were required for Ogden and nearby communities. Dams were built in the Weber and Ogden canyons to store high runoff streamflow for use during the low flow seasons of the year. Water use expanded to the groundwater system. The municipalities at last occupied so much farmland that water supply requirements in the Ogden area began to shift from irrigation to domestic use.

Beginning in 1908 the flows of the Weber River near Plain City were measured. A stream gage was also installed on the Weber River near Gateway and began operation in 1921. Other stream gages have been used at various locations but their records are quite short. The stream gages near Plain City and Gateway demonstrate the changes in water use and the present availability of water.

In the early 1950s the U.S. Bureau of Reclamation began construction of the Weber Basin project. This project included construction or enlargement of dams, installation of diversion structures and conveyance systems, building of power systems, drilling wells, and diking a portion of the Great Salt Lake for storage of fresh water. This system was essentially in operation by 1958. There have been no major changes in the system since that time.

Water for artificial recharge purposes must be available at the Gateway gage to be of use at the proposed site. In 1936 the Weber River Decree specified about 1500 cfs of water rights between the Gateway gage and the confluence with the Ogden River. In conjunction with the Weber Basin project, the USBR filed on most of the remaining water in the Weber Basin. Since the 1936 decree, some water uses have changed. Some power rights have been transferred as have some water rights. It would seem that the current high water right should be higher than the 1500 cfs specified in 1936. However, the Weber River Water Commissioner has stated that the current demands can be met with 700 cfs at Gateway. This conforms to the pattern of filing for more water than can be used at the time of filing so that water will be available for increased future needs. The major use of water below the gage near Plain City is for the bird refuge which requires a maximum of about 200 cfs. Maximum use is not continuous as the maintenance of a constant water level during the nesting season only is critical. During the remainder of the year, the water requirement is governed by maintenance of the habitat.

Figure 16 shows the average monthly flows at the Gateway gage for the period of record prior to the Weber project (1921-1957), and for the period subsequent to the project (1958-1977). Obviously major changes have occurred during the annual high runoff period due to the increase in storage capacity upstream from the gage. The flows from July through March have decreased only slightly. The changes during April through June have been from 200 to 500 cfs. Figure 17 shows the duration curves for these same two periods of record. The maximum flows have been significantly reduced while the flow greater than 700 cfs has been reduced from 23 percent to 16 percent of the time. Figure 18 gives the duration curves for the Weber River near Plain City for three periods (1908-1957, 1958-1977, and 1908-1977). The maximum flows have been reduced to about one-half of the preproject value, and the flows occurring up to about 75 percent of the time have been reduced. Flows greater than 200 cfs occur just under 50 percent of the time. Figure 19 shows mean monthly flows near Plain City. Since 1958 there has been about 300,000 ac-ft per year flow past the Plain City gage. A significant portion of that flow goes to the Great Salt Lake. It would seem that 5 to 10 cfs of flow would be available at least 50 percent of the time. However, physical and institutional availability do not always coincide. This problem would have to be resolved.

Physically there appears to be 5 to 10 cfs of excess water available. Some of the options for obtaining the water for recharge operations are:

1. File for water rights on excess runoff. These flows would occur for only 3 months at the most and would involve very high flow rates. High flows are very difficult to handle for recharge.

2. Purchase sufficient water rights from individuals.

3. Purchase water from the Weber Water Conservancy District.

4. The District might choose to donate the 5 cfs to help water users in the lower areas who have been paying taxes as well as water use fees for many years.

5. A filing could be made on an old USBR application that has not been perfected and the point of diversion could be changed.

In summary, there seems to be sufficient water to provide 7500 ac-ft per year for artificial groundwater recharge. This would be only about 2.5 percent of the amount of water passing the gage at Plain City from 1958-1977. The main problems are to complete the needed legal and institutional arrangements, obtain the cooperation necessary to get the desired amount of water to the recharge site, and have the needed facilities constructed and operated at optimum costs.

Proposed Operation for Artificial Recharge

The proposed operating system for the Weber Delta artificial recharge project would consist of a diversion works and two basins in series. The first basin would act as a settling pond to remove sediment before the water reaches the main recharge basin. Floating debris will also be removed

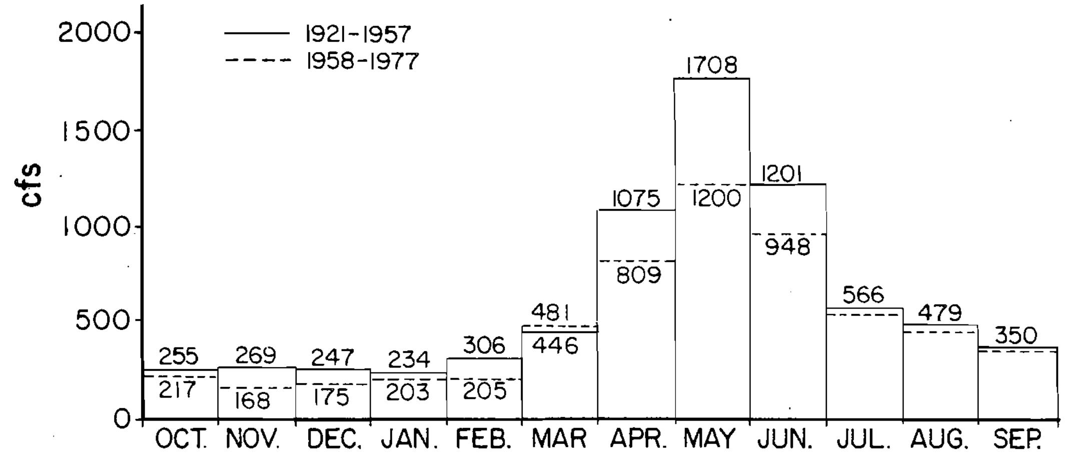


Figure 16. Average monthly flows, Weber River at Gateway, 10136500.

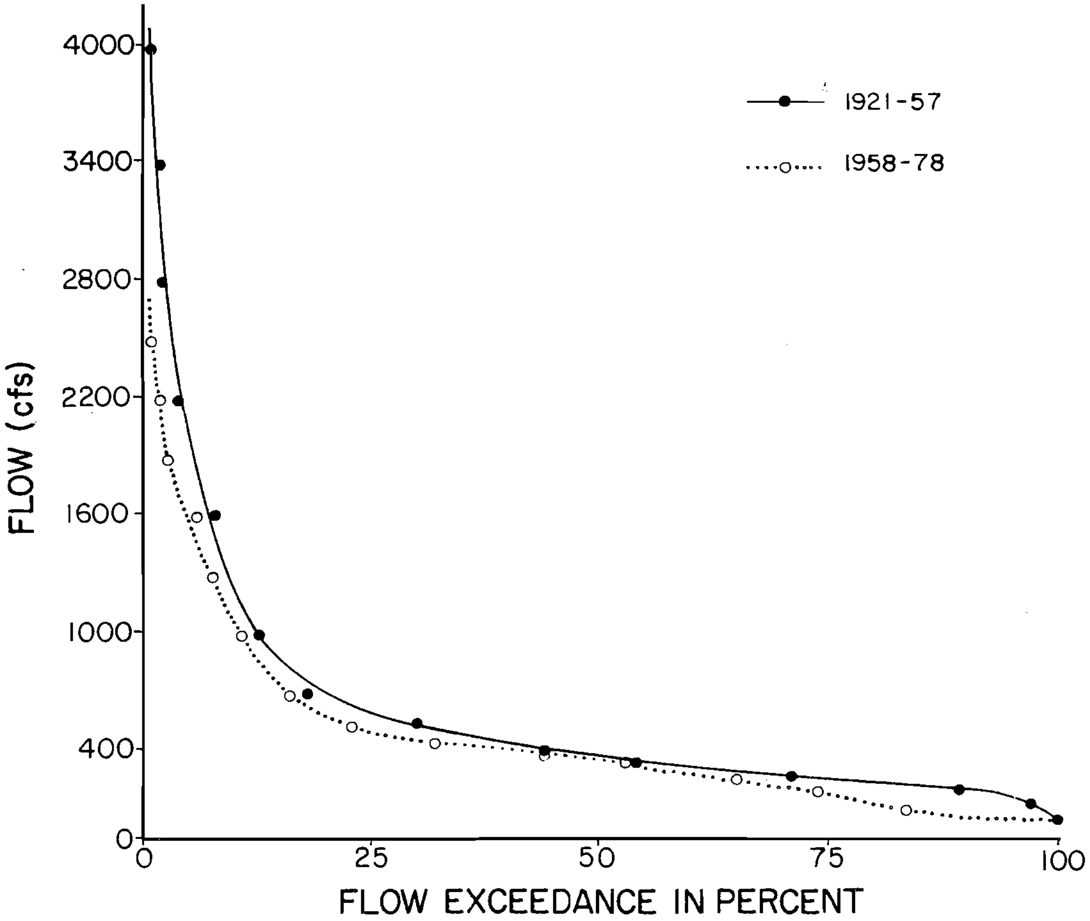


Figure 17. Flow duration curves for the Weber River at Gateway, 1921-1957 and 1958-1978.

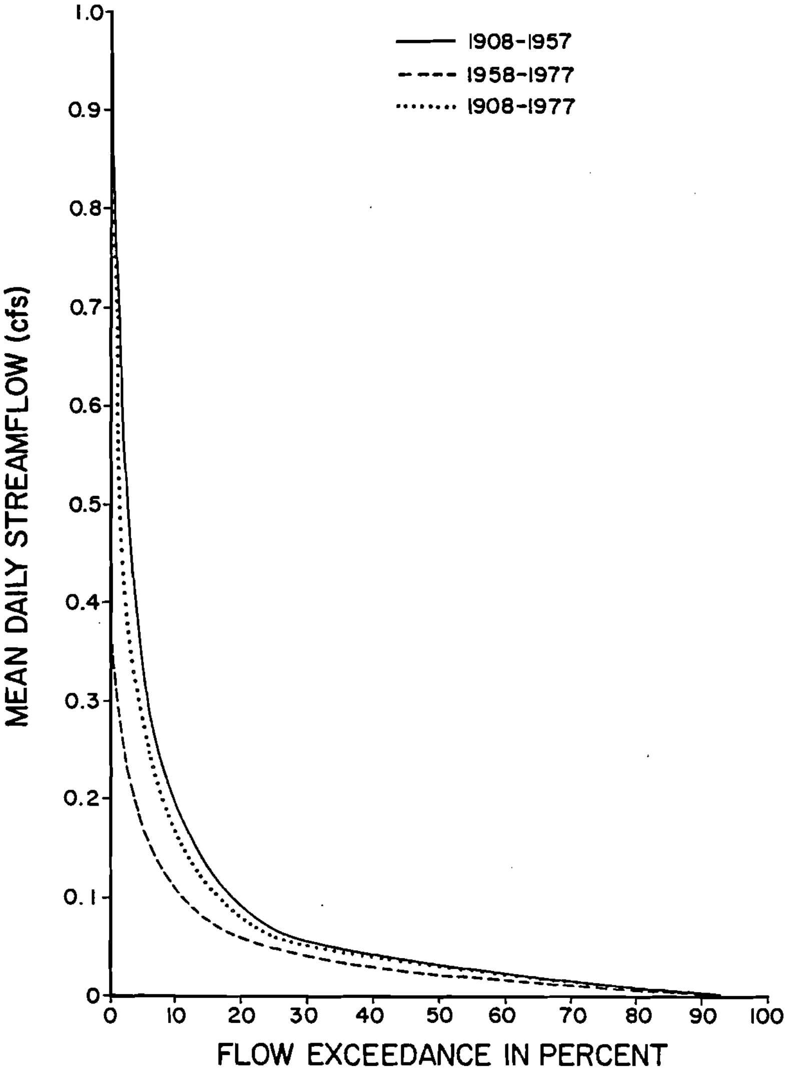


Figure 18. Flow duration curves for the Weber River near Plain City.

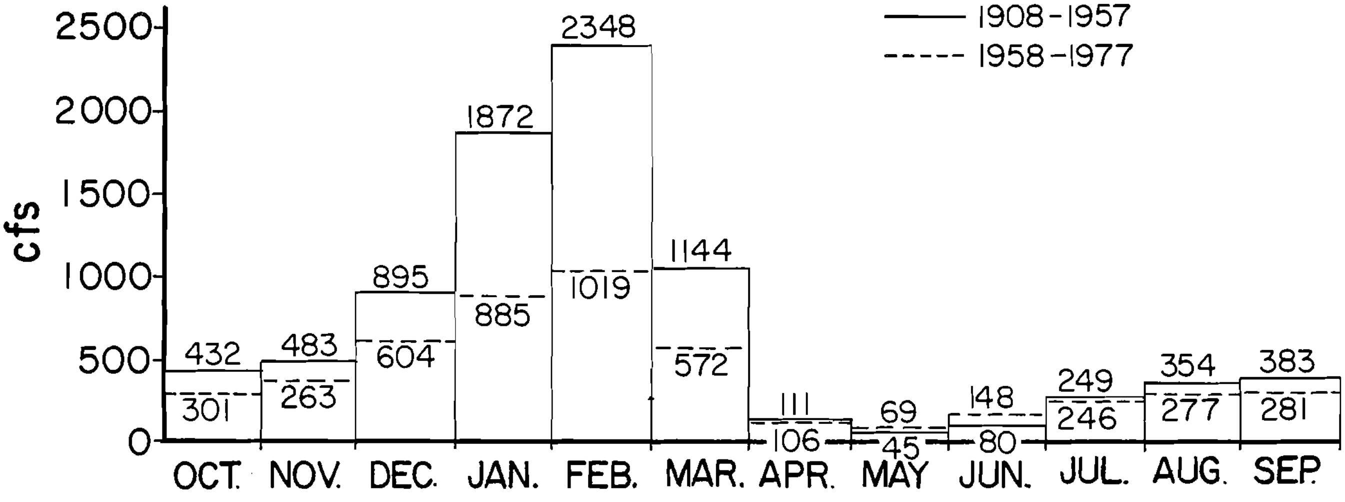


Figure 19. Average monthly flows for the Weber River near Plain City, 10141000.

before reaching the main basin. These basins will be divided into subbasins for operational purposes. The first basin would also act as a recharge basin although its capacity to function as such will reduce with time. Previous tests using recharge basins have proven this method to be appropriate for artificially recharging the groundwater supply.

Preliminary studies on water availability indicate that vast quantities of water are wasted into the Great Salt Lake annually as a result of high spring runoff. If utilized, this water would allow high head operating conditions in the recharge basin. Increased infiltration rates are obtained as water depth increases. During low flow periods any available water would still be used and the recharge basin operated under low head conditions. A computer model can be used to determine the quantities of recharge water needed and the periods in which they should be applied.

APPLICATION OF COMPUTER MODELS

As part of this investigation, a computer model simulation of regional groundwater flow in the Weber Delta area was developed. The model uses the recharge basin method for applying recharge water and places the basin in the proposed recharge area which occupies the same location utilized by the USBR during the recharge experiments of the 1950s (see Figure 2).

The use of a computer model facilitates the analysis and forecasts of possible outcomes of an artificial recharge project. Effects upon piezometric water levels under diverse conditions can be predicted, and decisions made regarding the economic implications of alternative conditions.

Discharges of the Weber River and their related probabilities had to be analyzed first using stochastic river flow models. The results of this modeling were assessed with known water rights to obtain a net probable flow available for use as recharge water. These results then allowed decisions to be made concerning alternate water supply sources available for artificial groundwater recharge.

Three models were utilized during this study. The first is a finite element hydrologic groundwater model developed at the Massachusetts Institute of Technology (MIT) and known as AQUIFEM-1. The second is based upon a stochastic generation method developed at Utah State University (Canfield 1983) which generates yearly river flows. The third is a statistical disaggregation model which calculates monthly streamflows from generated yearly streamflows.

Groundwater Model

The steps for model implementation described by Townley and Wilson (1981) for AQUIFEM-1 are:

1. Data collection. Required model inputs must be defined and collected.

2. Conceptualization. The available data and knowledge about the system must be transformed into a readily understandable form. This step includes such things as definition of boundary conditions, initial conditions, system inputs, and governing equations.

3. Discretization. Each known condition must be altered in some manner such that continuous events or boundaries are changed to discrete events or boundaries. This includes approximating a well by a node or element, or by using a series of straight lines to approximate a curved boundary, etc.

4. Parameterization. In this stage inputs such as permeability, etc., are changed to obtain a closer match between simulated and historical events. This is also known as calibration/verification of the model.

5. Application. The completed model can be run to simulate or predict the results of various management options.

Since the data used for this study were compiled from other sources and not by additional field work, the model implementation process will begin with conceptualization and the data will be presented in later sections.

Conceptualization

Governing equation. Groundwater movement throughout the study region is three dimensional in nature. Not only does water move westward from the mountain front, but it also radiates outward as it moves and strong vertical flow components may occur. However, three-dimensional flow models require a great deal more data concerning the adjacent aquifers than is available in the Weber Delta area. For this reason a two dimensional model with a leaky aquifer option was chosen to represent flow in the horizontal (x-y) plane.

AQUIFEM-1 is a two-dimensional, finite element model capable of simulating a wide variety of geohydrologic conditions. The governing differential equation used in the model for essentially horizontal groundwater flow in a nonhomogeneous, anisotropic aquifer with leakage is:

$$S \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(T_{xx} \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_{yy} \frac{\partial h}{\partial y}\right) + Q + \frac{K'}{B'}\left(h_a - h\right) \quad . \; . \; . \; . \; . \quad (1)$$

where

$S = S(x,y,t)$ = aquifer storage coefficient

$h = h(x,y,t)$ = depth averaged piezometric head, usually denoted ϕ for confined aquifers, expressed in units of length [L]

$T_{xx} = T_{xx}(x,y)$ = aquifer transmissivity in the x-direction, expressed in units of length and time $[L^2/T]$

$T_{yy} = T_{yy}(x,y)$ = aquifer transmissivity in the y-direction, $[L^2/T]$

$Q = Q(x,y,t)$ = net flux into the aquifer from point or distributed sources (and sinks), [L/T]

$K' = K'(x,y)$ = vertical permeability of the leaky semi-pervious layer above or below the principal aquifer simulated, [L/T]

$B' = B'(x,y)$ = thickness of the semi-pervious layer, [L]

$h_a = h_a(x,y,t)$ = piezometric head in a vertically adjacent aquifer, separated from the main aquifer by the semi-pervious layer, [L]

x,y = Cartesian coordinates (principal axes of the hydraulic conductivity or transmissivity tensor), [L]

t = time [T]

Boundary conditions. Specific boundaries must be defined for the model which relate as closely as possible to natural field conditions. Table 1 lists the available modeling capabilities of AQUIFEM-1 which must be considered for proper model application. For further details see Townley and Wilson (1981).

Groundwater recharge in the study area originates mainly from infiltration through the bed of the Weber River and subsurface inflow through faults and fissures along the mountain front. The Wasatch mountain front with groundwater flow across it was selected as the eastern boundary marked A-B in Figure 20.

Table 1. Modeling capabilities of AQUIFEM-1.

Boundary Conditions
   1. Specified heads are known
   2. Specified heads are known with time
   3. Fluxes are known (if flux is zero a streamline exists)

Sources and Sinks
   1. Point or area sources
   2. Constant head source with leakage flux
   3. Leakage from an adjacent aquifer
   4. Flowing wells
   5. Evapotranspiration
   6. Springs
   7. Land drainage
   8. Geologic faults
   9. Partial penetration of wells, streams, lakes, and springs
   10. Excavation dewatering

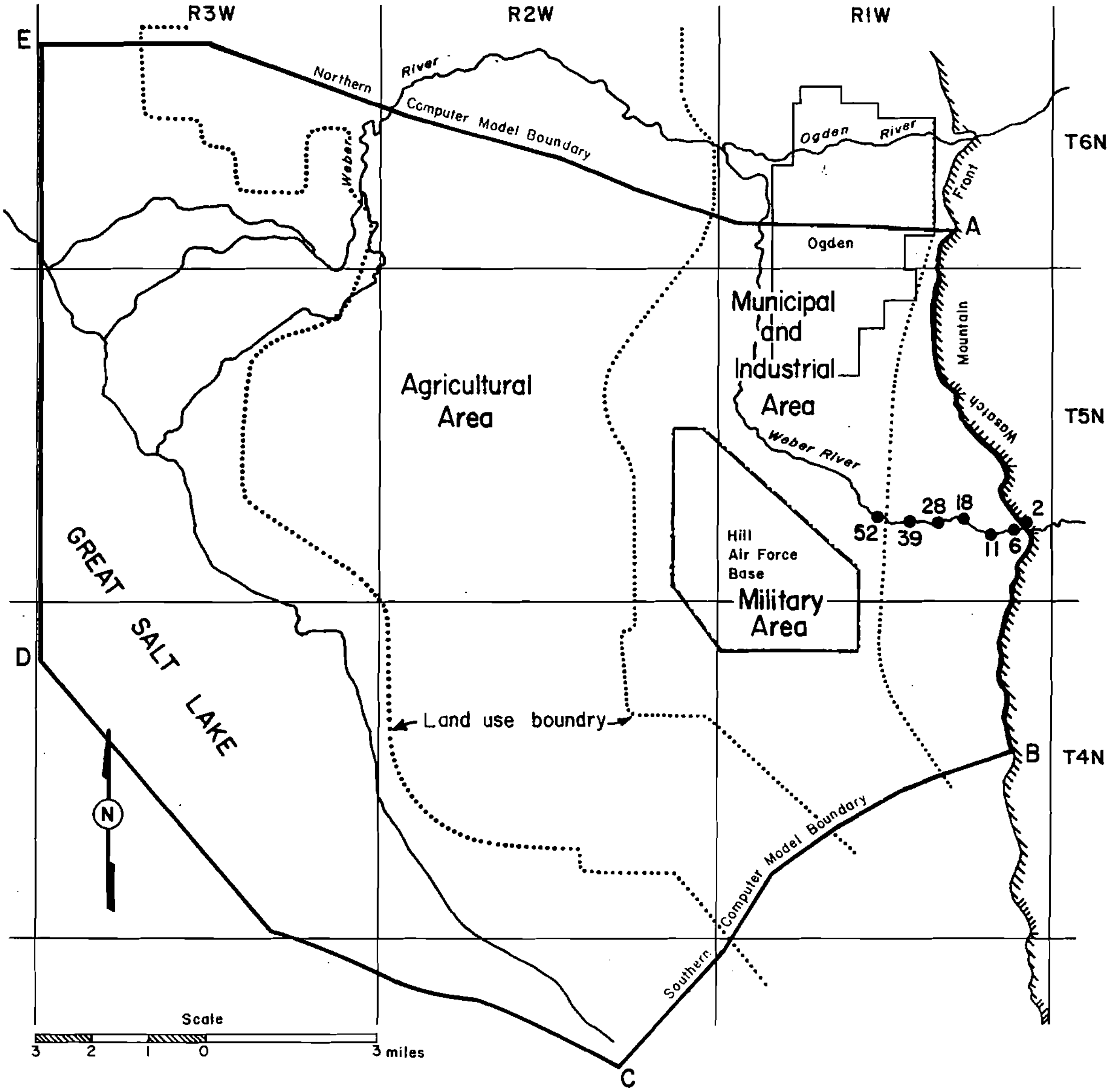


Figure 20. Computer model boundaries and simplified land use patterns.

The northern and southern model boundaries were obtained after piezometric contour maps were prepared for the years 1937 through 1980 (Figures 7 to 13). The general orientation of contour lines along the northern and southern sections of the map were virtually unchanged through time. These contour lines represent lines of equal piezometric head and groundwater moves along streamlines perpendicular to them. Therefore, boundaries B-C and E-A of Figure 20 were selected along streamlines across which no flow occurs. This constitutes a no-flow boundary condition for the model.

A no-flow boundary condition was also used along the western boundary C-D-E. Well logs indicate that lower permeability silts and clays predominate in the main Delta Aquifer to the west. This tightening of the aquifer system has the effect of increasing the movement of water vertically, thus feeding shallow aquifers in the vicinity of the Great Salt Lake. The presence of numerous springs and artesian wells in the western reaches of the study area support this concept.

In order to model the principal aquifer, its thickness and elevation must be known. The elevations for the top and effective bottom of the main member of the Delta Aquifer were taken from Figures 3 through 5 and also estimated from logs of intervening wells. Contour maps showing the top of the main member of the Delta Aquifer (Figure 21), the effective bottom of the aquifer (Figure 22), and its effective thickness (Figure 23) were constructed using these data.

Sources and sinks. Two basic approaches are available for modeling water sources or sinks (withdrawals). The first method uses a point source or sink, which best simulates the effects of individual wells. The second method uses elemental sources or sinks which can simulate discharge conditions or withdrawal spread over an area. Also, an area with numerous wells could be simplified into an elemental flux over one or more finite elements much easier than developing a finite element grid with a node at each well location.

The Weber River is a substantial source of recharge for the Weber Delta and appropriate nodes are identified later to represent its inflow.

Figures 7, 10, and 12 indicate the possible existence of a recharge source producing a piezometric mound along the western boundary. This recharge was modeled using an elemental source whose value was altered in direct proportion to mountain front recharge. How this water moves from the mountain front to the mound is not known. A possible mechanism for such an occurrence could be the lenticular structure of the Delta Aquifer. Direct bedrock (deep) connection is also possible.

Well pumpage was modeled by elemental sinks. The large number of wells made it impractical to model them as point sources. Pumping data and estimates were obtained from Thomas et al. (1952), Bolke and Waddell (1972), Feth et al. (1966), and from open files of the United States Geological Survey in Salt Lake City, Utah. Those records revealed the three main water uses are irrigation, municipal and industrial, and military.

Land used for irrigation, municipal and industrial, and military purposes was obtained (Weber River Water Quality Planning Council 1977) and generalized into the areas shown in Figure 20. Each area will be redefined in a later section after the finite element grid is developed.

Finite Element Grid

A finite element grid is a type of graphical representation of an area to be modeled. Each node can represent a point source or sink as well as a location reference for either known or calculated heads. Lines connecting nodes can represent line sources such as mountain front or river recharge. Similarly each element can represent an

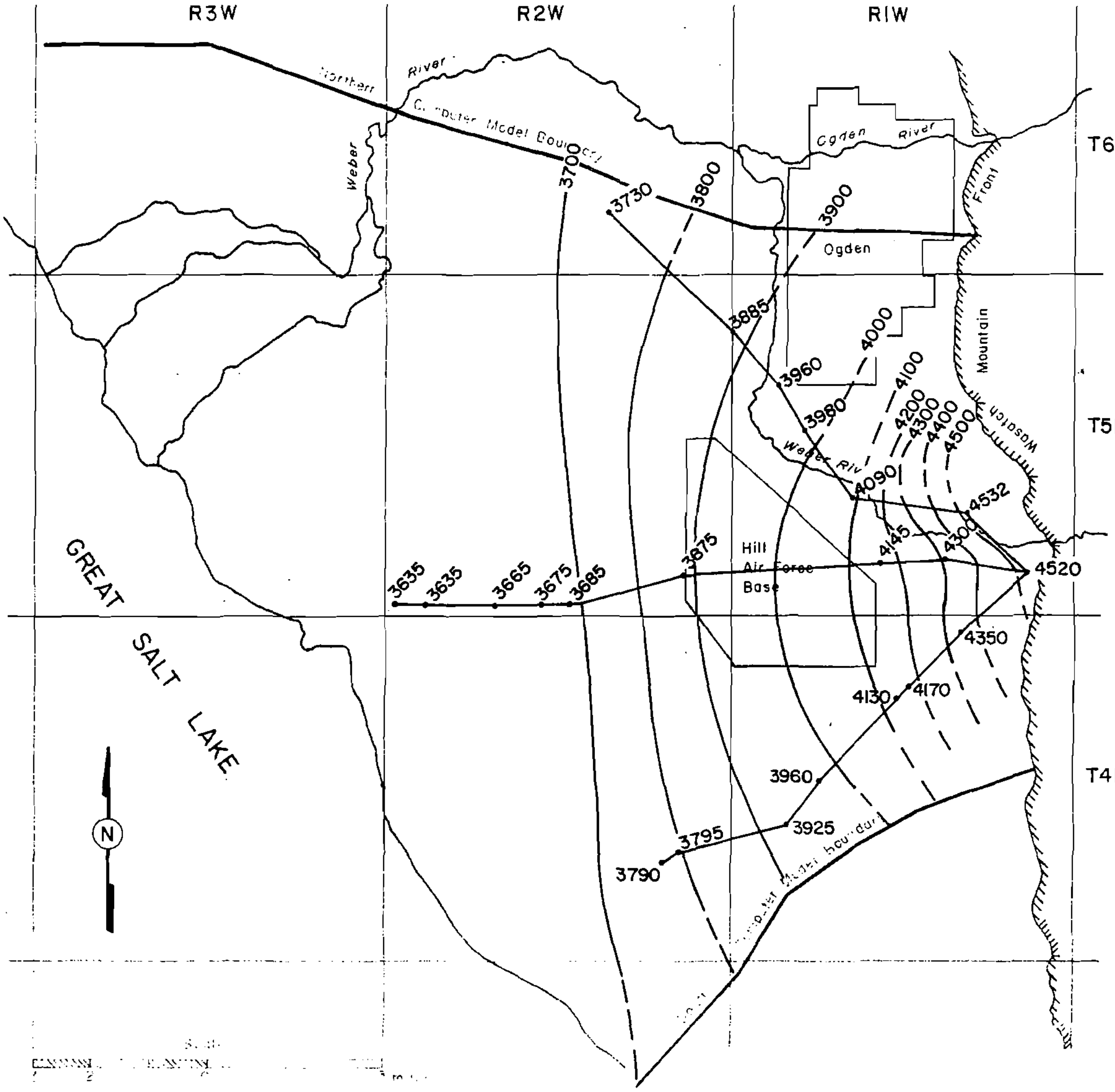


Figure 21. Contours on the top of the main Delta Aquifer.

areal source or sink. Such flexible conformation to boundary conditions and natural features is not as easily accomplished using a finite difference model due to its required rectangular grid structure.

In the initial stages of developing the finite element grid, nodes were placed at as many principal well locations as possible. This was done so that the historical data for those wells could be easily compared with the model results. Nodes 2, 6, 11, 18, 28, 39, and 52 were used to represent the contribution due to the Weber River (see Figures 20, 24, and 25). The remainder of the river was not modeled for two reasons; first, the permeability of the river bottom decreases with distance from the mountain front and second, the confining layers which produce pressurized conditions within the Delta Aquifer prohibit river recharge from entering directly into the deep aquifer system.

AQUIFEM-1 utilizes simplex triangles and calculates values based on linear interpolation between nodal points. For this reason computational accuracy increases with decreased distance between nodes. It is desirable to place a larger number of nodes in

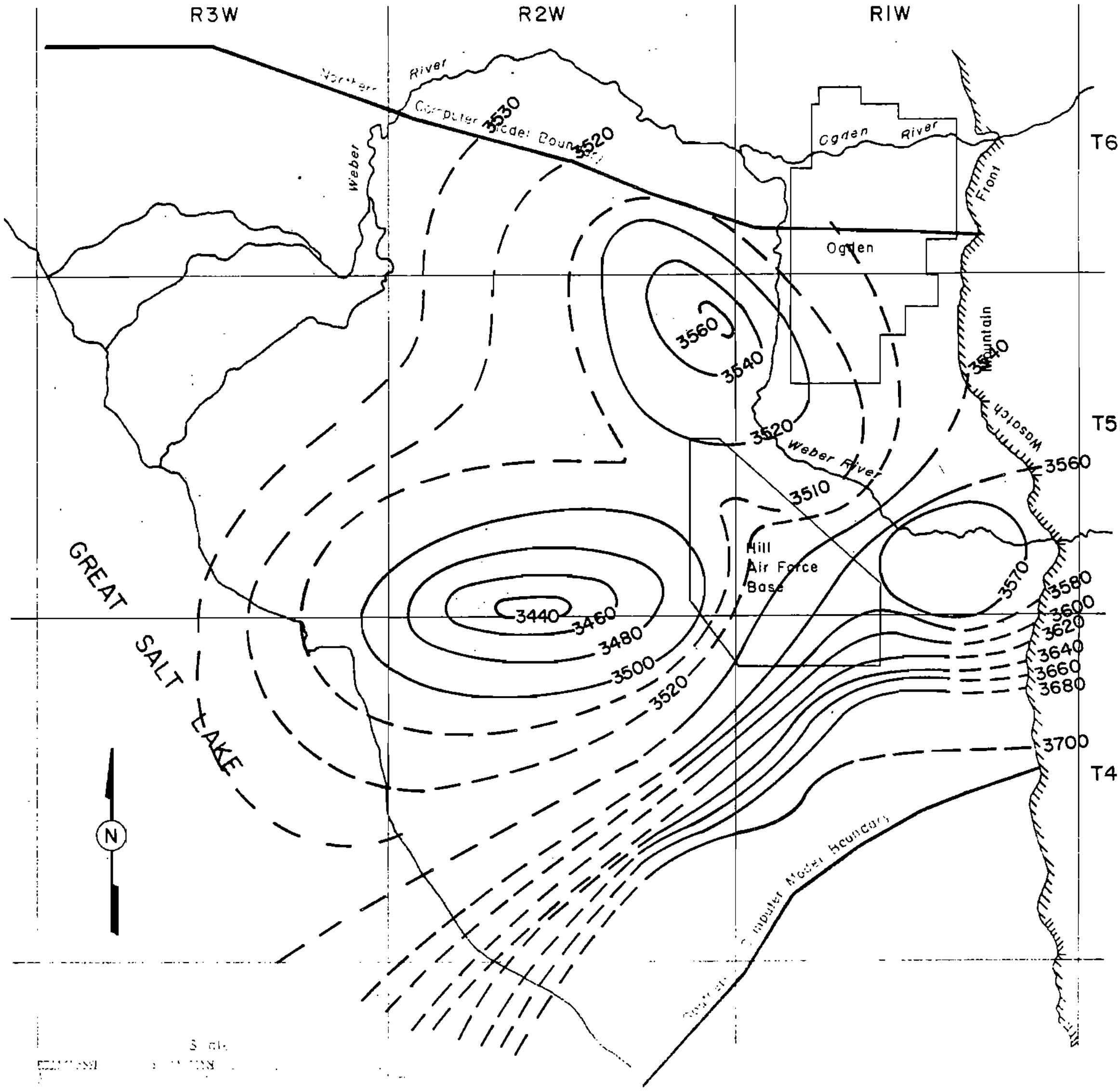


Figure 22. Contours on the effective bottom of the Delta Aquifer.

regions where conditions vary more rapidly than in others. Since recharge comes mainly from the Weber River and the mountain front, a larger number of nodes were placed in that zone so that better hydrologic simulation could be obtained. Similarly, fewer nodes were placed toward the western boundary because groundwater conditions are much more stable there.

Three important rules were followed for the construction of the grid:

1. All nodes must be at the vertexes of the triangular elements.

2. Triangular elements should be kept as nearly equilateral as possible to avoid unnecessary computational error.

3. The ratios of the areas of two adjacent elements should not exceed the range of 1/5 to 5/1.

Figures 24 and 25 illustrate the finite element grid selected for the Weber Delta area with the numbering systems to identify the nodes and elements.

Computer Input

This section discusses the basic principles of computer input and its

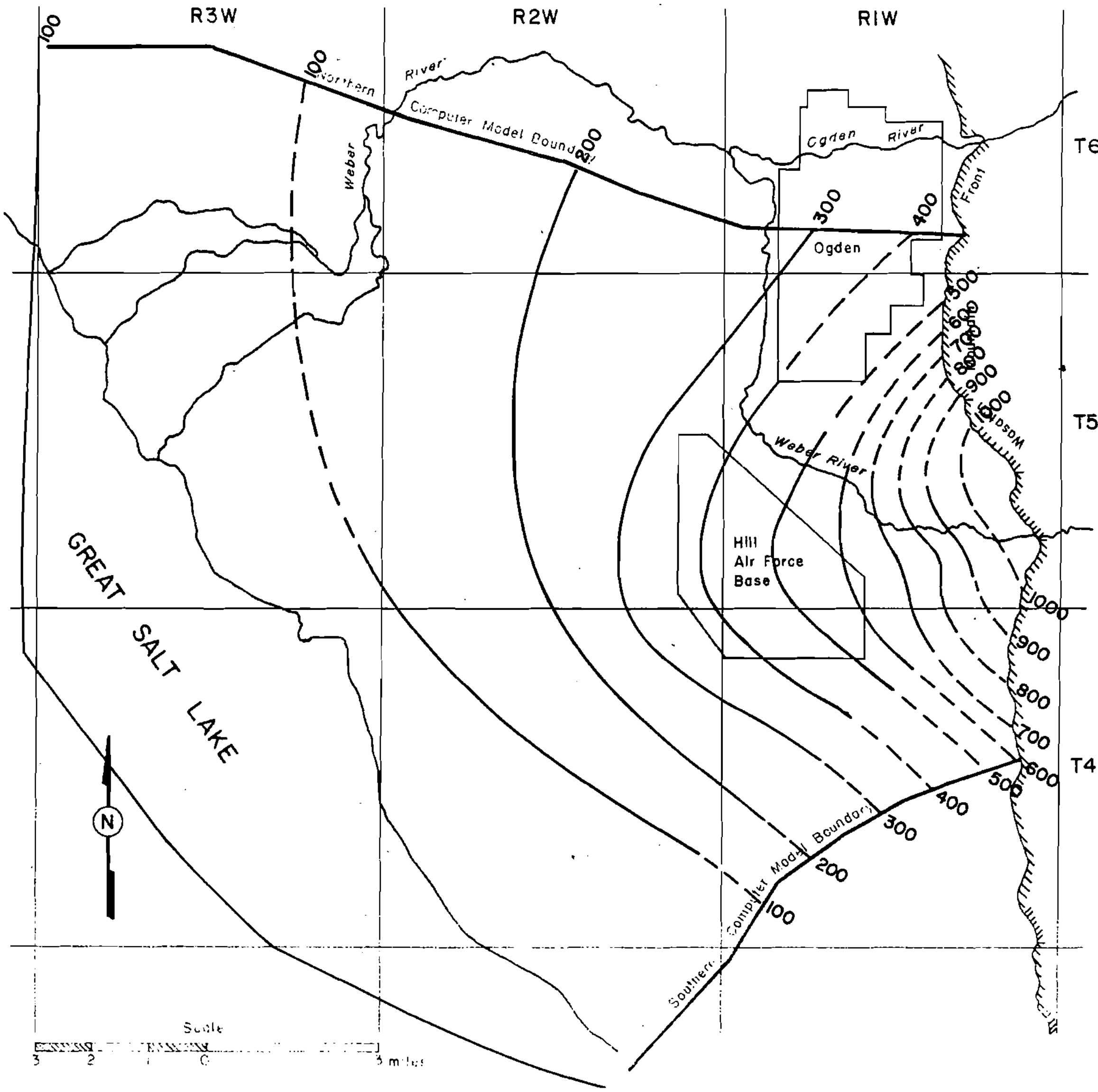


Figure 23. Effective thickness of the Delta Aquifer.

formulation based on knowledge about the system. There are 168 nodes and 294 elements in the computer model grid. At each of these nodes or elements there must exist data defining the conditions which either exist or are imposed upon the system. The computer input data include: 1) initial hydraulic head, 2) recharge, 3) hydraulic conductivity or transmissivity, 4) storage coefficient, and 5) pumping rate. Each of these are discussed below.

Aquifer characteristics. Much of the data utilized came from notes and reports obtained from the United States Bureau of Reclamation (1982) and Feth et al. (1966). These data along with data generated by the authors gave aquifer properties which describe the system insofar as the data permit. Aquifer properties required for input are listed in Table 2.

Hydrologic characteristics. Several hydrologic parameters are required before a computer model can be implemented. These are discussed below.

1. Recharge. Best estimates of subsurface mountain front recharge (Feth

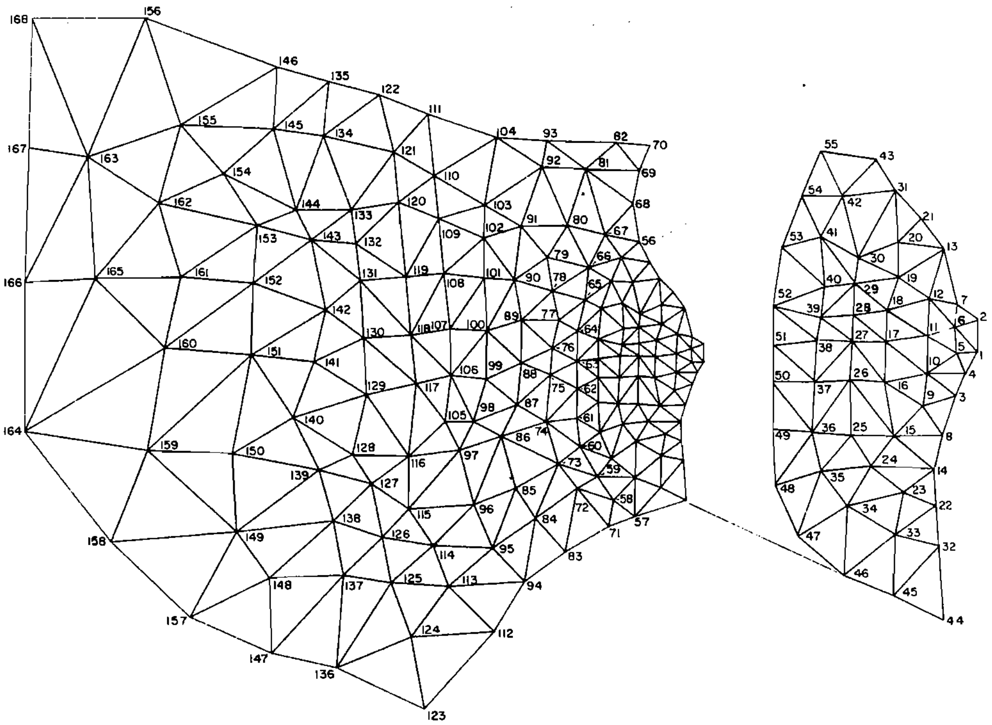


Figure 24. Nodal numbering system for the finite element grid.

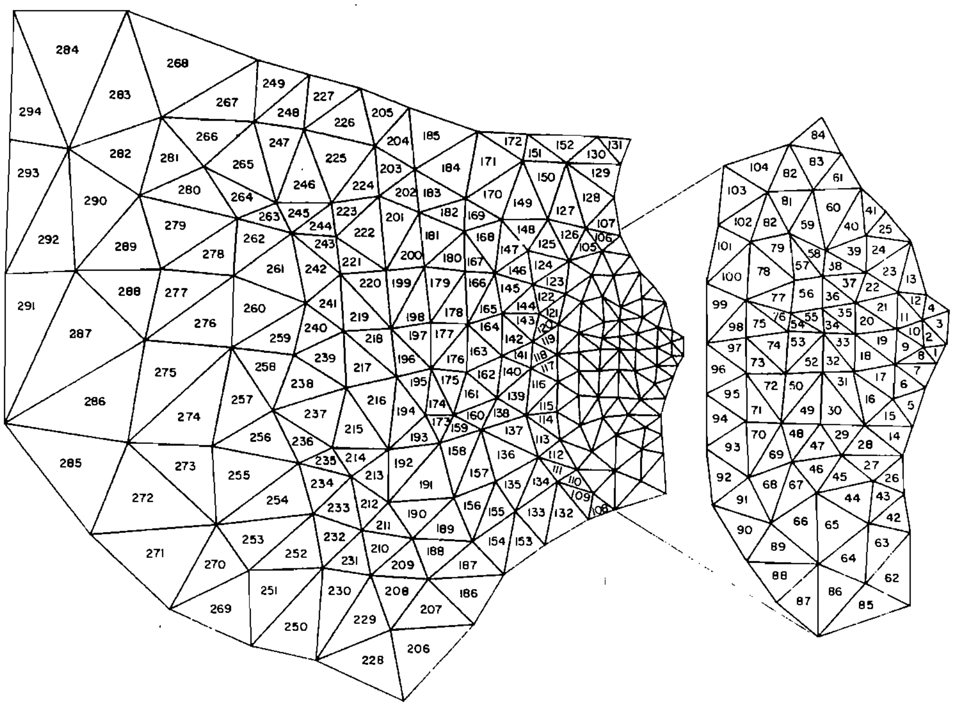


Figure 25. Element numbering system for the finite element grid.

Table 2. Aquifer properties for the main member of the Delta Aquifer and sources of information.

Aquifer Property	Sources of Information
Bottom elevation	Effective bottom elevation as shown in Figure 22.
Thickness	Effective thickness as shown in Figure 23.
Hydraulic conductivity	Initial values came from well testing done in the 1950s (Feth et al. 1966).
Storativity	Initial values were obtained from well testing done in the 1950s (Feth et al. 1966).
Storage coefficient	A uniform value typical of unconfined aquifers was used since no data were available.
K'/B'	Hydraulic conductivity of the leaky layer divided by its thickness was initially taken as a constant and was based on data from Feth et al. (1966).

et al. 1966) indicated that the flow volume should be in the order of 30,000 ac-ft (3700 ha-m) per year. This was distributed along the mountain front in a manner which weighted the areas adjacent to the canyon mouth more heavily than those distant from it. The distribution in terms of percent of average flow as utilized in the model is shown in Figure 26.

As explained earlier the piezometric contour maps indicate that there is an apparent source of recharge in the western part of the study area. The computer model included this recharge as an additional part of mountain front recharge. A later section will discuss the amount of this recharge source as derived during calibration.

Weber River recharge for the area was based solely on river seepage studies completed in the 1950 by the Bureau of Reclamation. In those studies river recharge was found to vary from 0 to 15 percent of the total river flow. A constant value of 7.8 percent of the river flow was utilized throughout time and applied as equivalent quantities of nodal recharge along the appropriate length of the river.

2. Discharge. Discharge occurs within the system through one of two methods, natural flow paths or well discharges. Natural discharges of water through the confining layer into the Sunset Aquifer were calculated by the computer model.

Pumping discharges were extremely difficult to acquire. The region contains numerous wells many of which are no longer on record with the State Engineer's office. Also many of these wells are small domestic or irrigation wells for which pumping data are not recorded. The best data available for a determination of what pumping has occurred were found to be that published yearly by the United States Geological Survey in the annual reports on Groundwater Conditions in Utah. These data, however, have only limited information with regards to both the specific study area and the pumping distribution within that area.

The yearly data published include the entire region known as the East Shore area of which the study area is a portion. Values taken from the Weber River 208 report (Weber River Water Quality Planning Council 1977) indicate

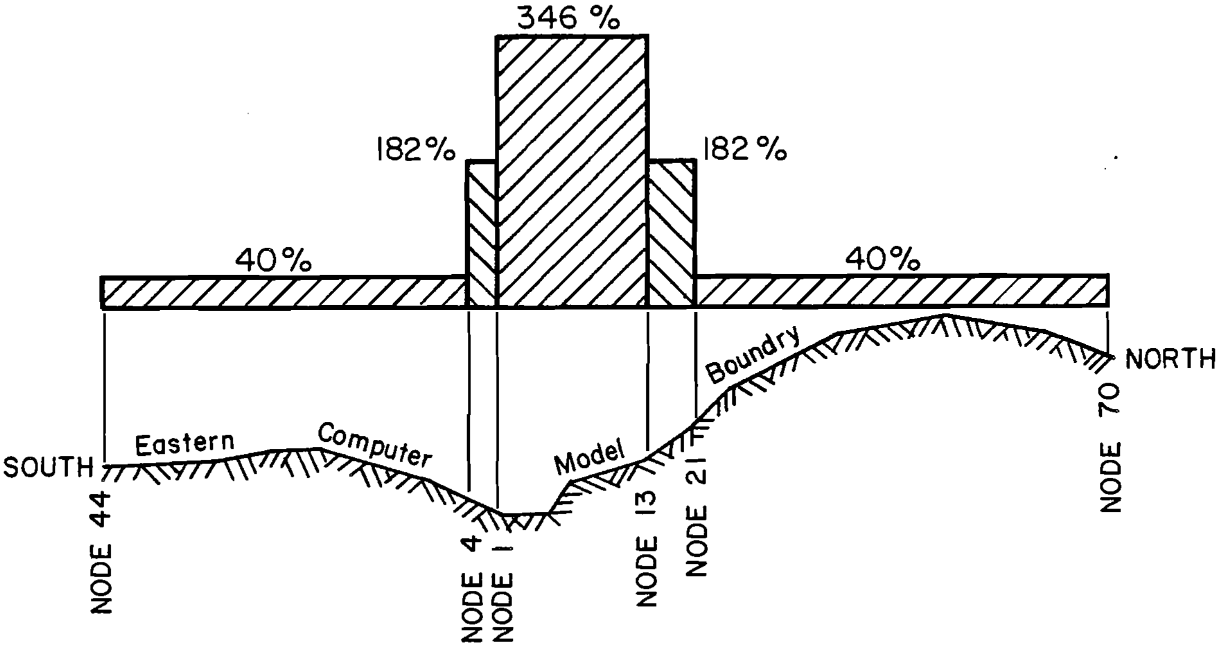


Figure 26. Distribution for mountain front recharge showing percent of average flow per foot.

that the study area includes approximately 50 percent of the total East Shore area agricultural acreage. By assuming an equal utilization of water per acre of land the quantities given on a yearly basis can be broken down into project area pumped irrigation totals. These values are then added to industrial and municipal pumping rates for the year to obtain a project yearly total.

This process was continued for the years 1968 to 1981. The values were then compared with the published East Shore area totals and tabulated as shown in Table 3. When plotted as in Figure 27 it is seen that there is a break in the slope around the year 1972. After that time there appears to be no change in the annual average pumping rate of approximately 63 percent of the total East Shore area pumping. This percentage was held constant after 1972. Table 4 lists the pumping data and references which were used in conjunction with the above method to obtain pumping withdrawals throughout time.

Municipal and industrial pumping estimates were obtained on a yearly basis from the United States Geological Survey. These values were used without alterations. Figure 28 was prepared to illustrate the recorded changes in municipal and industrial pumping with time.

Areal withdrawal distributions were obtained with the aid of the Weber River 208 study (Weber River Water Quality Planning Council 1977). Utilizing land use patterns presented therein and knowledge about the locations of municipal and industrial wells, three separate pumping regions were defined as shown in Figure 29. Region 1 represents the agricultural pumping zone, region 2 the municipal and industrial zone, and region 3 a zone of high pumping concentration consisting of wells operated by Hill Air Force Base.

3. Adjacent aquifer heads. Piezometric heads within the Sunset Aquifer overlying the Delta Aquifer have an important impact upon leakage either

Table 3. Project withdrawal percentage of East Shore area totals.[a]

Year	USGS Irrigation Estimate	Project Irrigation Estimate	Municipal & Industrial	Total	GWC Report Total[b]	Percent of Total
1968	27,100	13,550	10,359	23,909	46,400	51.53
1969	27,400	13,700	11,777	25,477	48,400	52.64
1970	17,000	8,500	13,061	21,561	39,000	55.53
1971	17,700	8,850	13,722	22,572	40,600	55.60
1972	16,400	8,200	16,170	24,370	40,000	60.93
1973	-	-	-	-	-	-
1974	17,500	8,750	21,778	30,528	47,000	64.95
1975	17,300	8,650	15,029	23,679	38,000	62.31
1976	17,000	8,500	14,177	22,677	37,000	61.29
1977	15,800	7,900	23,881	31,781	48,000	66.21
1978	15,700	7,850	13,884	21,734	36,000	60.37
1979	-	-	-	-	-	-
1980	16,000	8,000	20,877	28,877	45,000	64.17
1981	8,600	4,300	19,294	23,594	36,000	65.54

[a] Tabulated values are in ac-ft/yr.
[b] Values obtained from Yearly Groundwater Conditions in Utah reports.

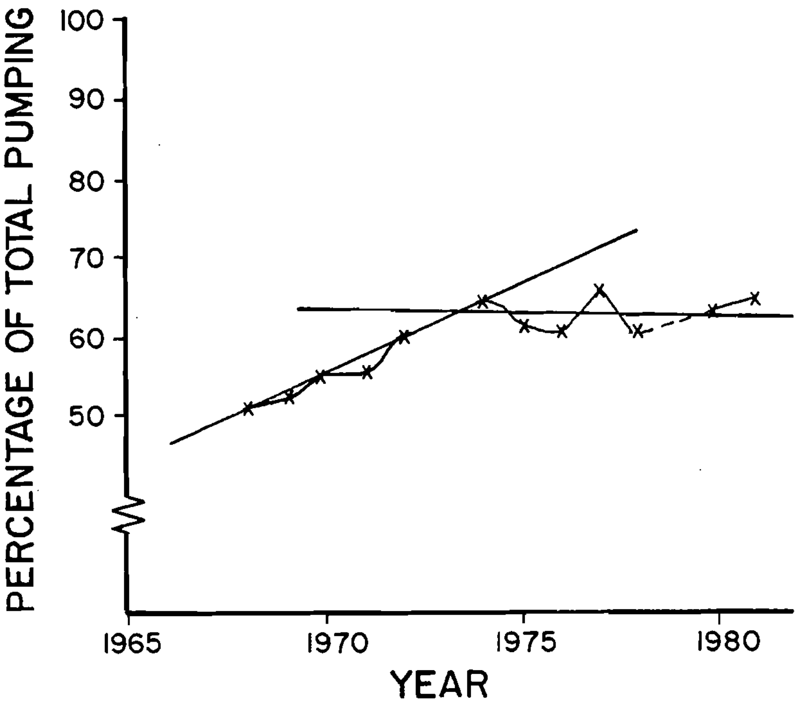


Figure 27. Project area pumping withdrawal as percentage of East Shore are totals as a function of time.

Table 4. Summary of well discharge history for East Shore area, Utah (ac-ft).

Year	Irrigation	Industrial	Public	Domestic + Stock	Total	Source[a]	Comments (Areas are for East Shore area unless otherwise noted)
1939					15000	2	Davis County wells
					26000	3	Small diameter wells
1946	8800				15000	2	Davis County wells
1954					33400	4	Weber Delta District (T3N-T7N)
1960			10000			3	
1961			15000			3	
1962			13000			3	
1963					36000	1	
			15000			3	
1964					55000	1	
			19000			3	
1965					59000	1	
			21000			3	
1966					55000	1	
			22000			3	
1967					53000	1	
			24000			3	
1968	27100	6800	12500	b	46400	1	
			20000			3	
1969	27400	6600	14400	b	48400	1	
			21000			3	
1970	17000	6400	15600	b	39000	1	
1971	17700	6500	16400	b	40600	1	
1972	16400	6900	18100	b	40000[c]	1	
1973					41000[c]	1	
1974	17500	7800	24400	b	47000[c]	1	
1975	17300	6300	17600	b	38000[c]	1	
1976	17000	6100	17500	b	37000[c]	1	
1977	15800	6700	29300	b	48000[c]	1	
1978	15700	5900	18100	b	36000[c]	1	
1979					46000[c]	1	
1980	16000				45000[c]	1	
1981	8600	6300	21000	b	36000[c]	1	

---

[a] 1 Utah Division of Water Resources, U.S. Geological Survey, 1963-1981; 2 Thomas et al. 1952; 3 Bolke and Waddell 1972; 4 Feth et al. 1966.

[b] Included in irrigation estimate.

[c] Adjusted values given in 1982 Groundwater Conditions in Utah Report, page 8.

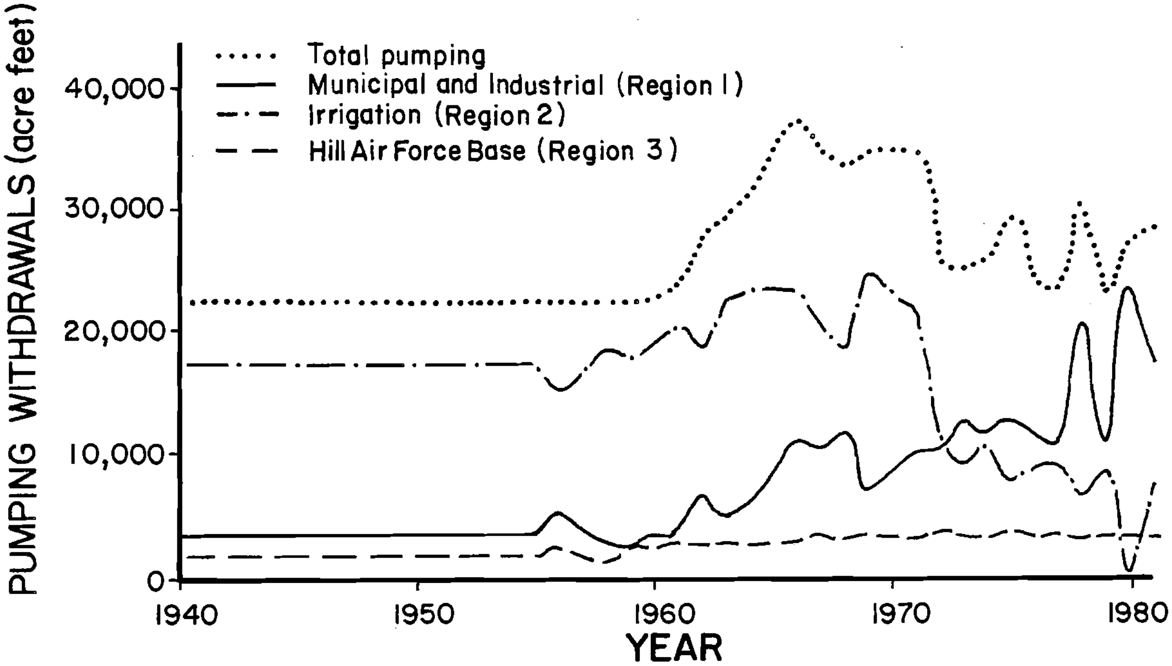


Figure 28. Historical pumping rates used for the Weber Delta area.

into or out of the Delta Aquifer. Early estimates of the heads in the Sunset Aquifer were obtained from several Water-Supply Papers published by the United States Geologic Survey. These publications, however, contain very little data for this adjacent aquifer after mid 1960.

4. Fixed head nodes. In order for the computer model to converge upon a solution it is usually required that one or more nodes be specified as a constant head node(s). With the physical boundary conditions as given in the modeled area, a well defined constant head node does not exist. The only region which might be suitable for such a condition is along the western reaches of the model in the area of the Great Salt Lake. Node 164 was chosen as an approximation to a constant head node due to the fact that the piezometric heads of the Delta Aquifer appeared to change less in that region than any other.

Limitations and Neglected Features

Several limitations to the model and input exist. Perhaps the greatest is the fact that a three-dimensional aquifer system is being modeled by a two-dimensional model with vertical leakage. Any vertical flow from the Sunset Aquifer would tend to decrease the heads in that aquifer. The computer model is unable to account for that dependent interaction internally and any head adjustments must be done manually.

To the writers' knowledge only one estimate of mountain front recharge has been made for the project area. Additional study would probably firm up this estimate. The unknown quantity of deep recharge occurring along the western reaches of the project area has already been mentioned.

Pumping rates include some error in terms of quantity and also in terms of areal distribution.

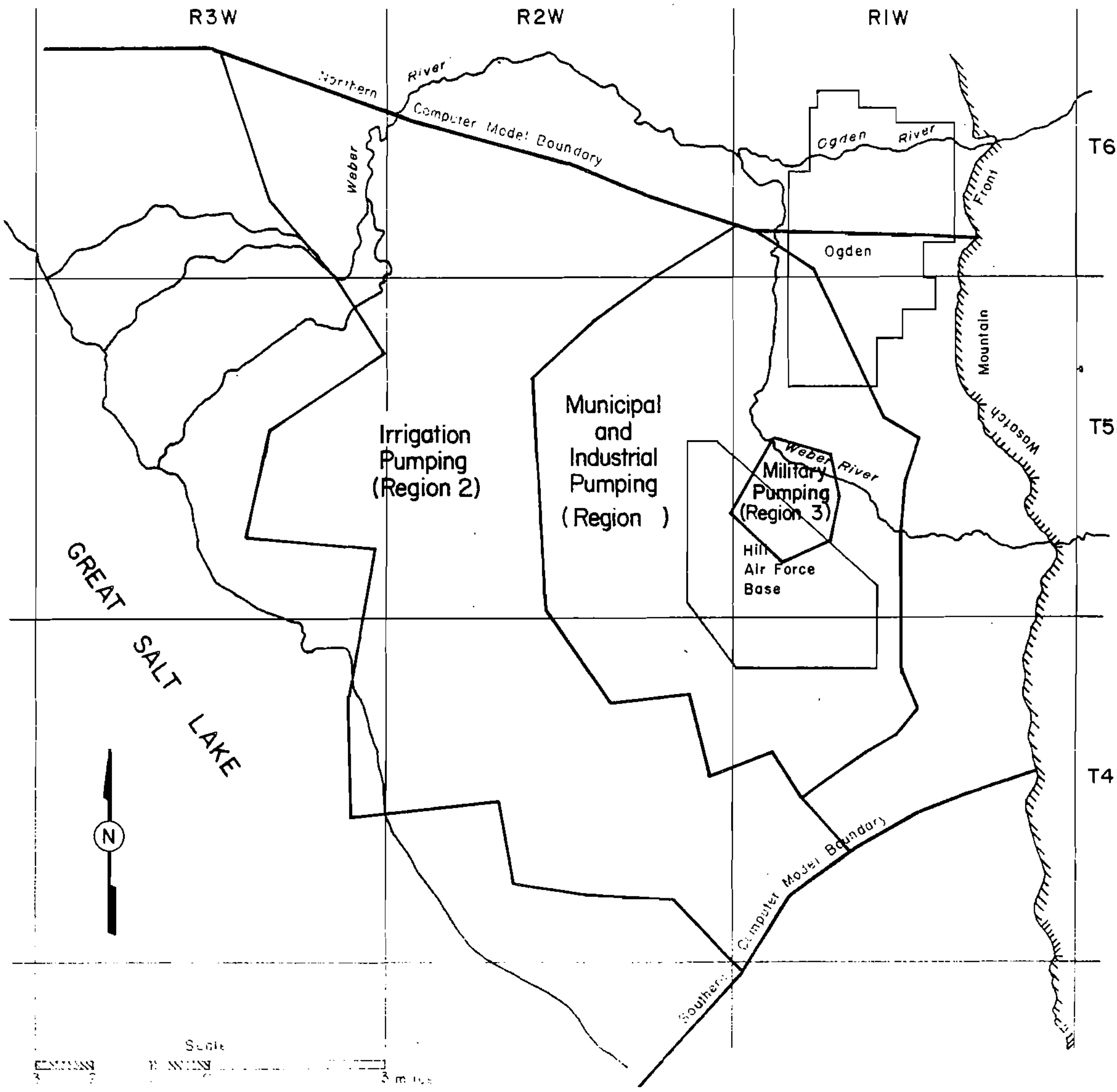


Figure 29. Municipal and industrial, irrigation, and military pumping regions.

Weber River recharge is not a constant percentage of the streamflow as assumed but varies with depth of flow and submerged area.

The streamlines which make up the northern and southern boundaries of the model actually somewhat vary with time. Since a gridwork cannot change within the model at advancing time steps, an average streamline position was chosen.

The withdrawal of water from the Delta Aquifer is not uniformly distributed by regions as assumed, but consists rather of an unknown distribution.

The aquifers involved consist of a wide range of alluvial materials in a complex array and distribution. Any values defined as pertaining to such a system are obviously an estimate or simplification of true conditions.

Statistical Models

In this study a statistical model was developed in order to study the probability of having water available for groundwater recharge. Water may be considered available when the flows within the Weber River are greater than the concurrent water rights. If a statistical model shows that water availability occurs with a small probability, then an alternate plan must be considered. Such a plan might include options such as operation only during available flow periods, or utilizing purchased water.

The time period for which any generated river flows are calculated is an important factor when considering available water. If the generated series and thus the available water are based on yearly intervals alone, important fluctuations in river flows would be totally missed. For example, during low flow periods with a simultaneously low water right demand a small change in river flow would result in available water during that period. The same sequence of flows when averaged over the entire year might, however, be very different and even indicate that no flow was available.

The degree to which a model is broken down depends upon the degree of accuracy desired and the amount of information available. The decision therefore hinges upon factors in both the resource and time domains. Much of the data gathered for analysis in this project is based on monthly values and therefore the resources would support a similar breakdown of the statistical model. The time constraints likewise indicate that a monthly breakdown should be used.

The statistical procedure involves the artificial generation of a sequence of river flows which possess the same statistical characteristics as the original series, and is not intended to suggest that future events will follow the same pattern as those produced by the generated series of flows.

In order to reliably reproduce the statistical characteristics of a historical sequence there must be sufficient data available for analysis. A rough estimate of the minimum number of required data points for a valid model is in the order of 60 (Canfield 1983). This does not indicate that only 5 years of monthly data are required for monthly generation in spite of the fact that 60 data points would be available. In keeping with the above rough estimate we would need 60 data points for each period over which natural changes occur. Therefore if a yearly trend was desired we would require 60 years of data. The determination of whether or not there exists sufficient data for the Weber River at Gateway to perform a stochastic analysis was done with the aid of a double mass plot. Figure 30 compares cumulative flows for the Weber River at Gateway versus those for the Weber River near Oakley, Utah. The Oakley station is above any major development and the flows in the Weber River at that point are taken as unaltered. When cumulative flows occurring at one station are plotted against the natural cumulative unaltered flows at another, an indication of the usable length of record of the first can be made. Figure 30 shows that there exists a break in slope between the two stations around the year 1968. What this means is that for a statistical model only the data obtained after that date should be used in the analysis. If this rule is followed explicitly, then only 14 years of record exist over which statistical parameters can be obtained. In order to accurately generate both seasonal and long term streamflow fluctuations, the statistical model was divided into two parts: 1) annual time series generation based on a comparison with nearby long record gages and 2) monthly time series generation to establish seasonal flows.

Annual Time Series Generation

The most widely used form of stochastic generation uses the autocorrelation function. The autocorrelation function describes the degree of

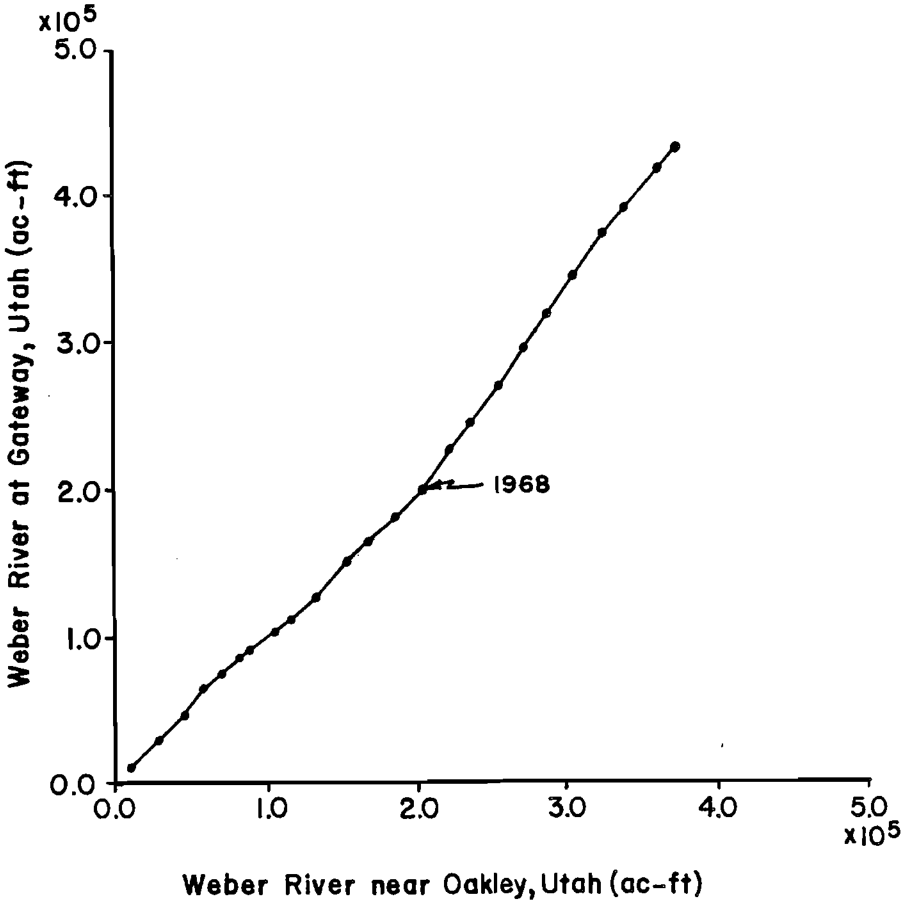


Figure 30. Double mass flow plot for the Weber River at Gateway and the Weber River at Oakley, Utah.

sequential dependence or correlation in a historical time series. If the autocorrelation function is transformed to the frequency domain it is known as the spectral density function (Jenkins and Watts 1968). Once such a conversion is made the spectral density can be used directly to generate stochastic series. The benefit of using the spectral density is that if a river station can be found with a similar spectral density and a longer record, the spectral density of the longer record can be utilized to forecast flows at the desired location (Canfield 1983).

Since the purpose of the statistical model is to simulate present conditions, it was desirable to locate a river station with similar conditions to those found at the Gateway Station. James et al. (1979) published what they called present modified flows for the Weber River at Plain City. These values were calculated on a yearly basis so as to account for man's activities as though they had occurred since the beginning of the available record. A comparison between the characteristics of the said modified flows and the Gateway Station is outlined next.

A program utilized to calculate the spectral density function (called STAT.FOR) can be found in Appendix B. The reader is referred to Jenkins and Watts (1968) for a detailed discussion of spectral analysis of time series. The results of an analysis on the

Weber River are shown in Table 5 and Figure 31.

Another method of calculating the spectral density is to utilize the Fast Fourier Transform (Canfield 1982). A program named FFT.FOR utilizing this method is also found in Appendix C and the results are shown in Table 6.

Since the spectral density can be calculated using either method, the choice is left to the user. The values from the two methods are not exactly the same. This is due to the method of smoothing the raw spectral density (Jenkins and Watts 1968).

From Figure 31 it can be seen that the spectral density of the present modified flows on the Weber River at Plain City is a reasonable estimate of that found at the Gateway Station and is therefore used in the remaining analysis.

Table 5. Calculated spectral densities for the Weber River for the period 1921-1977.

Frequency	Spectral Density	
	Weber River at Gateway	Modified Weber River at Plain City
0.00	2.10	2.90
0.04	2.46	2.92
0.07	1.97	2.03
0.11	1.35	1.27
0.14	1.61	1.57
0.18	1.43	1.40
0.21	0.91	0.80
0.25	0.57	0.50
0.29	0.63	0.58
0.32	0.54	0.42
0.36	0.23	0.15
0.39	0.17	0.12
0.43	0.29	0.26
0.46	0.49	0.37
0.50	0.57	0.37

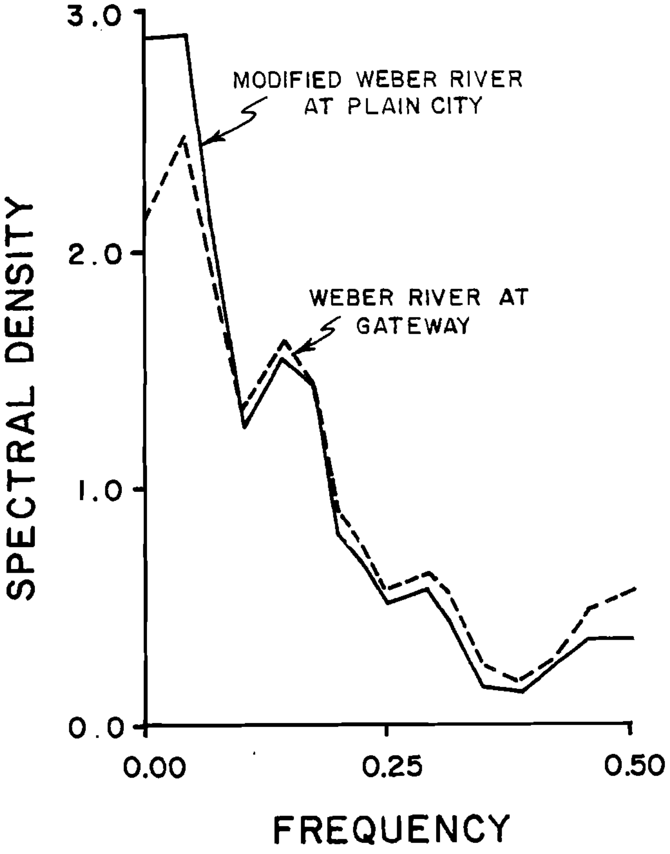


Figure 31. Comparisons between spectral density functions for the Weber River.

Table 6. Spectral density for the Weber River at Gateway using FFT.FOR.

Frequency	Spectral Density
0	2.71
0.03	3.47
0.07	2.20
0.10	1.04
0.13	1.71
0.17	1.51
0.20	1.32
0.23	0.62
0.27	0.49
0.30	0.66
0.33	0.48
0.37	0.17
0.40	0.11
0.43	0.13
0.47	0.33
0.50	0.39

Once the spectral density is calculated a sequence of generated flows can be developed utilizing the program named GENSPEC as listed in Appendix D. Details of the generation procedure can be found in Canfield (1982). Since the result of generation based on the spectral density is a normal distribution with zero mean and a standard deviation of one, the results must be modified. This is done by multiplying each generated value by the sample standard deviation and then adding the mean. This is accomplished within the above mentioned program.

For verification that generated and observed inflows were statistically similar, a series of 50 generated sequences of 7 annual values each was found to be N(0.02,1.03) as compared to the theoretical N(0,1) distribution.

Monthly Time Series Generation

Once yearly values have been obtained, some method must be used to disaggregate them into a proper distribution for further monthly analysis. The method used herein is based upon natural flow characteristics derived from the available record. The disaggregation model (called MONGEN in Appendix E) requires the following data inputs (Canfield 1983).

1. Variance-covariance matrix between monthly data transformed to common logarithms.

2. Mean monthly streamflows.

3. The lagged monthly means for any of the previous year's months which have a significant correlation with the present year's months. For an illustration note Table 7. For large data sets the difference will be negligible and the regular data mean value can be used.

4. Yearly total flows to be disaggregated.

5. Average recorded yearly flow.

6. Previous year's flows which the model uses as initial values. The model allows average monthly values to be used and asks which option is desired during execution.

The amount of data available limits the input for items 1, 3, and 4. Numbers 1 and 3 can contain data correlating present year's flows with one or all of last year's flows. If all of last year's flows are utilized the matrix described in number 1 would be a 24 by 24. The maximum possible maxtrix size for the Weber River at Gateway is limited to 13 (N-1) since there exists only 14 data points. The following discussion will be somewhat more general in that it will be assumed that correlations can be made with last year's October, November, and December flows. The concept is then presented in theoretical form and the matrices can be expanded or contracted as required.

Table 7. Difference between monthly means and lagged monthly means.

Year	Month		
	January	December	December[a]
1968	7,095	7,913	7,337
1969	14,656	8,362	7,913
1970	8,735	6,734	8,362
1971	12,443	8,497	6,734
1972	12,488	4,394	8,497
1973	6,143	4,018	4,394
1974	7,631	2,949	4,018
1975	3,008	11,107	2,949
1976	9,986	2,749	11,107
1977	2,226	2,768	2,749
1978	2,630	3,800	2,768
1979	6,533	2,502	3,800
1980	7,743	3,539	2,502
1981	2,823	3,454	3,539
Means	7,240	5,199	5,476

[a] Data have been lagged one year.

The required vectors and matrices are:

$$\text{mean monthly flows } (\hat{\mu}_{\underline{x}}*) = \begin{Bmatrix} \bar{X}_1 \\ \bar{X}_2 \\ \bar{X}_3 \\ \cdot \\ \cdot \\ \cdot \\ \bar{X}_{12} \\ \bar{X}_{10}^* \\ \bar{X}_{11}^* \\ \bar{X}_{12}^* \end{Bmatrix}$$

$$\text{data vector } (\underline{w}) = \begin{Bmatrix} X_{10}^* \\ X_{11}^* \\ X_{12}^* \\ T \end{Bmatrix}$$

$$\begin{array}{l} \text{Variance -} \\ \text{Covariance} \\ \text{Matrix from} \\ \text{Data Set} \\ (\hat{\Sigma}\underline{\mu}*) \end{array} = \left[\begin{array}{cccccc|ccc} \sigma_1^{\,2} & \sigma_{1,2} & \sigma_{1,2} & - & - & \sigma_{1,12} & \sigma_{110*} & \sigma_{111*} & \sigma_{112*} \\ & \sigma_2^{\,2} & \sigma_{23} & \sigma_{33} & - & \sigma_{212} & \sigma_{210*} & - & \sigma_{212*} \\ & & \ddots & & & \sigma_{312} & \vdots & & \vdots \\ & & & \ddots & & & \vdots & & \vdots \\ \text{Symmetrical} & & & & \ddots & \sigma_{12}^{\,2} & \sigma_{1210*} & - & \sigma_{1212*} \\ \hline & & & & & & \sigma_{10*}^{\,2} & \sigma_{10*11*} & \sigma_{10*12*} \\ \text{Transpose of upper} & & & & & & & \sigma_{11*}^{\,2} & \sigma_{11*12*} \\ \text{right quadrant} & & & & & & \text{Symmetrical} & & \sigma_{12*}^{\,2} \end{array} \right]$$

where:

$\bar{X}_i$ = mean monthly flow for month i

$\bar{X}_i*$ = mean lagged monthly flow for month i as illustrated in Table 7

X_i* = previous year's flow for month i

T = this year's total flow

σ_i^2 = variance of month i flows

σ_{ij} = covariance between months i and j

$\sigma_{ij}*$ = covariance between month i and previous year's month j

σ_i^{2*} = variance of previous year's month i flows (for large data sets this equals σ_i^2)

σ_{i*j*}= covariance between previous year's i and j flows

If

$$\hat{\mu}_{\underline{x}} = \begin{bmatrix} \hat{\mu}_{\underline{x}}* \\ T \end{bmatrix}$$

then find [A] such that

$$A\ \hat{\mu}_{\underline{x}}* = \hat{\mu}_{\underline{x}}$$

the A matrix is then

$$A = \begin{bmatrix} \text{10 - - - - - - -} & \\ \text{010} & \\ \text{ 010} & \text{0's} \\ \text{ 010} & \\ \text{   010} & \\ \text{   010} & \\ \text{   010} & \\ \text{   010} & \\ \text{   010} & \\ \text{0's   010} & \\ \text{   010} & \\ \text{   010} & \\ \text{   010} & \\ \text{   010} & \\ \text{- - - - - - - -01} & \\ \text{1111111111111000} & \end{bmatrix}$$

Now $\hat{\Sigma}x = A\hat{\Sigma}\mu*A^T$ which results in a 16 x 16 matrix of the form

$$\hat{\Sigma}x = \left[\begin{array}{c|c} \Sigma y & \Sigma yw \\ (12x12) & (12x4) \\ \hline \Sigma yw^T & \Sigma w \\ (4x12) & (4x4) \end{array}\right]$$

From the above matrix a variance-covariance matrix for the system can be found by the equation:

$$\Sigma \underline{y}/w = \Sigma \underline{y} - \Sigma \underline{yw}\ \Sigma w^{-1}\ \Sigma \underline{yw}^T \quad . \quad . \quad (2)$$

This is a 12 x 12 matrix and is used as input into the RNVR subroutine of the program MONGEN along with the mean vector $\mu \underline{y}/w$ as calculated from Equation 3.

$$\mu \underline{y}/\underline{w} = \mu \underline{y} \quad \Sigma \underline{y}/\underline{w}\ \Sigma w^{-1}\ (\underline{w} - \mu \underline{w}) \quad . \quad . \quad (3)$$

where

$\mu \underline{y}$ = vector of monthly means

$\mu \underline{w}$ = mean w vector

all other terms are as presented in the above discussion

The results obtained from MONGEN are a series of length N $\leq$ the number of data points which simulate the statistical characteristics of the series. Modeling results are presented in the following section.

MODEL RESULTS

Statistical Models

Yearly Flow Generation

The accuracy of the yearly generation program named GENSPEC listed in Appendix D was checked by comparing the generated versus theoretical (ideal) statistics as shown in Table 8.

Upon generating a yearly sequence, the historical mean and standard deviation were used to convert the N(0,1) distribution back into one with historical statistics. This is accomplished by multiplying each generated value by the standard deviation and then adding the mean.

Monthly Flow Generation

The monthly disaggregation program called MONGEN as listed in Appendix E converts yearly streamflow into monthly streamflow according to the historical statistics at the Weber River Gateway station. Disaggregated monthly flow statistics generated by MONGEN were compared to the monthly flow statistics of the observed data and the results are as shown in Table 9. The results could be improved if more data points were available from which to obtain a better estimate of the true monthly statistics.

Table 8. Comparison between the theoretical and generated means, standard deviations and skews for GENSPEC.FOR.

	Mean	Standard Deviation	Skew
Theoretical	0	1	0
Generated	-0.0	1.01	-0.04

The results presented herein are also limited by the fact that the $\hat{\Sigma}\underline{\mu}*$ matrix described in the preceding section was limited in size due to the lack of river data. Since the variance-covariance matrix is the means whereby the model simulates the correlation between monthly flows, its completeness is important. In most natural systems the dependence of the present months surface flow on those of previous months will decay rapidly. Since the Weber River is highly regulated the characteristics of management are also included within the monthly correlations. Table 10 shows the correlation matrix for the January through December flows for the Weber River at Gateway. From Table 10 the general trend of correlations is to decrease with time for a few months then increase somewhat before continuing a downward trend. This lagged correlation increase might very well be explained by management practices on the river, however, its source is not confirmed nor studied further here.

From Table 10 it is also noted that correlations can be made between any two months of the present year. However, the complete variance-covariance matrix described in the preceding section contains only one column which correlates each of the present years months with last years December flows. Therefore January can only be correlated with the previous December which is a one month correlation. On the other hand this years December can be correlated with the previous years December giving

Table 9. Comparison between generated and observed monthly statistics (mean/standard deviation).

Month	Historical Values	Run 1	Run 2	Run 3	Run 4	Run Avgs.
Jan	7440/3968	7452/4258	8345/7338	7731/4494	8161/5809	7922/5475
Feb	8252/4496	8406/4947	8909/5452	9225/5220	9072/5648	8903/5317
Mar	18844/12031	18238/7950	20693/10211	20067/9372	19174/9334	19543/9217
Apr	30774/17430	30228/14730	33431/16617	32845/15147	30337/13028	31710/14880
May	47276/21478	48943/17959	43771/16593	46081/15800	46194/18595	46247/17237
Jun	33756/16742	35027/16640	33917/16554	32308/15577	33512/17167	33691/16485
Jul	17016/6016	16189/5778	16432/6343	16431/6047	16568/6023	16405/6048
Aug	13957/2128	13338/4579	12938/4477	13267/4624	13608/4709	13288/4597
Sep	10725/2070	10321/3771	10114/3441	10281/3672	10717/4022	10358/3727
Oct	7210/2552	6827/3027	6790/3129	7021/2959	7316/3344	6989/3115
Nov	5092/2594	5285/2538	4691/2401	4991/2432	5270/2425	5059/2449
Dec	5199/2767	5038/2621	5261/4150	5042/2863	5362/2880	5176/3129

Table 10. Correlation between January through December Weber River flows at Gateway.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Feb	0.845										
Mar	0.737	0.848									
Apr	0.586	0.812	0.933								
May	0.382	0.570	0.762	0.859							
Jun	0.009	0.124	0.341	0.490	0.762						
Jul	0.181	0.368	0.502	0.613	0.713	0.735					
Aug	0.658	0.652	0.759	0.769	0.833	0.625	0.769				
Sep	0.494	0.585	0.735	0.715	0.724	0.514	0.711	0.855			
Oct	0.470	0.610	0.634	0.638	0.623	0.579	0.760	0.770	0.715		
Nov	0.357	0.395	0.517	0.485	0.660	0.636	0.769	0.774	0.604	0.848	
Dec	0.236	0.163	0.248	0.257	0.401	0.614	0.759	0.634	0.423	0.756	0.849

a 12 month correlation. The inability to correlate this years monthly flows with the January through November flows from the previous year is a noted disadvantage.

Available Flows

Available river flow for recharge purposes can be determined in two ways. First, if the total legal water right for the Weber River between Gateway and the Great Salt Lake were determined, net available water could be found by subtracting rights from river flows. This method is very complex due to the large number of water right holders along the Weber River whose rights vary according to time of year and climatologic conditions. It is further complicated by the fact that the court decreed legal right is often not used to its fullest extent. In some cases quantities may be based upon the carrying capacity of the ditch, canal, pump, or pipe and may not be truly representative of the actual water used.

The second method involves determining the quantity of water being wasted into the Great Salt Lake. This can be accomplished by either a direct measurement of the flows as they enter the lake or by subtracting the water rights of downstream users after the Weber River passes the Plain City gaging Station. The number of users downstream of said station are few and the task would be much simpler than using the legal water rights. This method would appear to allow more recharge input because it would be a measure of actual use rather than legal right.

Estimates for the average wasted water entering the Great Salt Lake were obtained by subtracting the water right held by the Ogden Bay Bird Refuge from the 21 year average river flows near Plain City. The values shown in Table 11 do not include the few water right holders downstream of the Plain City gaging station, but they do show that there is a significant quantity of water wasted each year to the Great Salt Lake. A groundwater recharge simulation discussed in the next section is based on the premise that water would be available for much of the year as is shown in Table 11. Since the wasted water flow at Plain City also includes Ogden River water, care would have to be taken to ensure that the water right allocation was filled between the point of the recharge diversion on the Weber River and the joining of the two river systems.

Since water rights along the Weber River are so complex, and perhaps artificially high in terms of available water, a simplification was sought which would be a more realistic estimate of actual water use. Water use estimates are broken into two parts. The first is for the normal withdrawal of water by small users as administered by the Weber River commissioner and the second is the average withdrawal of water for Willard Bay to be used for subsequent pumping and distribution by the Weber Basin Water Conservancy District. Since a clear and consistent withdrawal pattern for Willard Bay does not exist, three values for total withdrawal will be used for each month as shown in Table 12. The first value includes the Willard Bay calculated mean plus one standard deviation flow, the second its calculated mean, and the third its calculated mean minus one standard deviation. For recharge purposes these three values approximately represent drought, normal, and flood conditions, respectively.

Computer input values for available recharge water were obtained by subtracting the values shown in Table 12 from the series of monthly streamflows generated by the statistical models previously mentioned.

Groundwater Model

In order to forecast the results of any action through the use of a computer

Table 11. Average wasted Weber River flows into the Great Salt Lake (1956-1977).

Month	Average Monthly Flow (cfs)	Ogden Bay Refuge Right (cfs)	Average Wasted Flow	
			cfs	Acre-feet/month
Jan	307	20	287	17,647
Feb	376	20	356	14,218
Mar	622	50	572	35,171
Apr	878	135	743	44,212
May	1060	135	925	56,876
Jun	576	135	441	20,241
Jul	101	80	21	1,291
Aug	65	80	0	0
Sep	135	80	55	3,273
Oct	237	150	87	5,349
Nov	275	150	125	7,438
Dec	288	150	138	8,485

model, the following three main steps must be successfully completed:

1. Steady state calibration
2. Transient calibration
3. Verification

Steady State Calibration

One common problem encountered in model calibration is the selection of a period of time during which conditions do not change. In natural systems this is often difficult because of the many sources of recharge and discharge all of which are seldom constant.

In the Weber Delta area the Weber River is a direct source of recharge which varies continuously with time. Sequential periods of time which have the same distributions and quantities of recharge seldom occur. Other recharge sources such as mountain front recharge are more constant than the river recharge. These sources, however, can also vary in sufficient amounts to make the selection of a period of steady state conditions difficult.

Man's activities also influence the occurrence of steady state conditions. If man's influence on the flows continue to change throughout the period of record, it may be impossible to determine an initial steady state condition. In such a case an initial starting condition must be assumed based on the historical sequence of events and their effect on the system.

Recorded water well level data for the Weber Delta area began in the late 1930s. From these data two types of contour maps were prepared.

The first type is presented in Figures 7-13 as piezometric contour maps for the period 1937 through 1980. The second type is shown in Figures 14 and 15. Figure 15 illustrates the change in position of the 4280-ft contour line with time. Figure 14 in a similar fashion compares the changes made by the 4300-ft contour over the same time interval. Comparison of these figures indicate that the early period of history between 1937 and 1945 appears to be an adequate starting point for a steady state calibration. Figure 28 also suggests that early pumping rates were quite constant prior to 1956 showing that the early recorded history

Table 12. Monthly estimates for utilized Weber River water rights (ac-ft).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean plus one standard deviation	15827	15926	28773	42998	81122	58794	39393	38262	38152	41280	1662	7172
Mean	9025	8465	16893	25407	63165	45696	37163	36547	36586	37804	646	3418
Mean minus one standard deviation	2223	1004	5013	7816	45208	36000	36000	36000	36000	36000	0	0

would be suitable for a steady state analysis.

The equation of groundwater motion presented in the preceding section is

$$S\frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right) + Q + \frac{K'}{B'}(h_a - h) \quad . \; . \; . \; . \; (1)$$

Under steady state conditions this equation reduces to:

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right) + Q + \frac{K'}{B'}(h_a - h) = 0 \quad . \; . \; . \; . \; (4)$$

The geologic characteristics on which Equation 4 depends are T_{xx}, T_{yy}, and K'/B'. The dependent hydrologic characteristics for steady state calibration are Q and h_a. This means that during the initial calibration phase the values of T_{xx}, T_{yy}, K'/B', Q, and h_a must be either initially defined or determined through the calibration process. The only known variable of those mentioned above are the values of the heads in the adjacent aquifer (h_a). By assuming that T_{xx} is equal to T_{yy} the number of variables is reduced by one. The hydraulic conductivity of the medium and the saturated thickness are entered into the program which then calculates T. The remaining variables were found through the calibration process. Initial estimates of recharge, hydraulic conductivity and K'/B' were obtained from Feth et al. (1966), along with unpublished data provided by the United States Bureau of Reclamation. Figure 32 shows the calibrated areal distribution of permeability in feet per year, and the distributions of K'/B' and S are shown in Figures 33 and 34 respectively. Values of flow (Q) include both recharge and discharge. The final calibrated recharge from the mountain front was found to be equal to 24,200 ac-ft (2,904 ha-m) per year. Stream recharge was estimated to be 7.8 percent of the river flow (Feth et al. 1966) and deep subsurface recharge along the western borders of the project area was found to be approximately 19,500 ac-ft (2,340 ha-m) per year.

The methodology used to calibrate the model was to make comparisons between contour maps developed from well data and those derived from the computer. This comparison was made by making a visual scan for overall fit rather than a numerical optimization routine. Figure 35 compares the final calibrated contours to the assumed 1937 contours.

Transient Calibration

The transient calibration process was continued over the time interval from 1940 to 1970. From Equation 1 the addition variable to be calibrated is the storativity (S). It is also possible to improve some of the previously calibrated variables somewhat during transient calibration. It was found in this model for example that localized changes in K did little to affect the steady state solution.

Some interesting phenomena were observed during this transient calibration phase. Perhaps the most important of these is that mountain front recharge has apparently decreased dramatically over the past 40 years. During calibration it was impossible to achieve the measured drawdown throughout the region without either increasing pumpage or decreasing recharge. Since records or reasonable estimates of pumpage can be obtained it was decided that the decrease in water levels was due more to recharge decreases than pumping increases. Well B-5-1-36bbb was utilized

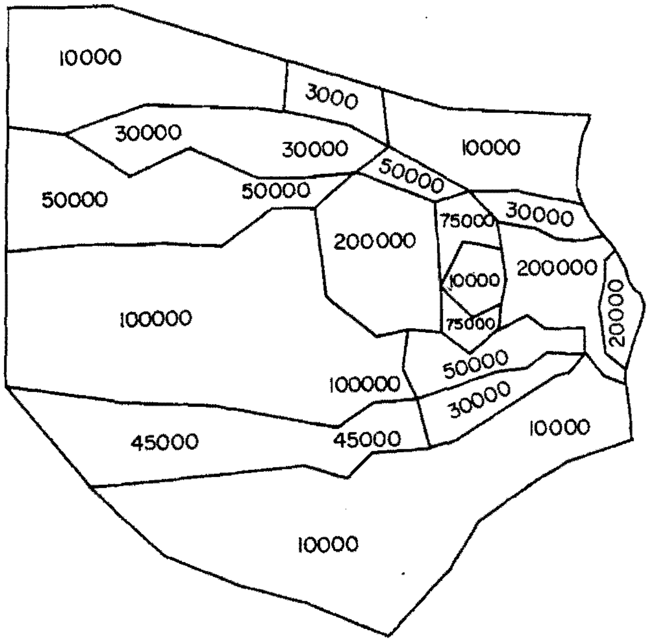


Figure 32. Calibrated permeability distribution in ft/yr.

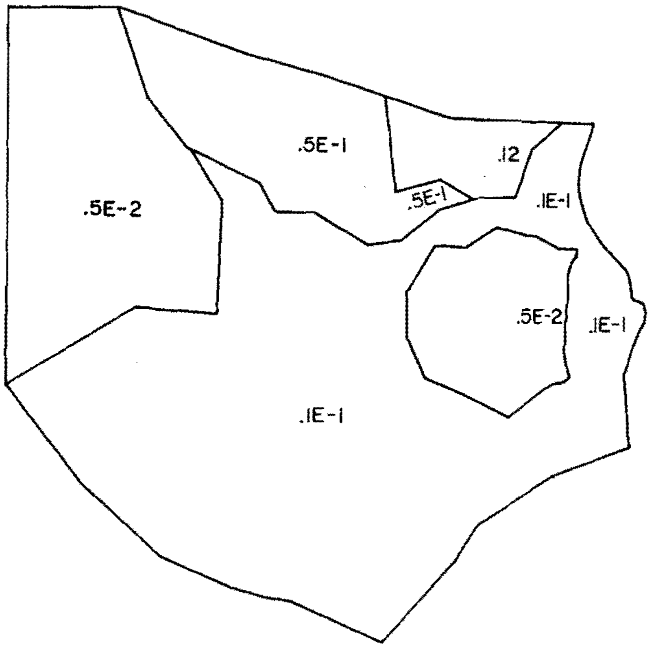
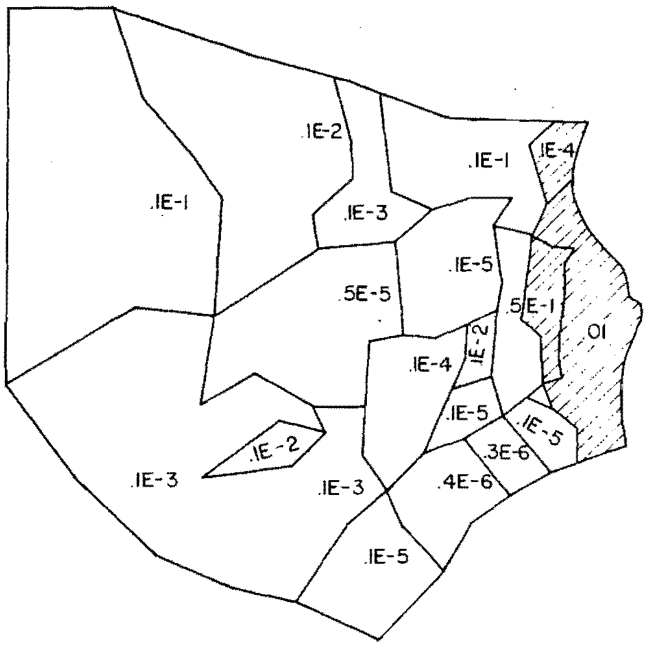


Figure 33. Calibrated K'/B' distribution in 1/yr.



Note: Storage coeficient (Sy) for the shaded region was equal to 0.01.

Figure 34. Distribution of calibrated specific yield and storativity coefficients.

to confirm this point.' This well was installed as an observation well in 1952 by the Bureau of Reclamation and is located within one-half mile of the mountain front. Since there are no pumping centers near this well, any drawdown would be mainly caused by fluctuations in mountain front recharge.

Well B-5-1-36bbb was continuously recorded from 1953 to 1961 and then again from 1966 to 1968. The sparse data between 1961 and 1966 and beyond 1968 made it desirable to correlate the well fluctuations with those of another well to lengthen the record. By so lengthening the record and observing the variation in well water levels over the period of record, a change in mountain front recharge might be detected. The regression of well 36bbb with B-4-1-30bba is shown in Figure 36. Water

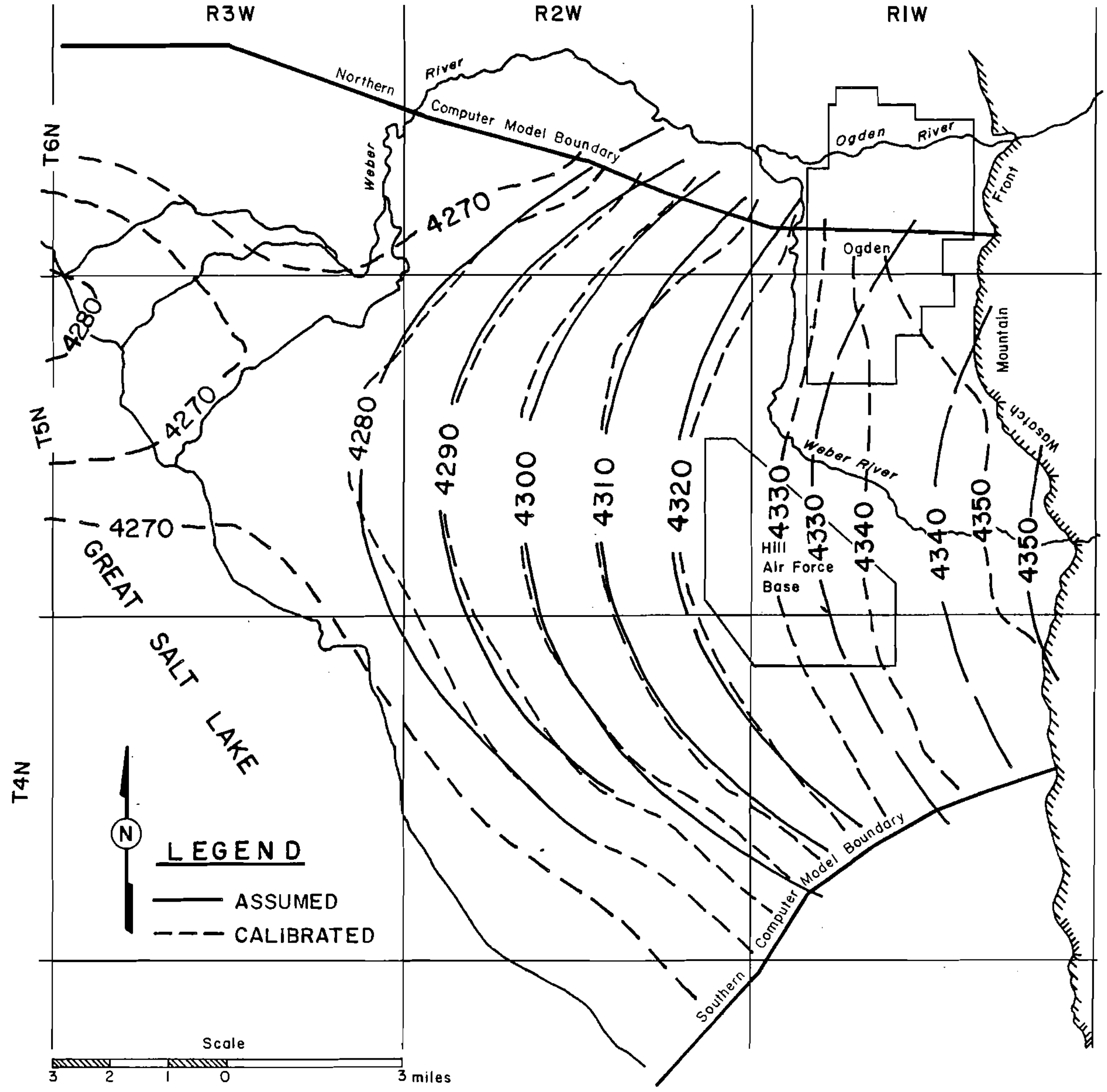


Figure 35. Calibrated and assumed 1937 contour lines.

levels were then compared for the regressed and historical well and are shown in Figure 37.

During calibration it was found that decreases in recharge had to be made at times which were closely related to the decreases observed in well B-5-1-36bbb (see Figure 37). The sudden drop of approximately 40 feet over a 1 year period in this well was confirmed by examining the continuous recording from the well.

The transient calibration process also helped clarify and refine some of the geologic characteristics of the area. For example there exists a corridor of highly transmissive material which extends westward from the mouth of the Weber Canyon. Unpublished data obtained from the Bureau of Reclamation contain well tests which indicate that the transmissivity of the Delta Aquifer in the region of Hill Air Force Base (HAFB) should be in the order of 78,000 gpd/ft (969 $m^3/m \cdot d$). Within 1 mile to the north this value increases to 508,000 gpd/ft (6310 $m^3/m \cdot d$) and within 2 miles to the east it is as high as 1,186,500 gpd/ft (14,740 $m^3/m \cdot d$). Because of partial penetration effects and the uncertain aquifer thicknesses the values of the true hydraulic conductivity K are unknown but the ratios should be similar.

During the initial steady state calibration runs the model did not indicate that local variations in hydraulic conductivity around HAFB were present. This however required alteration during the transient calibration because it was found that the modeled conductivity values were so high that no localized drawdown developed in later years as shown in Figures 11 and 12. The final calibrated values for hydraulic conductivity were shown previously in Figure 32.

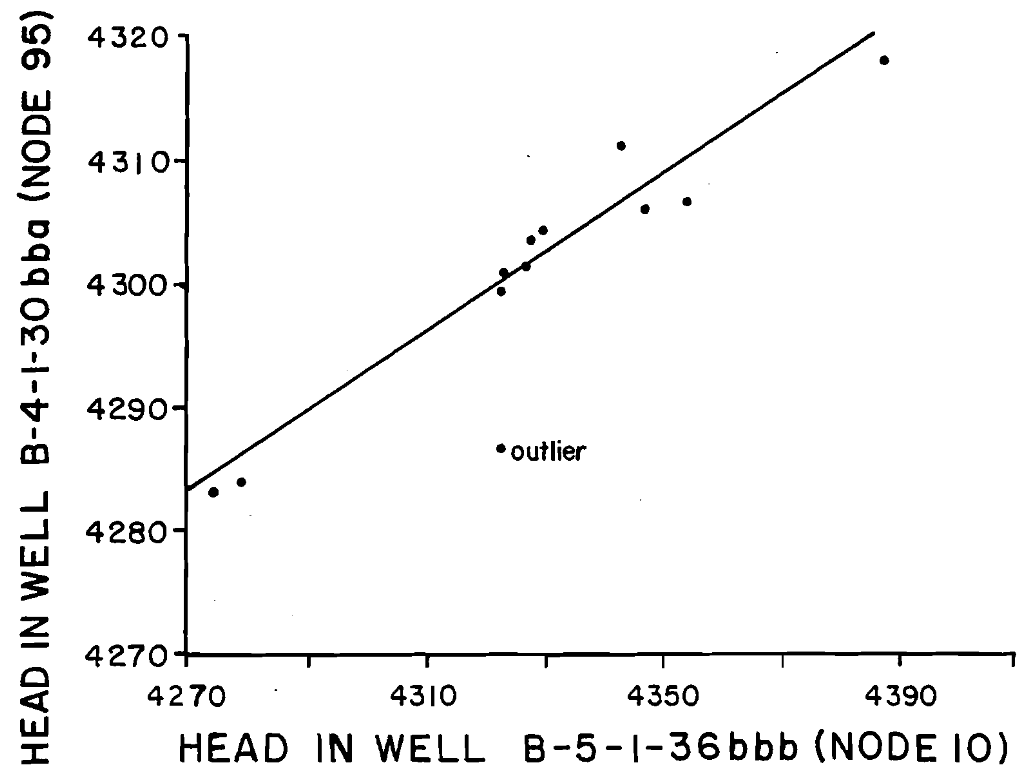


Figure 36. Regression of well B-5-1-36bbb (node 10) versus well B-4-1-30bba (node 95).

Since AQUIFEM-1 is a two-dimensional model, provision must be made to manually adjust the adjacent aquifer heads. This became a problem during transient calibration because little data exist over much of the time span involved, especially in later years. The variation of adjacent heads may have a significant impact upon the response of the model. This problem was solved by continuing the recorded trend of the adjacent aquifer heads through the period of sparse data.

Figures 38 to 48 compare simulated versus historical hydrographs for selected wells. All hydrographs plotted use a third order cubic spline interpolation. Figure 49 shows the relative location of each node presented. Comparisons between the assumed and simulated piezometric contours were made for the years 1940, 1945, 1955, 1964, and 1970 and are shown in Figures 50 through 54 respectively. The actual location of the piezometric surface in Township 5 north, Range 1 west is uncertain due lack of data in this region.

Verification

Verification of the calibrated model covered from 1970 to 1981. It was started in 1970 because the model was already calibrated to that year and it was a simple procedure to extend the record from that initial point. During verification it was found unnecessary to change the values of mountain front or deep recharge from their base values reached in 1963. This agrees with the simulated hydrograph for well B-5-1-

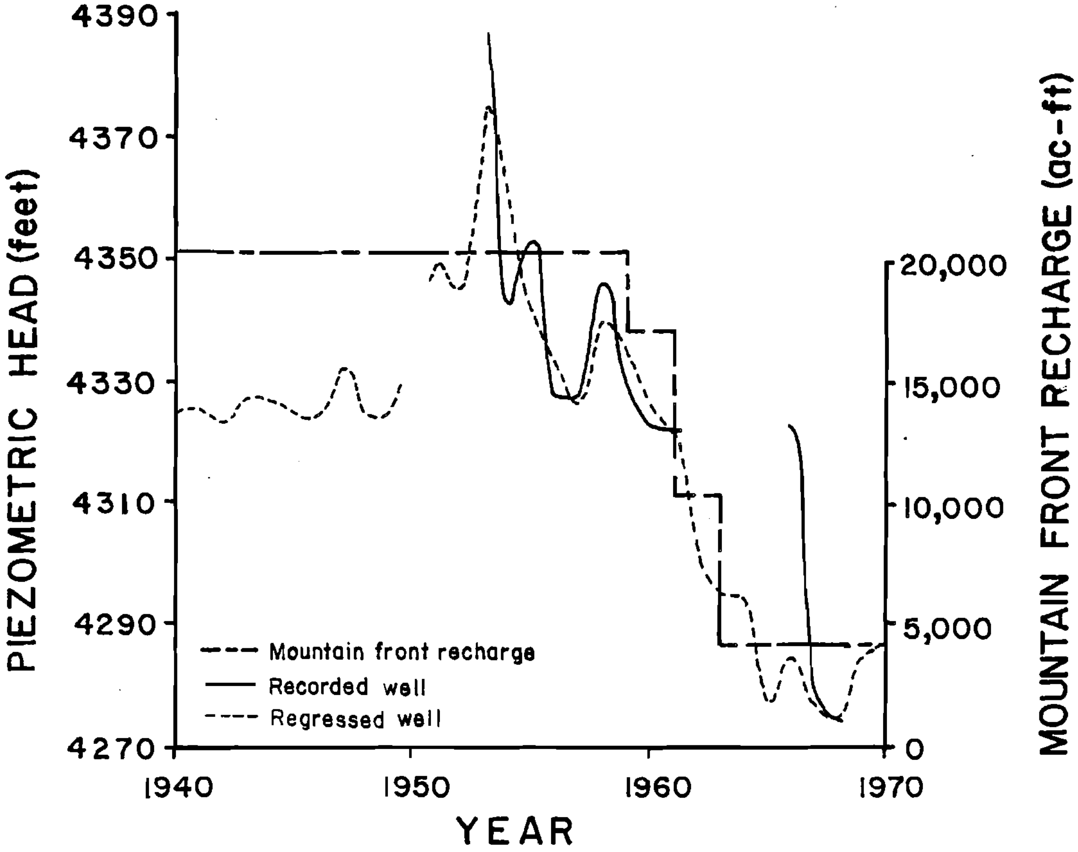


Figure 37. Comparisons between unaltered and regressed well B-5-1-36bbb (node 10) and mountain front recharge.

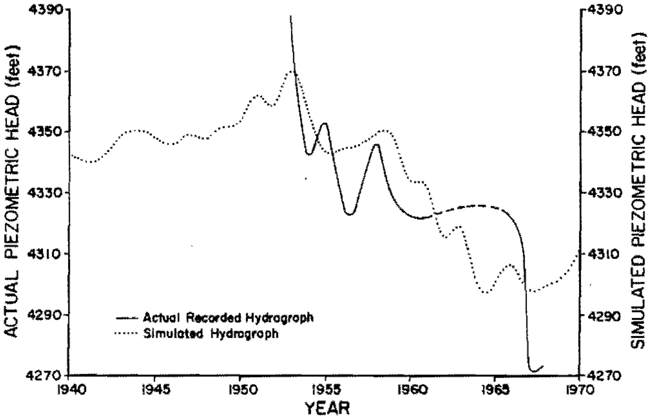


Figure 38. 1940-1970 simulated vs. historical hydrographs for well B-5-1-37bbb (node 10).

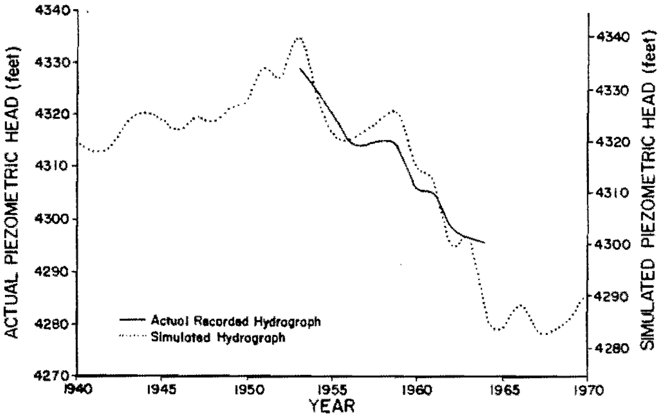


Figure 39. 1940-1970 simulated vs. historical hydrographs for well B-5-1-33cda (node 62).

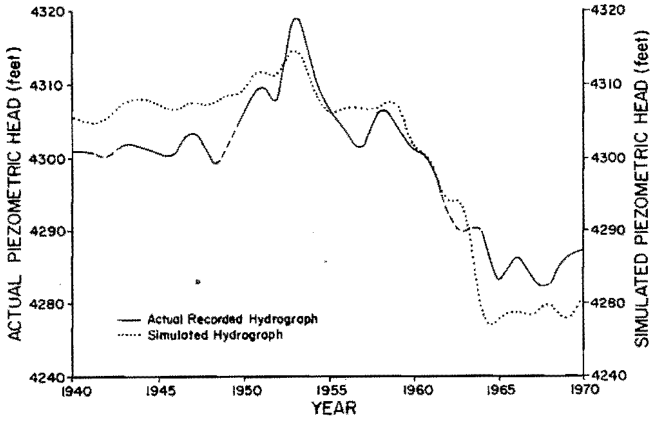


Figure 40. 1940-1970 simulated vs. historical hydrographs for well B-4-1-30bba (node 95).

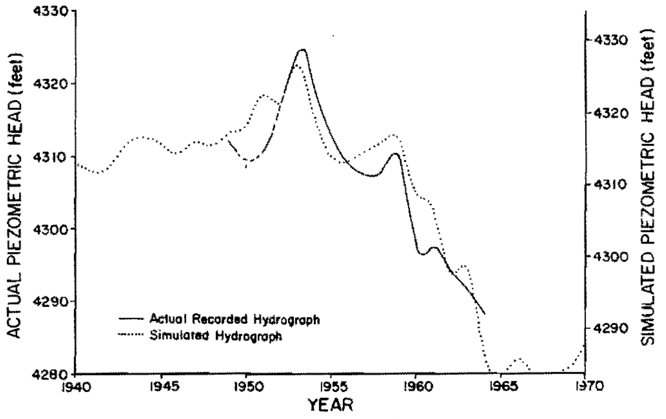


Figure 41. 1940-1970 simulated vs. historical hydrographs for well B-4-2-12bcd (node 97).

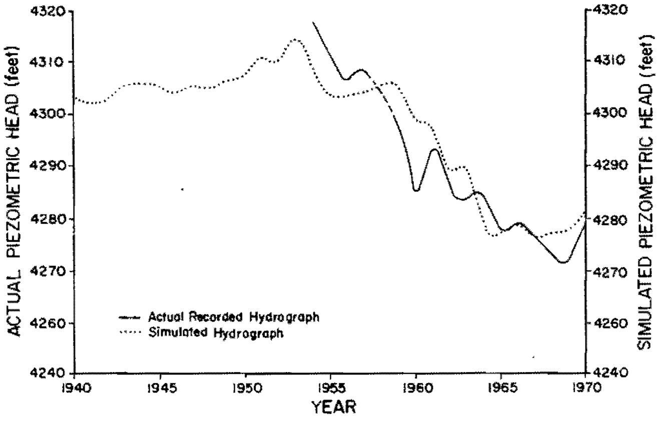


Figure 42. 1940-1970 simulated vs. historical hydrographs for well B-6-1-30cca (node 104).

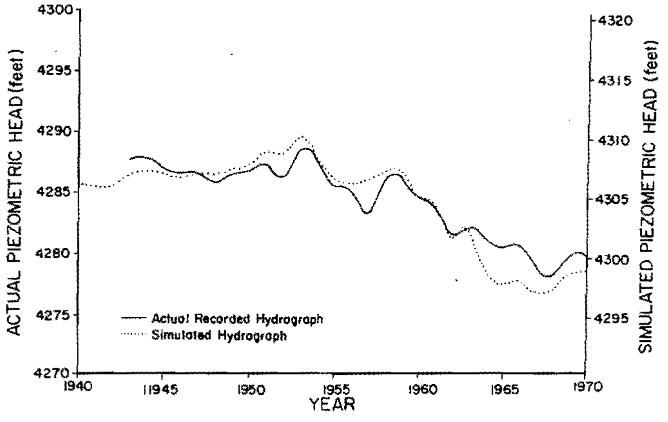


Figure 43. 1940-1970 simulated vs. historical hydrographs for well B-5-2-33ddc (node 129).

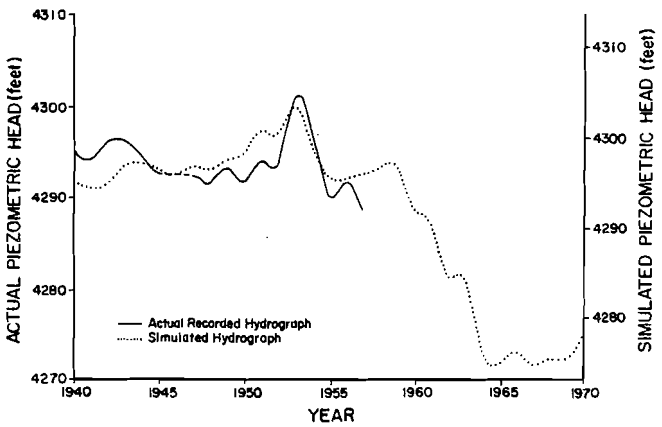


Figure 44. 1940-1970 simulated vs. historical hydrographs for well B-5-2-4ddc (node 133).

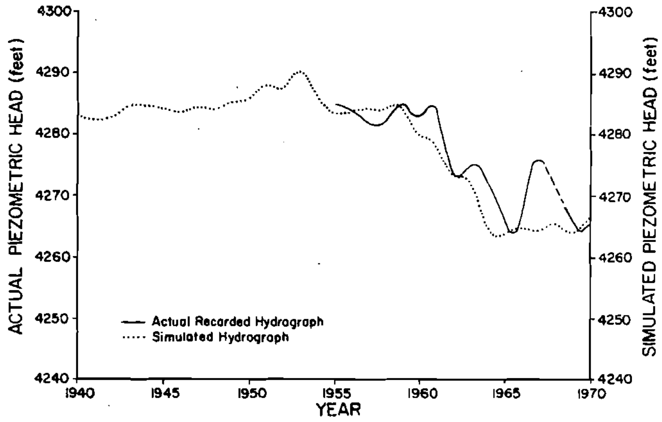


Figure 45. 1940-1970 simulated vs. historical hydrographs for well B-4-2-20ada (node 138).

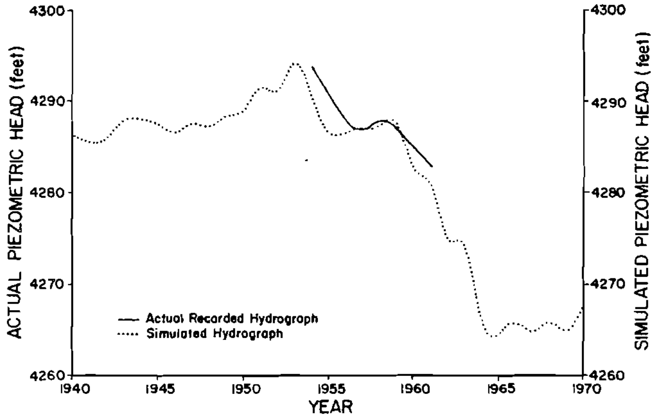


Figure 46. 1940-1970 simulated vs. historical hydrographs for well B-4-2-8dcc (node 139).

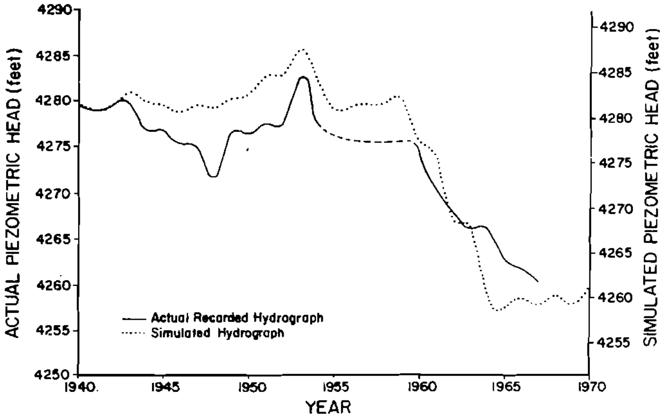


Figure 47. 1940-1970 simulated vs. historical hydrographs for well B-5-3-13ddc (node 152).

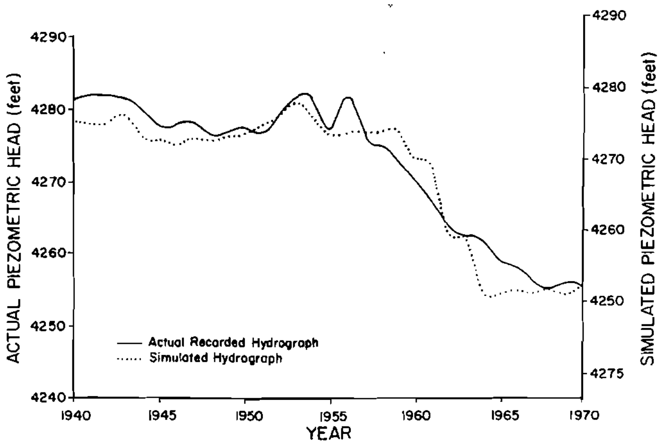


Figure 48. 1940-1970 simulated vs. historical hydrographs for well B-5-3-15dda (node 161).

36bbb shown in Figure 37 in that the well level remains low after its downward trend which occurred during the 1960s. If this well is an indication of mountain front recharge it indicates that recharge has remained at a low level since 1963. The only change necessary was to adjust the heads in the adjacent aquifer so as to simulate their continued decline.

The results of verification presented in hydrograph form can be found in Figures 55 through 65 with the relative locations of each node shown in Figure 49. Comparisons were also made of assumed and simulated piezometric contours for the years 1974 and 1980 as shown in Figures 66 and 67 respectively.

Sensitivity Analysis

The computer model was checked for sensitivity to alterations in the values of conductivity, storativity, and confining layer permeability divided by its thickness for three nodal locations. The three nodes along with the adjacent elements which were altered are shown in Figure 68. Sensitivity runs were made by holding all variables constant except one. The changing variable was

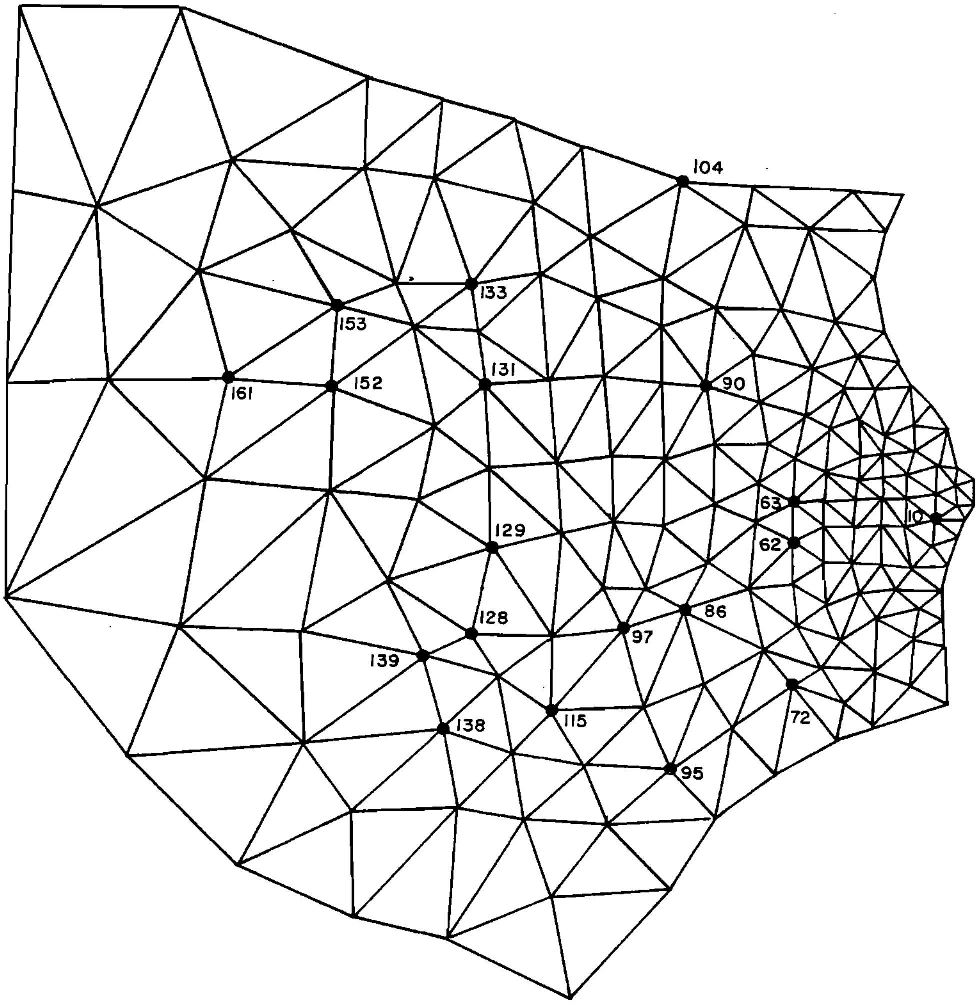


Figure 49. Nodes used for comparison of simulated vs. historical well response during calibration and verification.

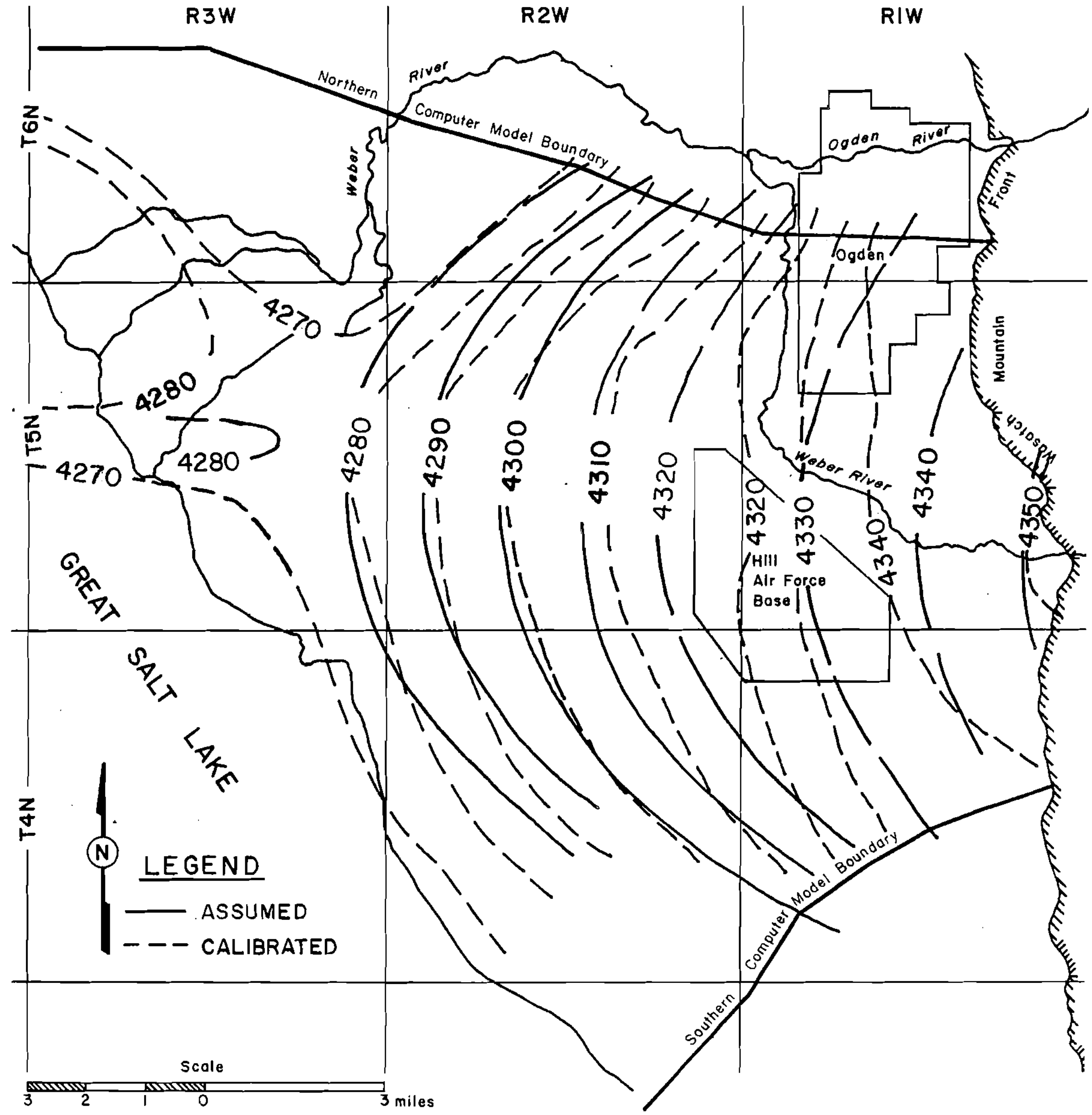


Figure 50. Comparison between assumed and simulated piezometric contours for 1940.

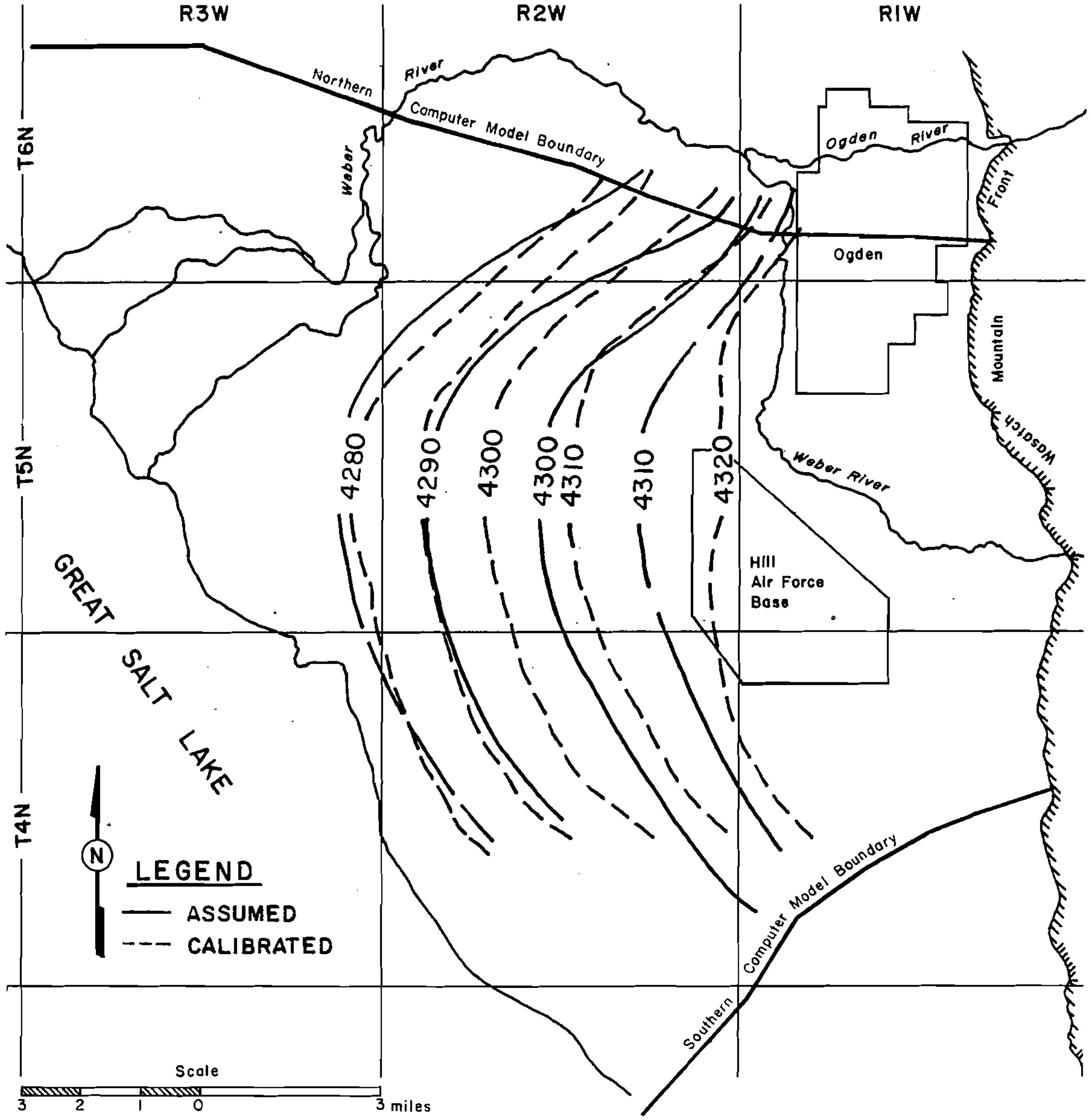


Figure 51. Comparison between assumed and simulated piezometric contours for 1945.

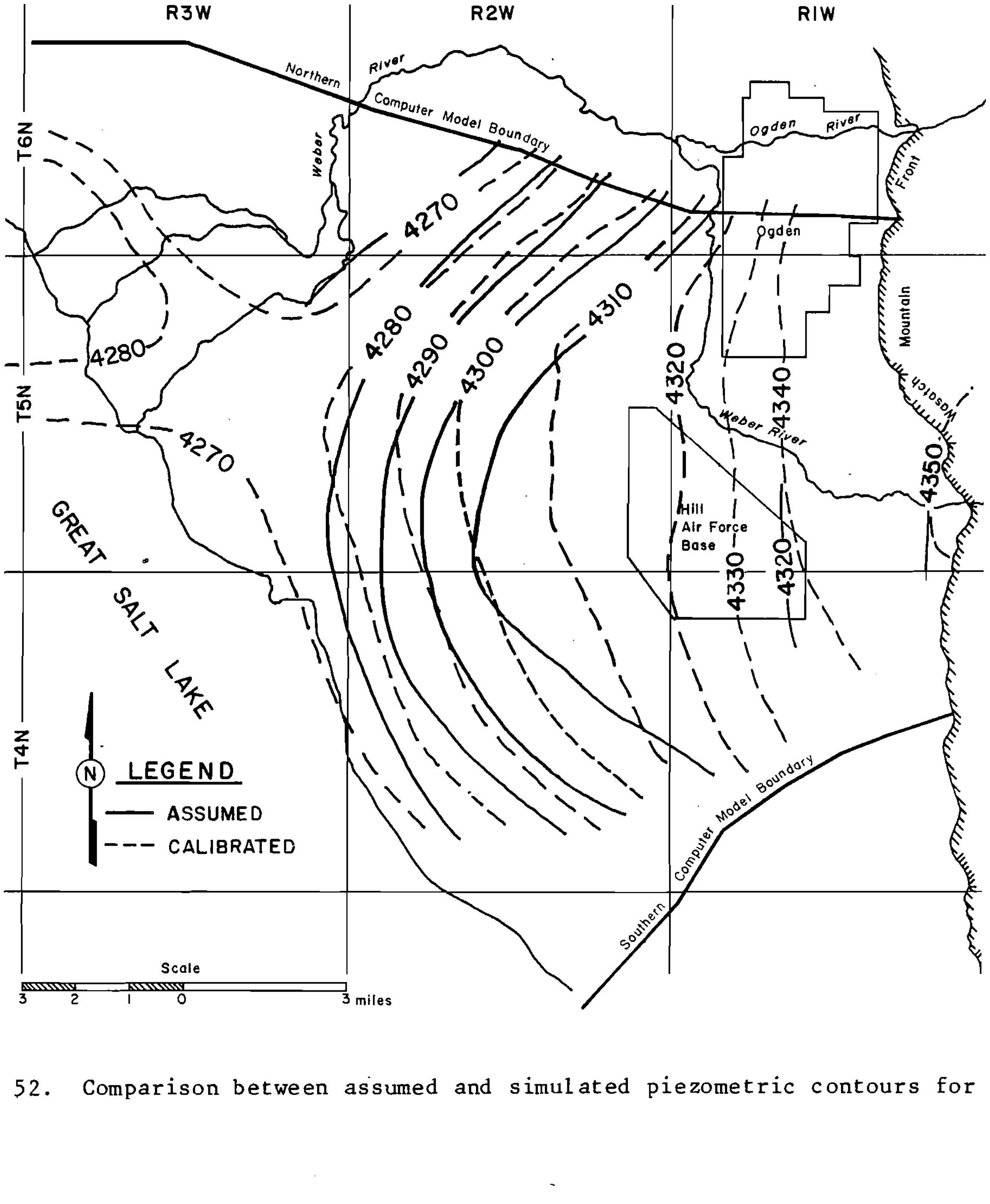


Figure 52. Comparison between assumed and simulated piezometric contours for 1955.

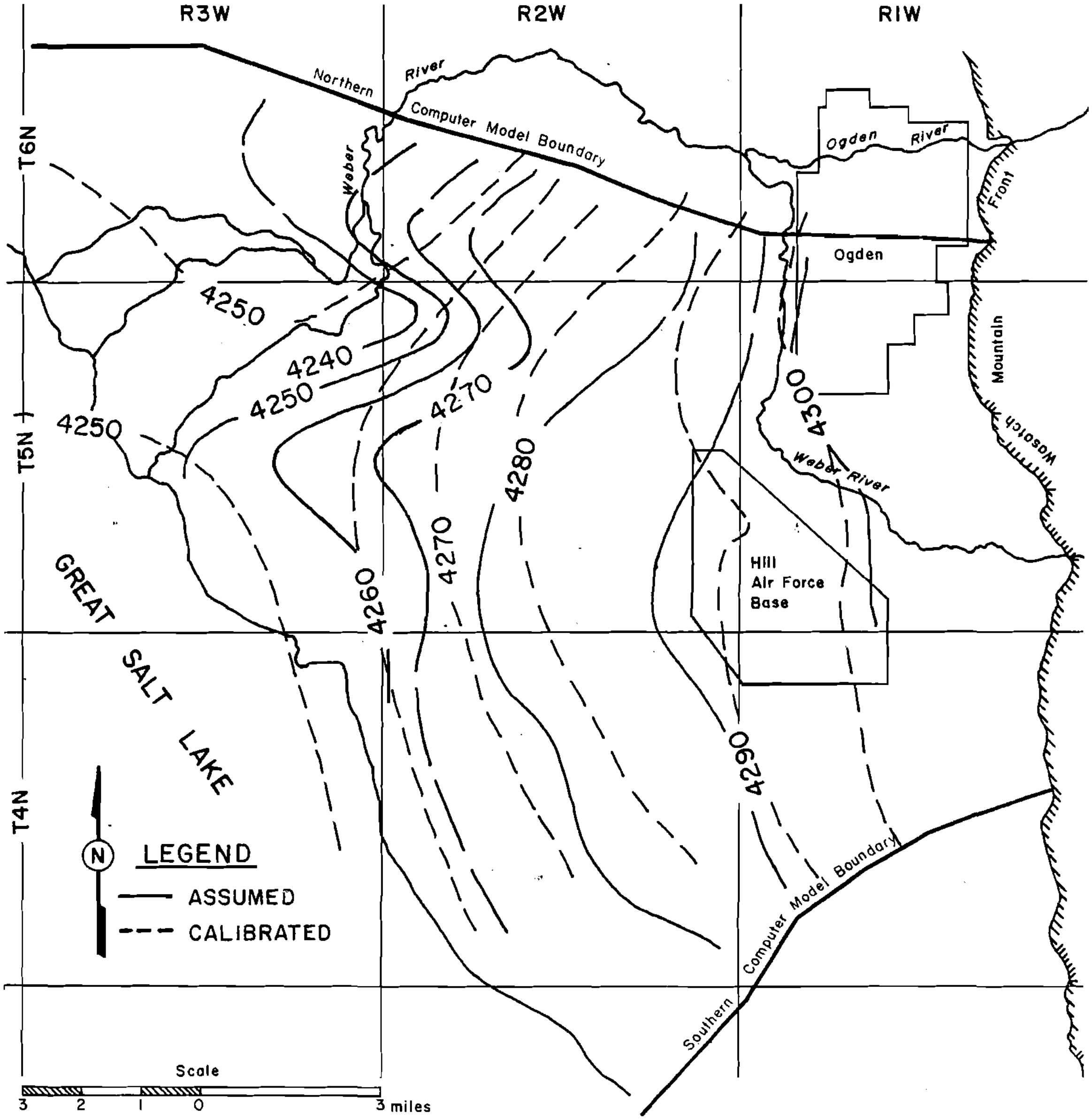


Figure 53. Comparison between assumed and simulated piezometric contours for 1964.

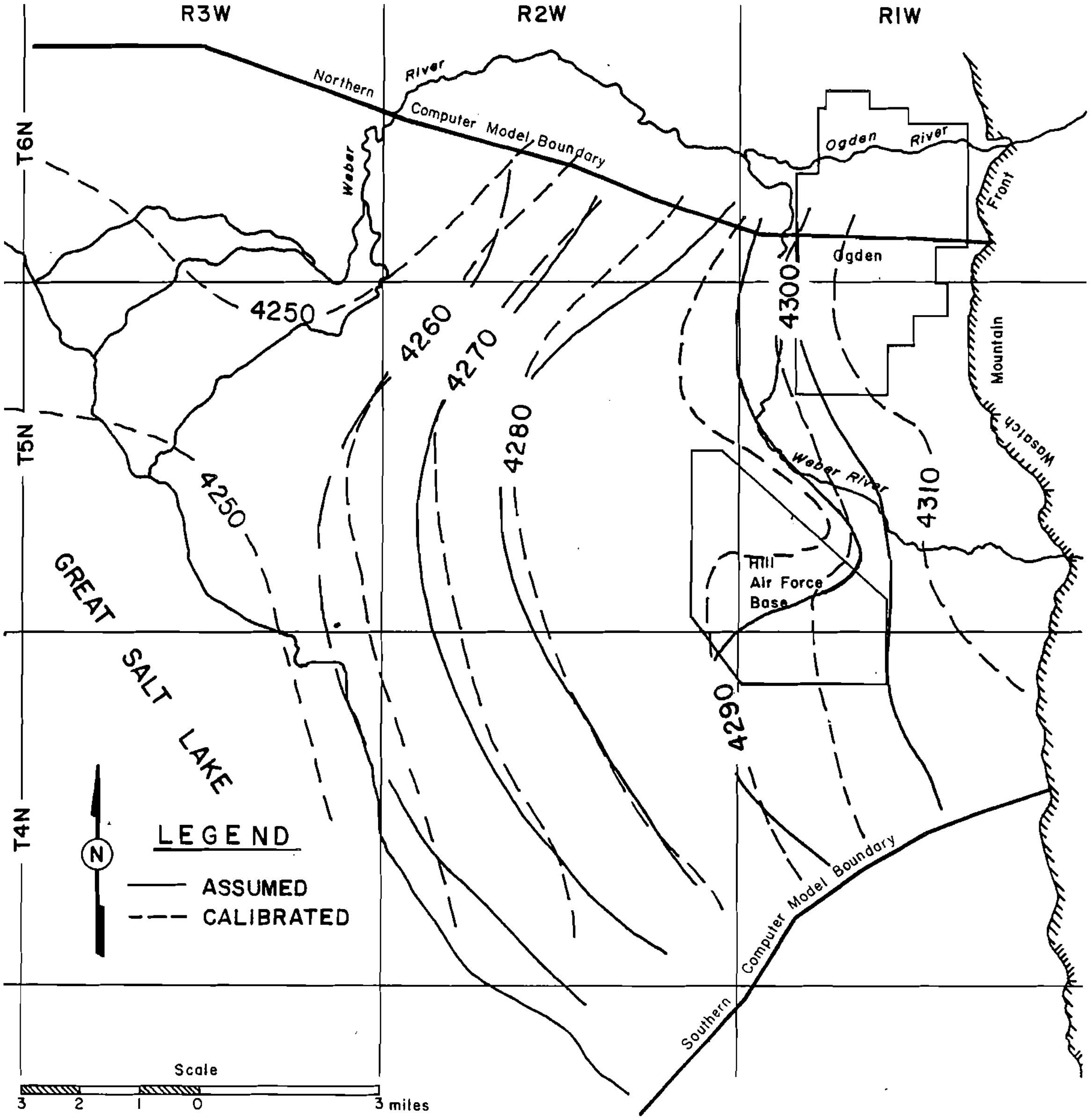


Figure 54. Comparison between assumed and simulated piezometric contours for 1970.

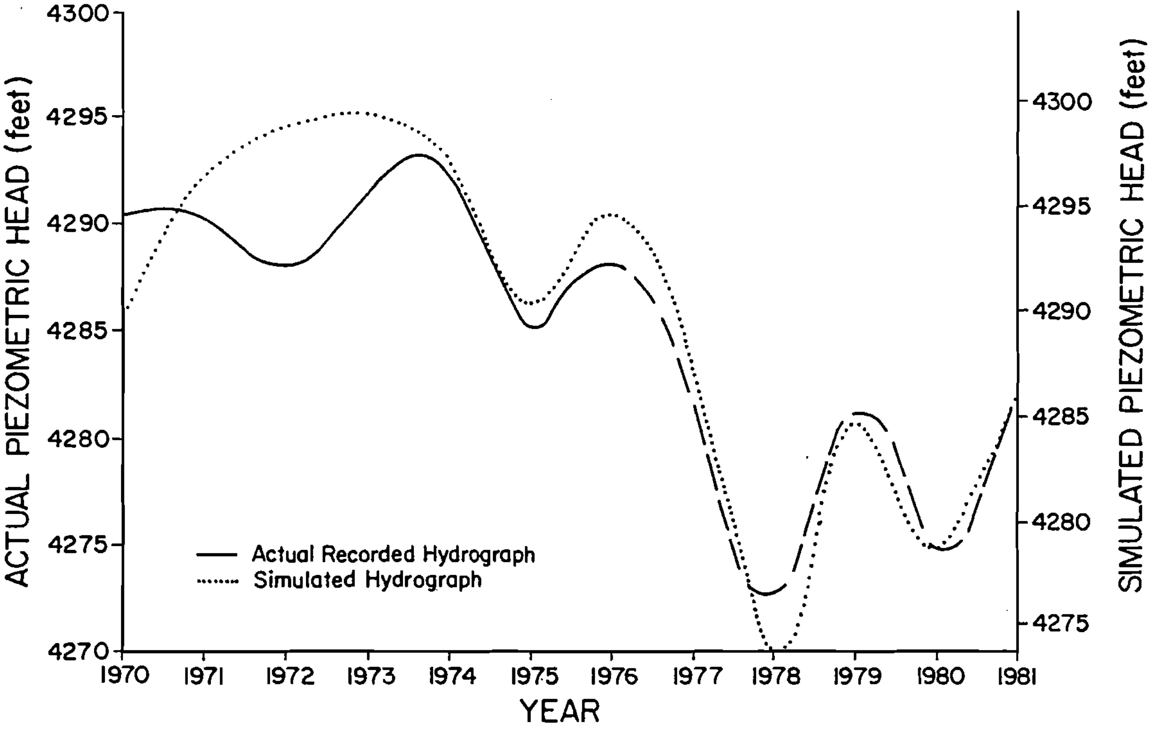


Figure 55. 1970-1981 simulated vs. historical hydrographs for well B-5-1-33baa (node 63).

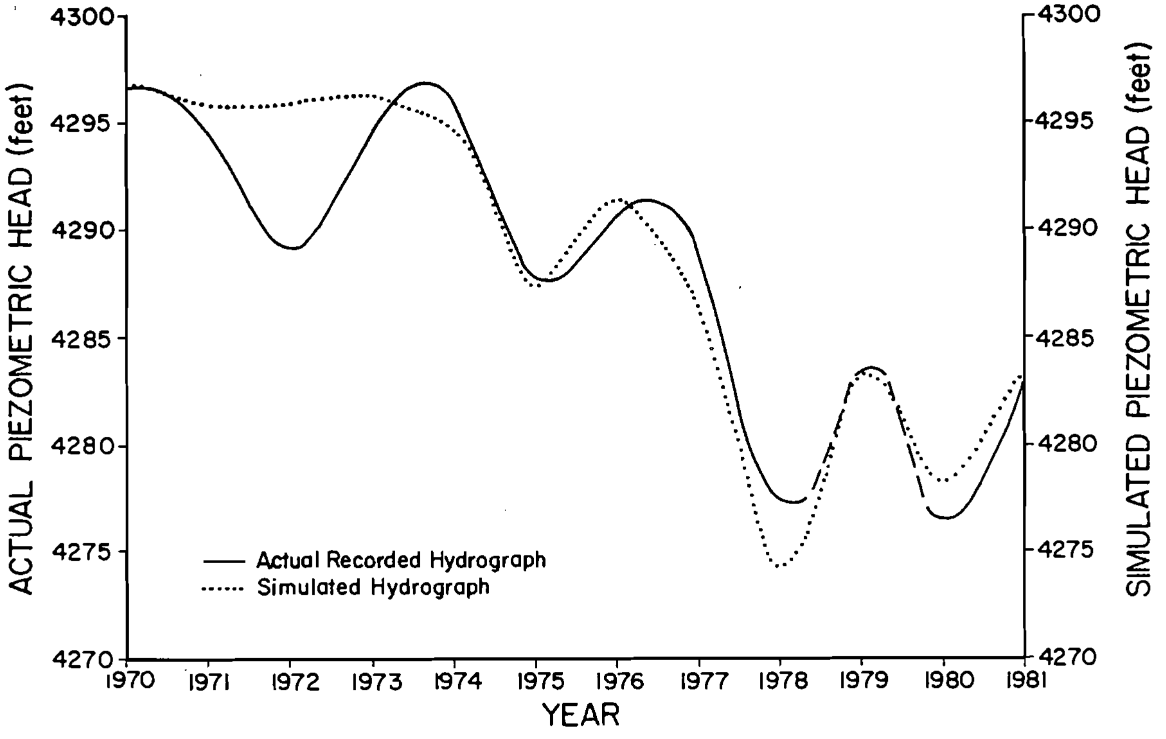


Figure 56. 1970-1981 simulated vs. historical hydrographs for well B-4-1-16bdd (node 72).

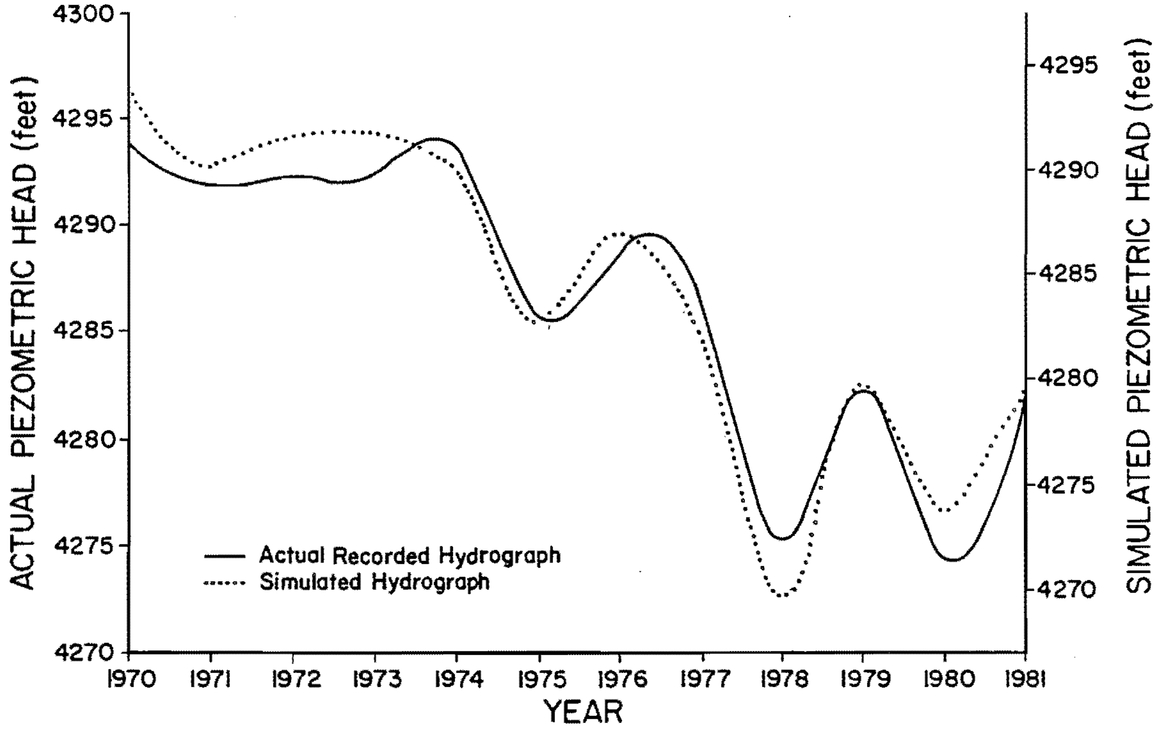


Figure 57. 1970-1981 simulated vs. historical hydrographs for well B-4-1-7baa (node 86).

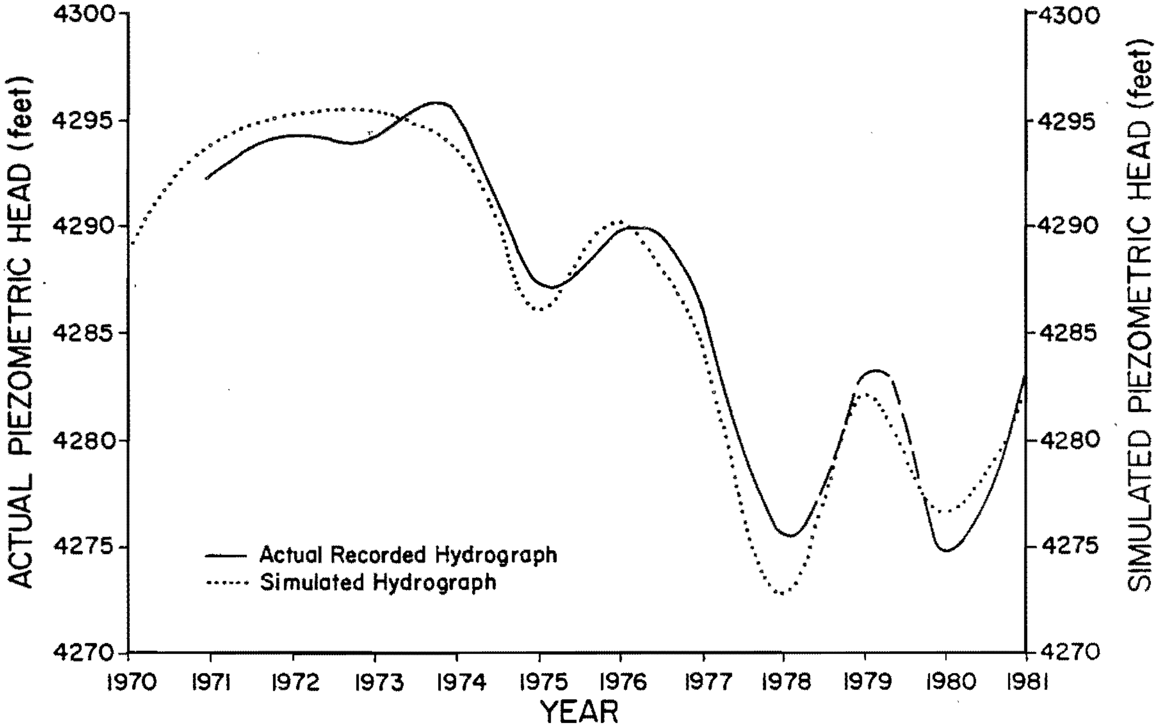


Figure 58. 1970-1981 simulated vs. historical hydrographs for well B-5-1-18abb (node 90).

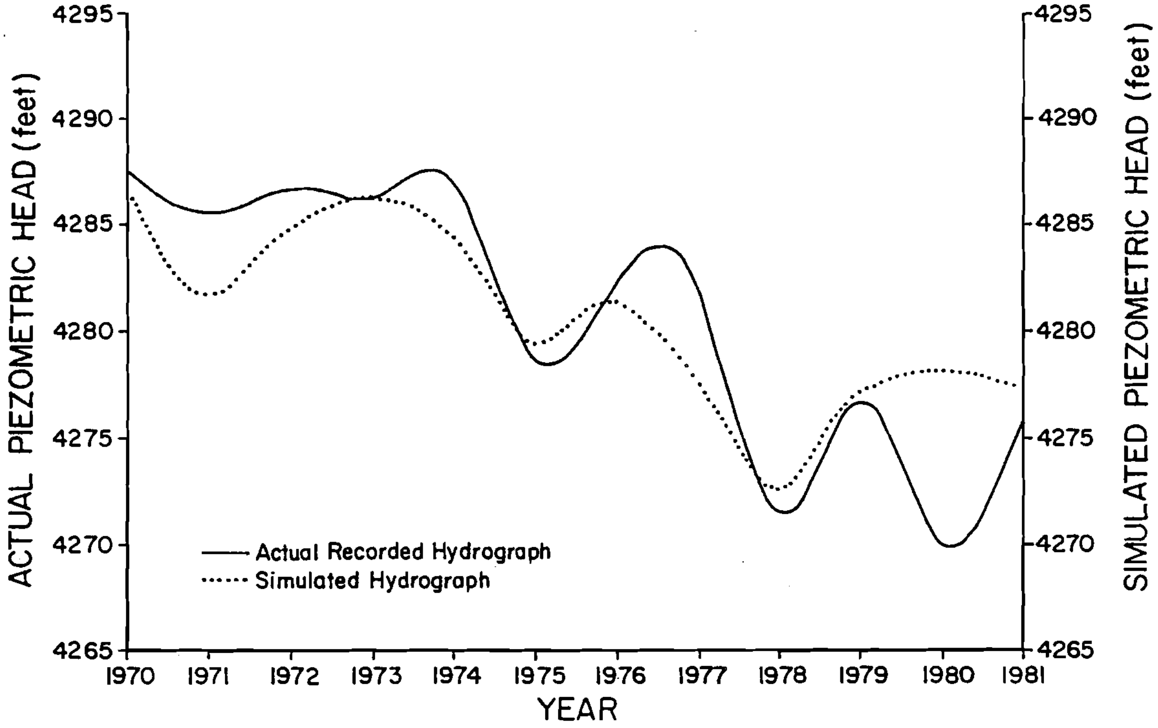


Figure 59. 1970-1981 simulated vs. historical hydrographs for well B-4-1-30bba (node 95).

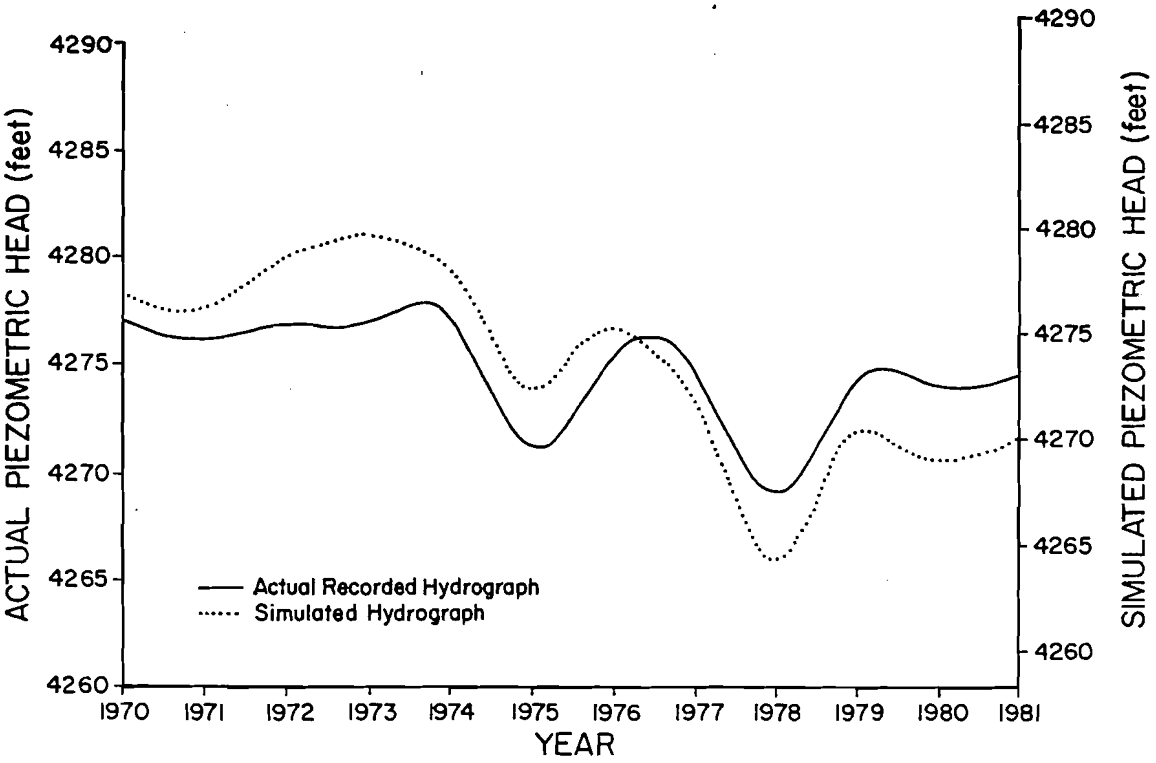


Figure 60. 1970-1981 simulated vs. historical hydrographs for well B-4-2-20aaa (node 115).

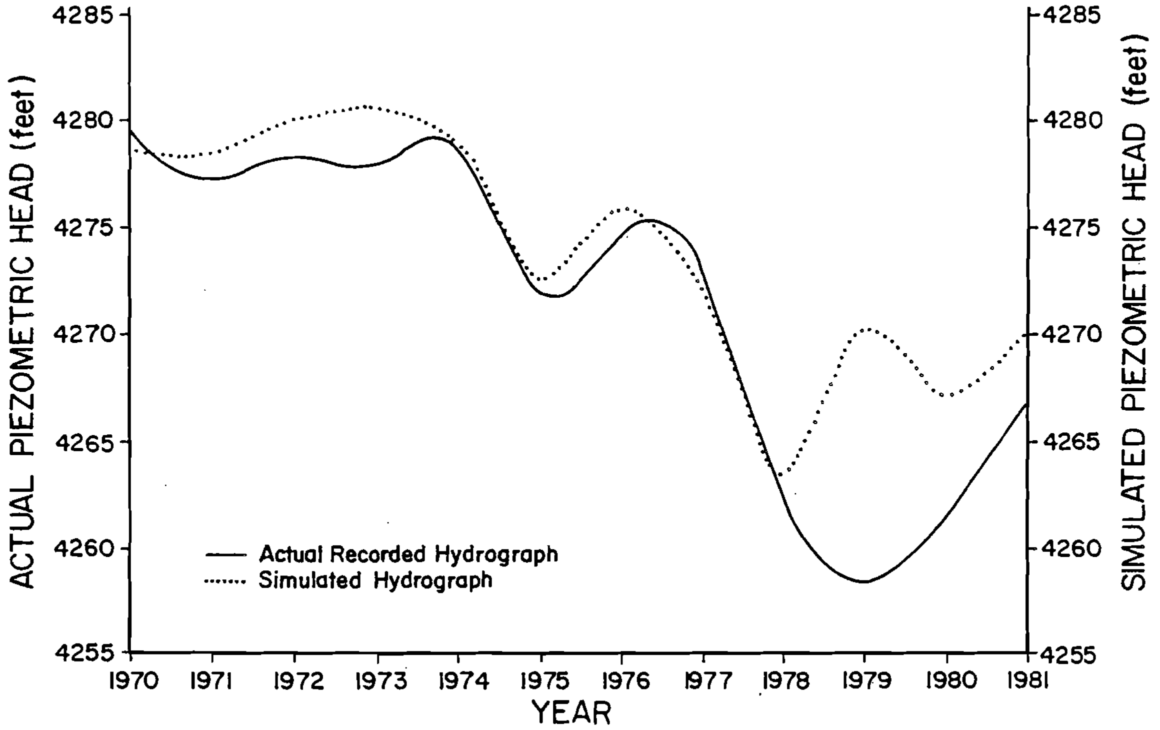


Figure 61. 1970-1981 simulated vs. historical hydrographs for well B-5-2-33ddc (node 129).

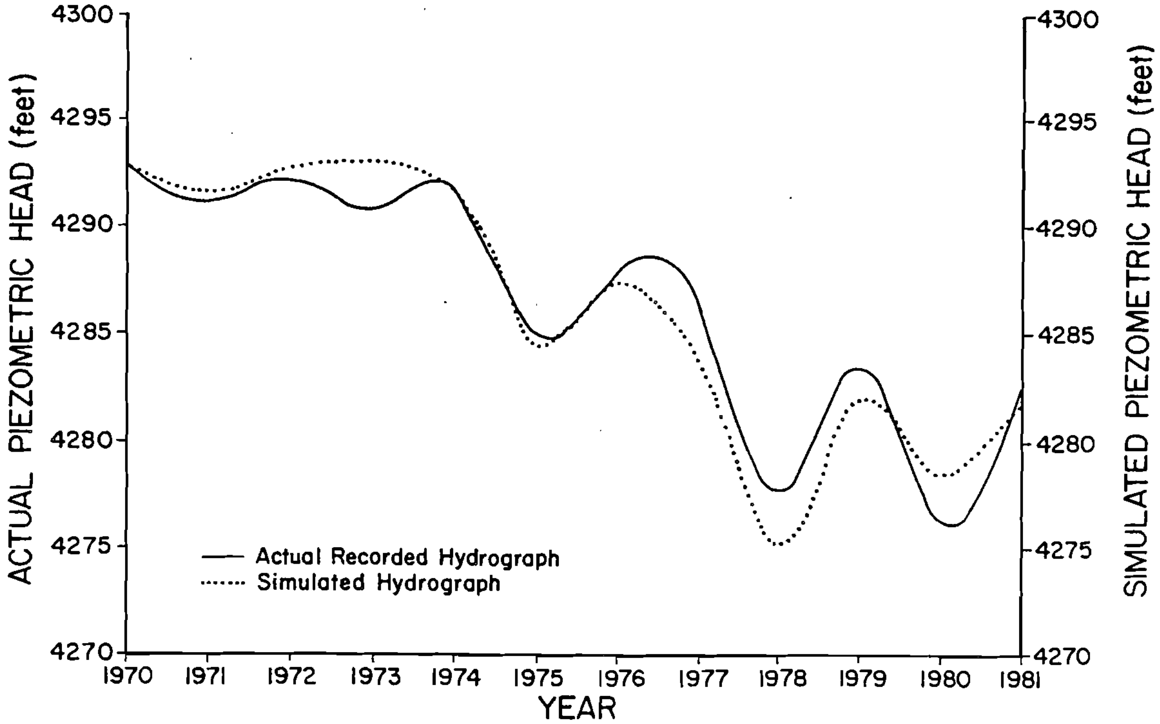


Figure 62. 1970-1981 simulated vs. historical hydrographs for well B-5-2-16dcd (node 131).

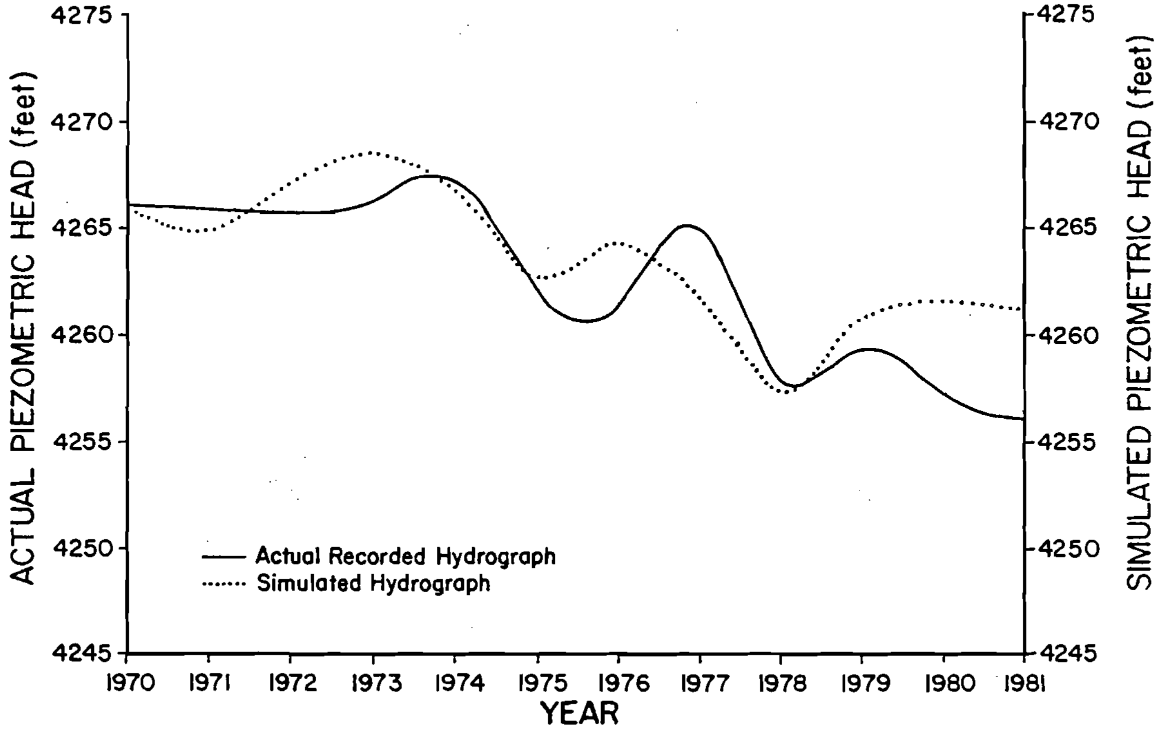


Figure 63. 1970-1981 simulated vs. historical hydrographs for well B-4-2-20ada (node 138).

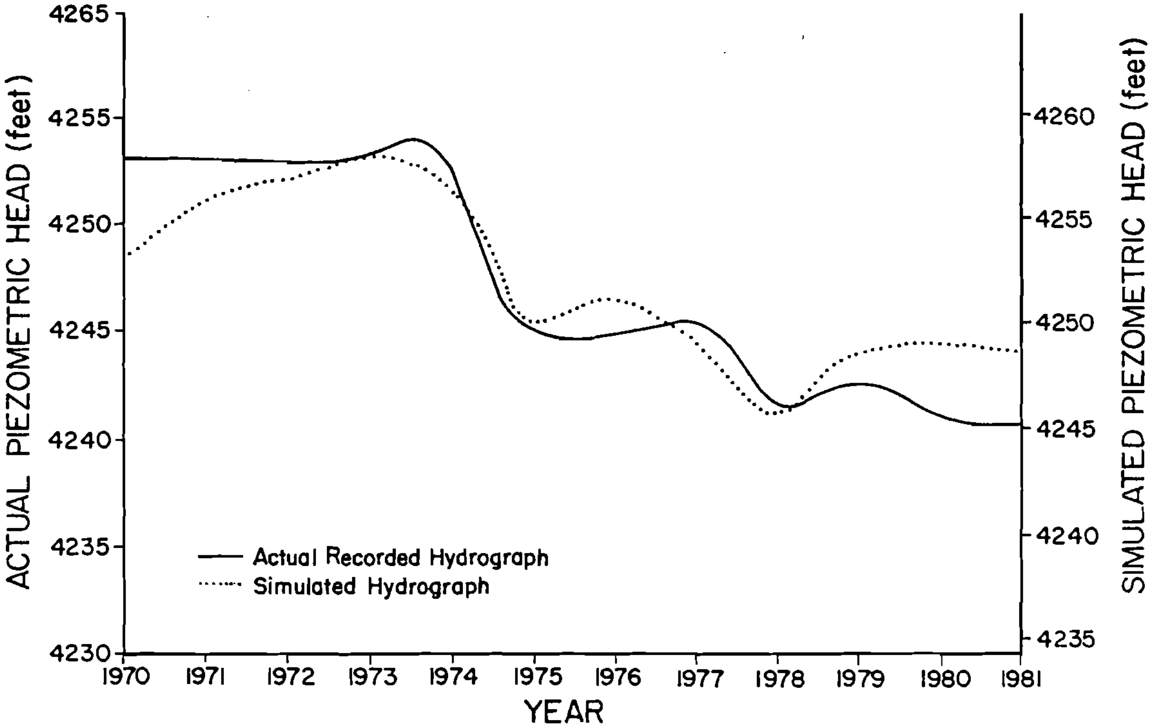


Figure 64. 1970-1981 simulated vs. historical hydrographs for well B-5-3-12add (node 153).

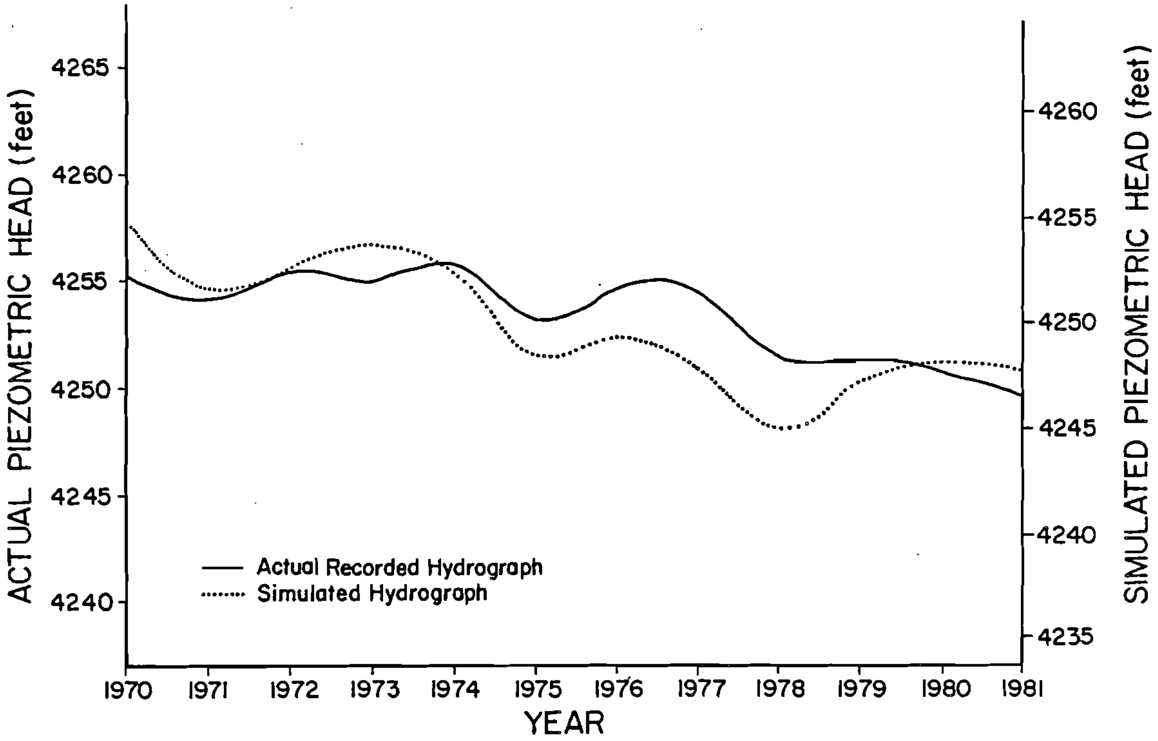


Figure 65. 1970-1981 simulated vs. historical hydrographs for well B-5-3-15dda (node 161).

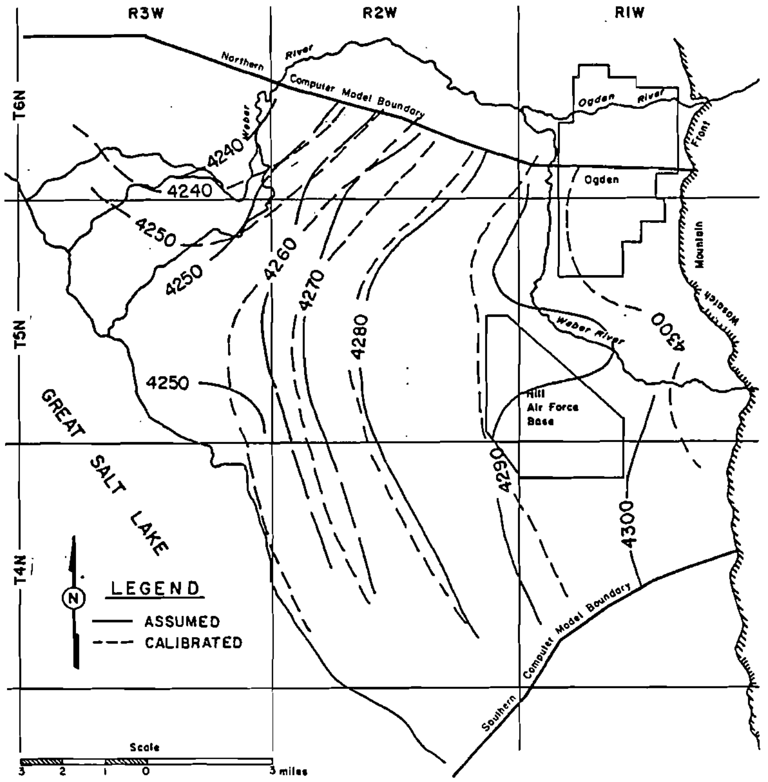


Figure 66. Comparison between assumed and simulated piezometric contours for 1974.

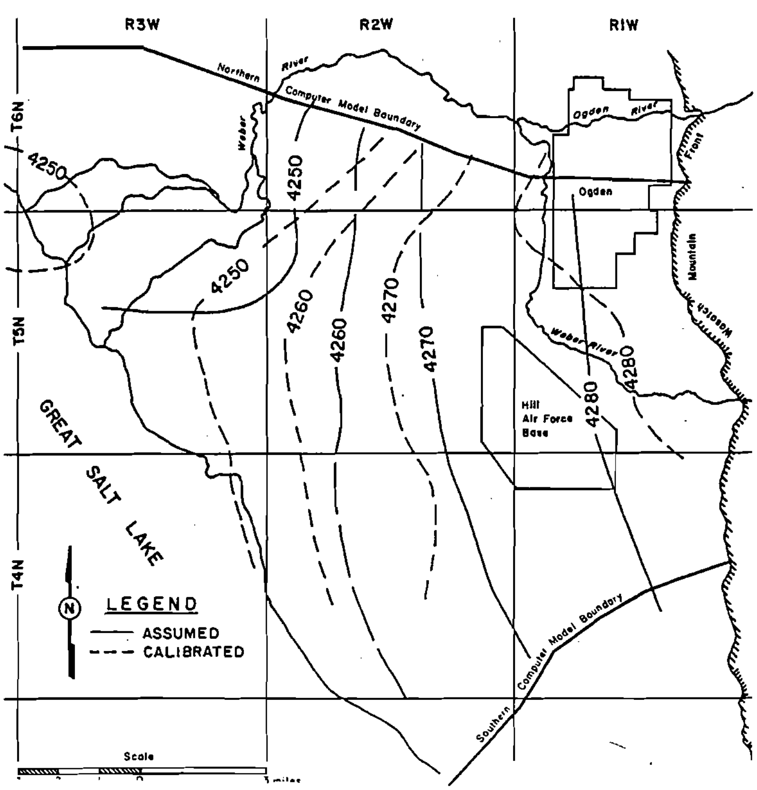


Figure 67. Comparison between assumed and simulated piezometric contours for 1980.

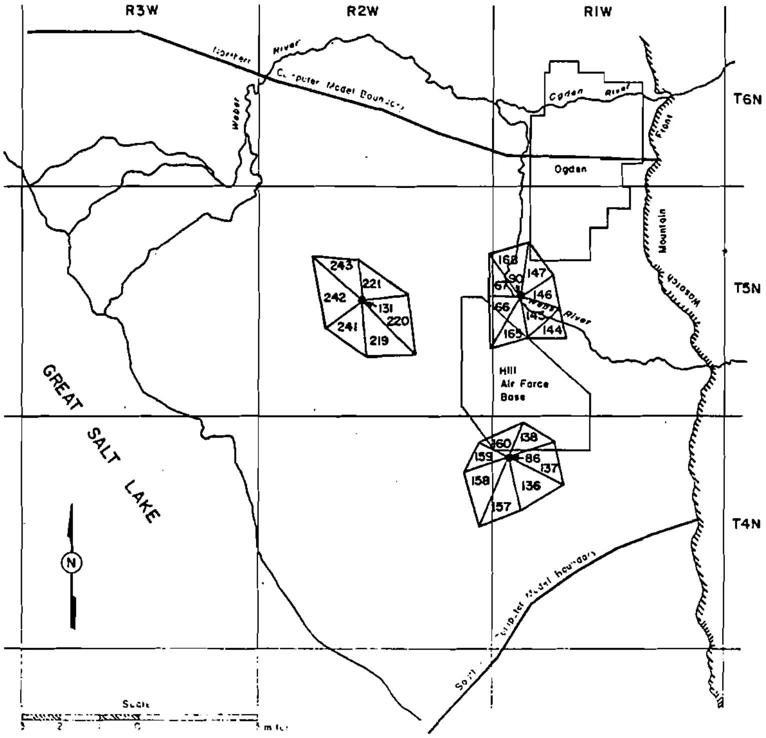


Figure 68. Central nodes and surrounding elements used in the sensitivity analysis.

tested at 50, 75, 125, and 150 percent of its calibrated value and the results are shown in Figures 69, 70, and 71 for nodes 86, 90, and 131 respectively. Figures for storativity are not shown because little variation occurred over the range tested. From the figures mentioned it is seen that alterations in the aquifer characteristics over the range specified produce only minor effects upon the hydraulic response of the aquifer at any one of the three nodes.

Recharge Simulation Runs

Artificial groundwater recharge can be managed in two basic ways. First a constant flow can be recharged over a long period of time which will attempt to keep the piezometric surface at a higher level throughout time. The second management technique is to recharge only during specific time intervals. This method attempts to recharge water into the system so as to provide the greatest benefit at a specific time of the year so as to alleviate a specific problem. If a region has light pumping demands over much of the year but does contain an interval of heavy pumping the second method might be more appropriate. The aquifer can be recharged just before the heavy pumping period thus decreasing the pumping lift at the time relief is most needed.

The method of recharge also depends on whether or not the objective is to prevent large pumping declines at selected locations or to increase the entire water table. Since the system response in this case is so rapid, the short term pumping declines could be eliminated quite easily if water were available just prior to and during the maximum demand periods. On the other hand if the desired result is to increase the entire piezometric surface then recharge should be continued on a more continuous basis since the system response is so rapid that gains are quickly lost when recharge is stopped.

During the prediction phase of the study various quantities of recharge were tested for their impact on the piezometric surface. Initial runs included a maximum allowable recharge rate equal to 1350 ac-ft per month. This value is based on the same recharge rate and pit size as obtained from and used by the Bureau of Reclamation during its tests in the mid 1950s. Each recharge rate is discussed below in terms of its effect on the piezometric surface and the economic benefit gained by the reduced pumping lift.

Three prediction runs based on available water at Gateway according to Table 12 were made for a maximum allowable recharge of 1350 acre-feet per month. Each of these runs were then compared to a simulation run without artificial recharge for 11 nodal points. Six of the 11 nodes are shown in Figures 72 through 77. The remaining five nodes were located further away from the recharge source and showed little variation between runs.

The economic benefit for any given month is calculated by an areal integration of reduced pumping lifts and pumping rates. It is important to note that the only economic benefits considered in this analysis are those associated with reduced pumping costs. The program named ENERGY.FOR listed in Appendix F calculates an average reduction in pumping lift for each element, then uses the pumping rate and cost of energy to calculate energy savings for that element. A cost of power equal to 7 cents per kilowatt hour was used throughout the analyses herein. The process is continued until the entire savings are summed up over the finite element grid. The economic benefit from a maximum recharge rate equal to 1350 ac-ft/month with flood recharge conditions is approximately $2250 per year. By repeating the same process for a maximum recharge rate equal to 2700 acre-feet/month the economic benefit was found to be $4480 per year.

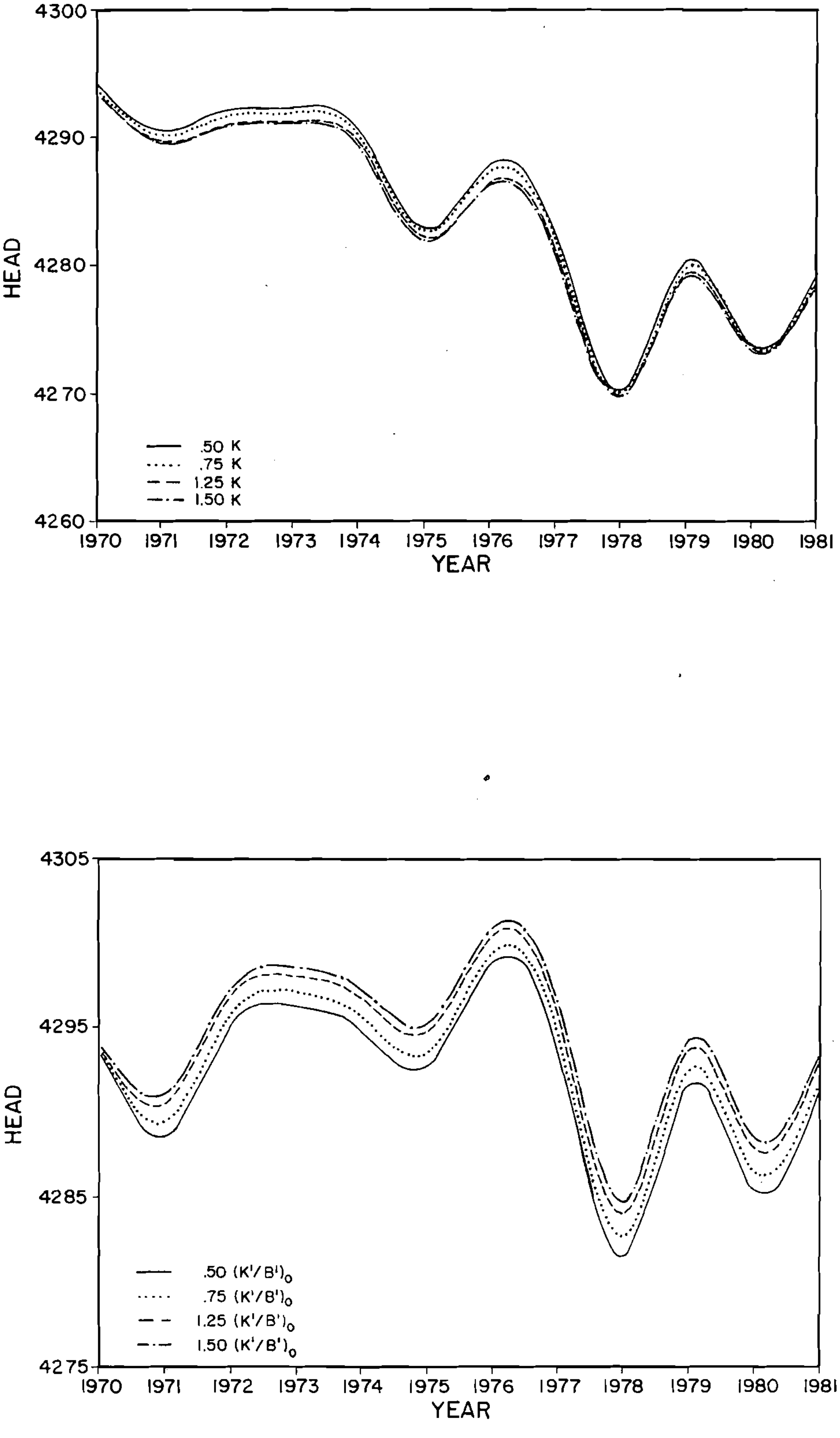


Figure 69. Sensitivity plots for node 86.

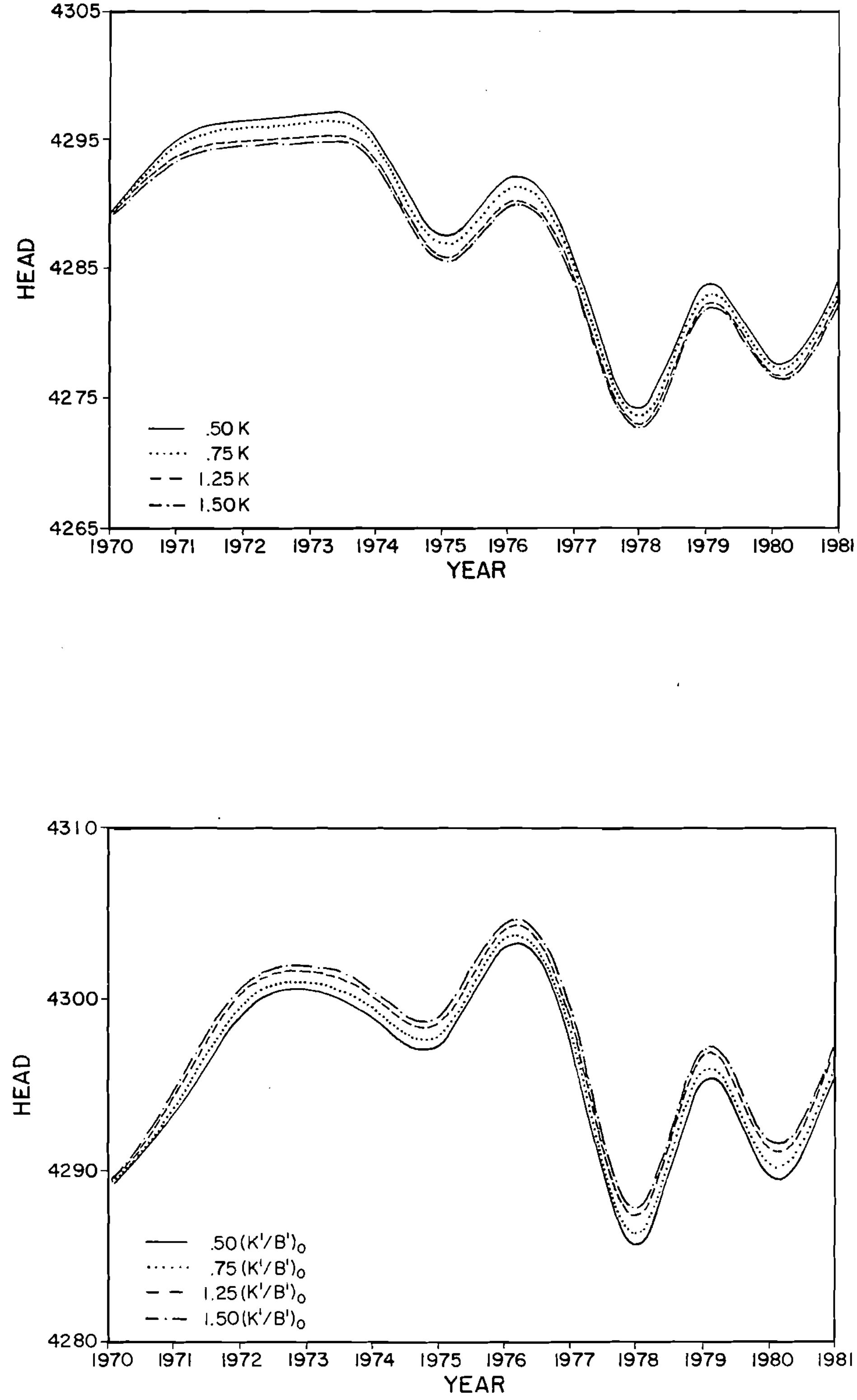


Figure 70. Sensitivity plots for node 90.

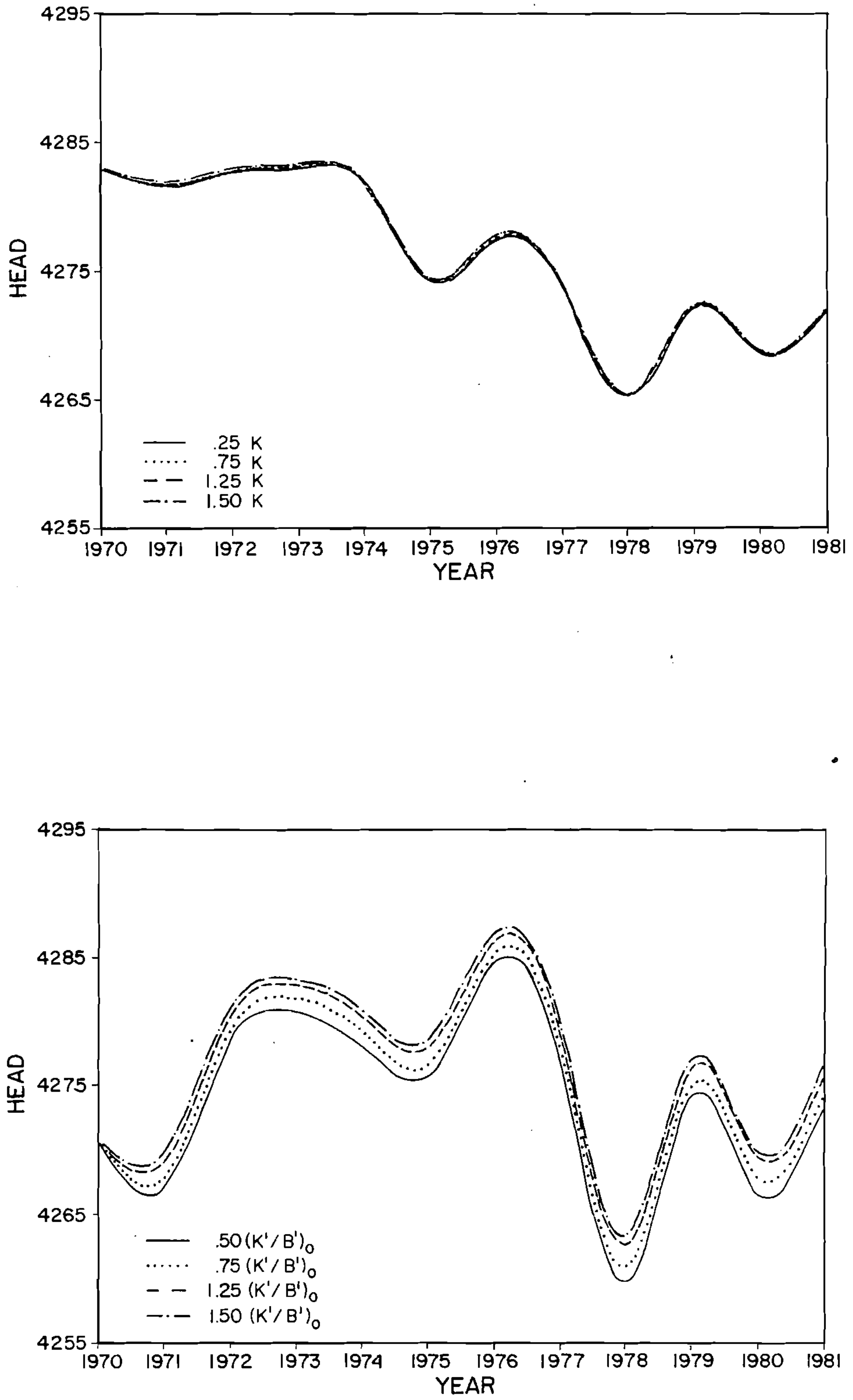


Figure 71. Sensitivity plots for node 131.

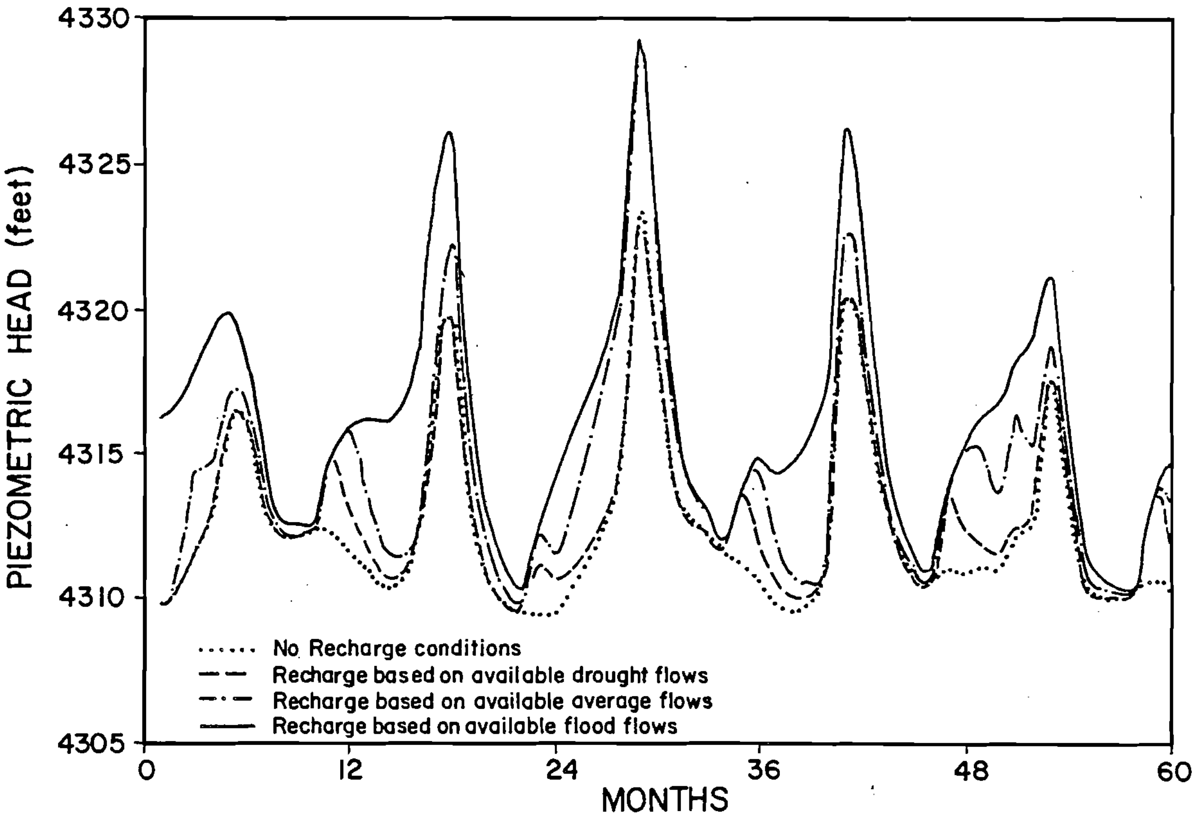


Figure 72. Recharge hydrograph comparisons for node 63 with a maximum recharge rate of 1350 ac-ft per month.

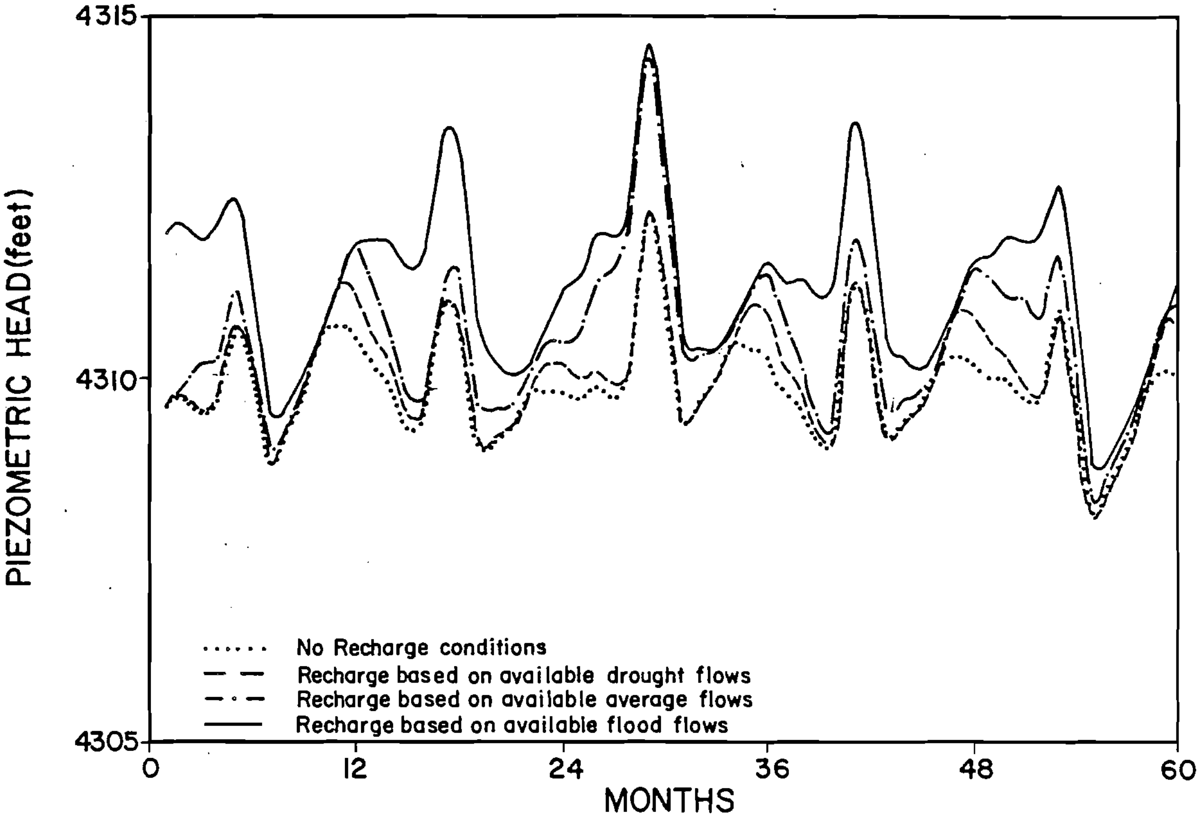


Figure 73. Recharge hydrograph comparisons for node 72 with a maximum recharge rate of 1350 ac-ft per month.

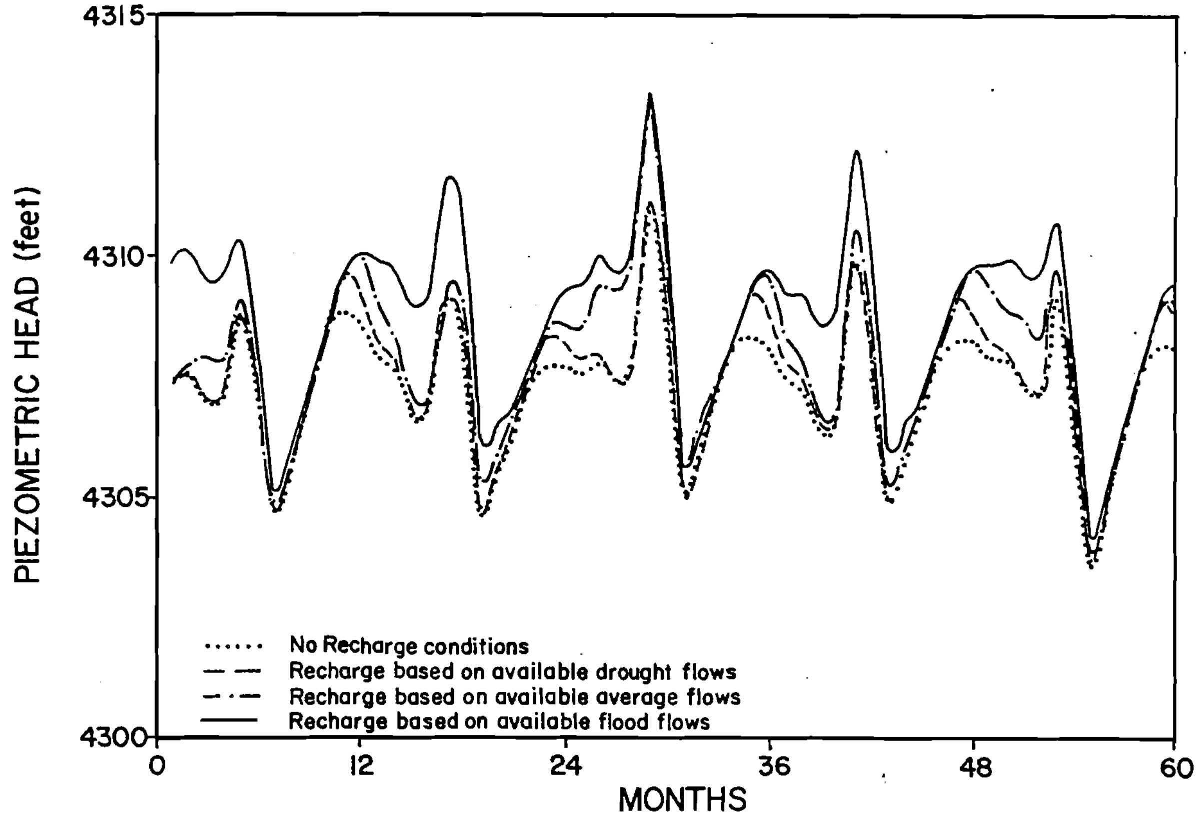


Figure 74. Recharge hydrograph comparisons for node 86 with a maximum recharge rate of 1350 ac-ft per month.

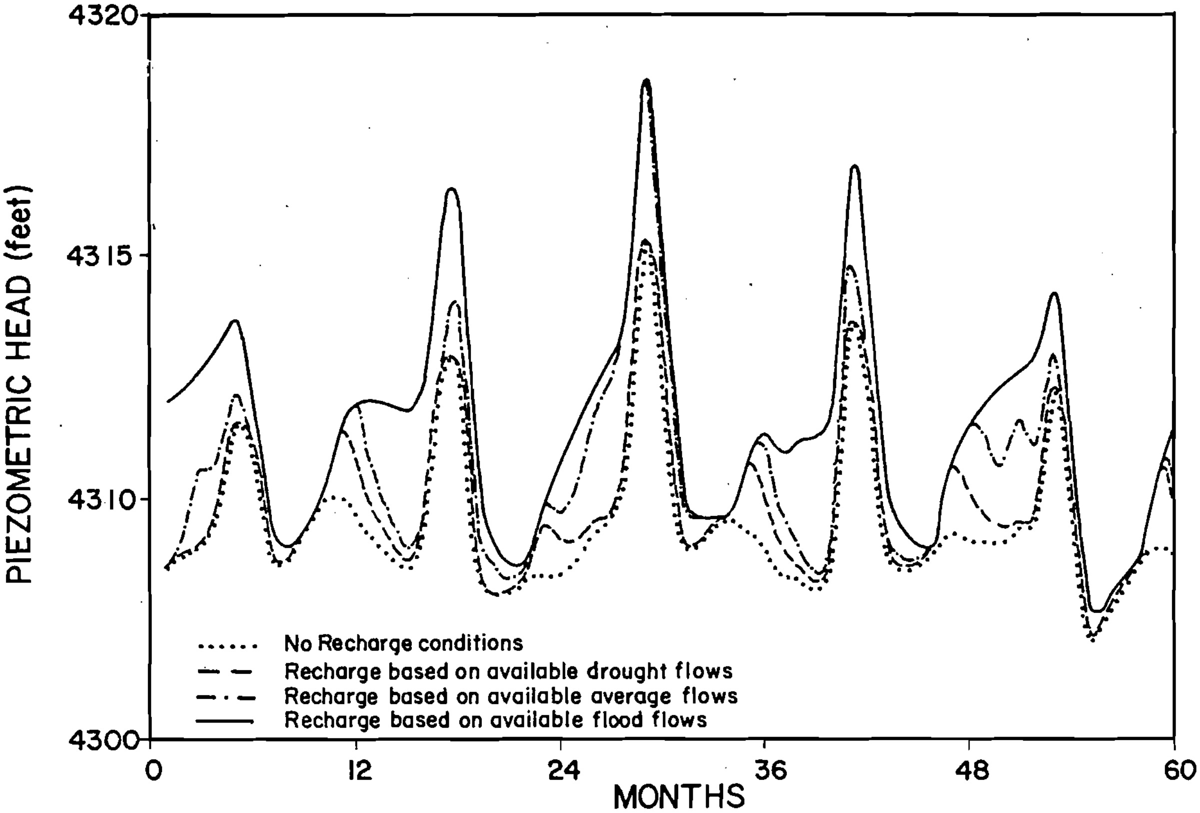


Figure 75. Recharge hydrograph comparisons for node 90 with a maximum recharge rate of 1350 ac-ft per month.

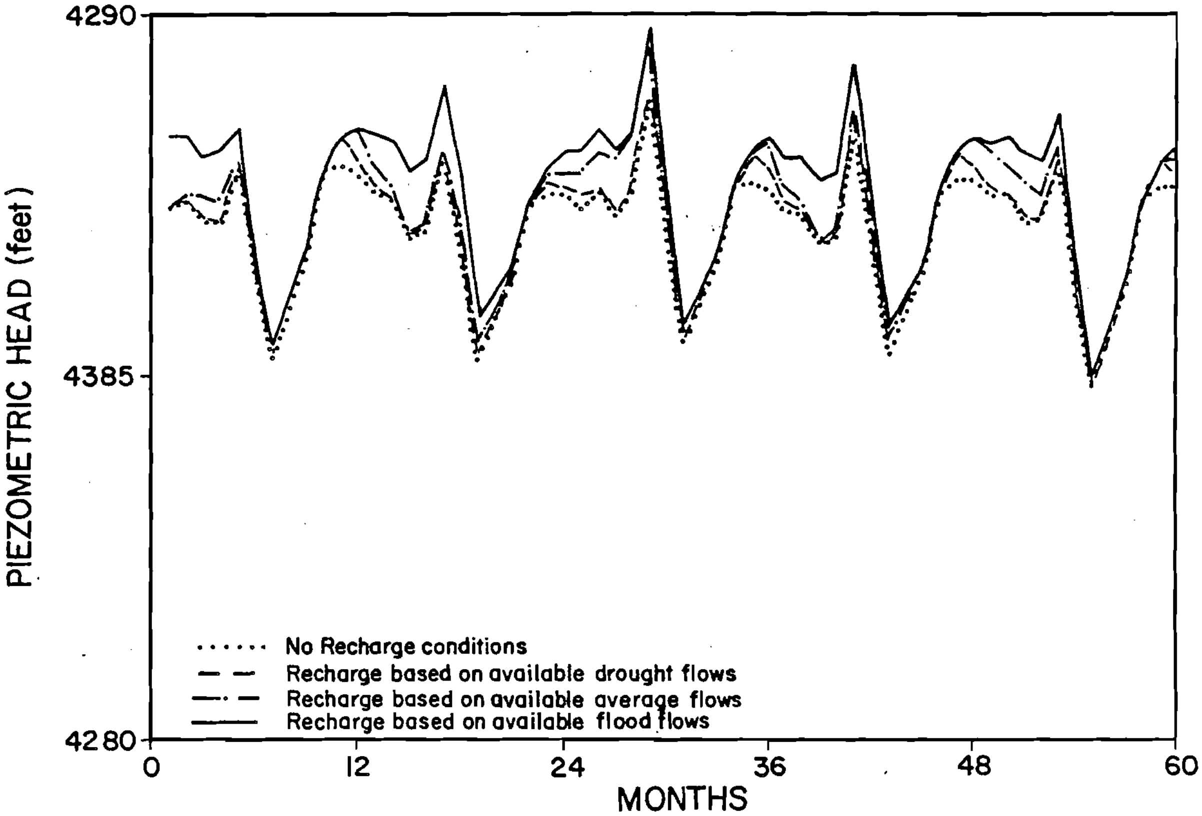


Figure 76. Recharge hydrograph comparisons for node 129 with a maximum recharge rate of 1350 ac-ft per month.

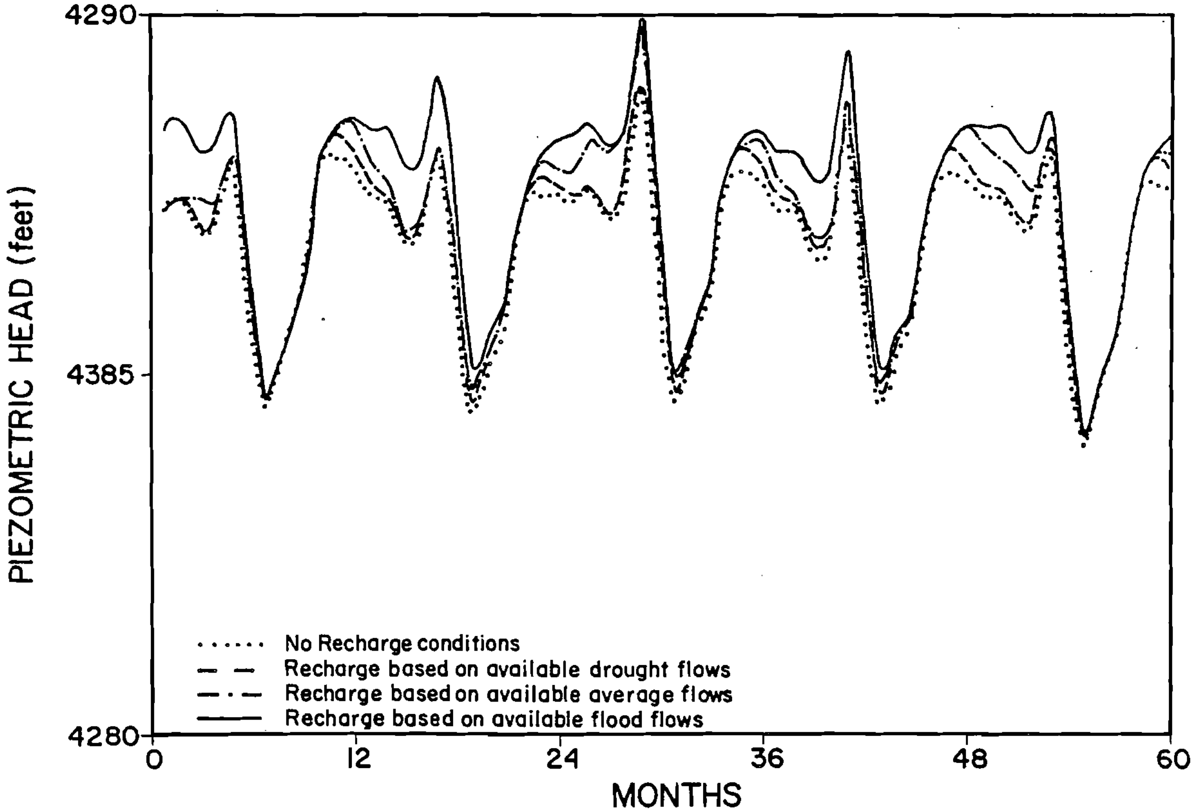


Figure 77. Recharge hydrograph comparisons for node 131 with a maximum recharge rate of 1350 ac-ft per month.

Table 13. Maximum available water at Gateway and Plain City (ac-ft/mo).

	Month												Total
	J	F	M	A	M	J	J	A	S	O	N	D	
Second year simulated Gateway available flows	5084	3756	7374	14748	2794	13007	0	0	0	0	2611	3572	52,946
Wasted flows at Plain City	17633	14198	35129	44197	56838	26198	1282	0	3252	5359	7420	8473	219,978

Table 14. Hypothetical quantities and distribution of recharge for extreme recharge conditions.

	Month											
	J	F	M	A	M	J	J	A	S	O	N	D
Quantity (ac-ft)	61908	61900	61900	61900	61900	61900	0	0	0	0	61900	61900

Since the calculated savings for the previous runs are so small, attention was turned to the effect that could be produced if all of the excess water were utilized. Table 13 includes monthly values for excess water calculated from simulated flood water right conditions at Gateway and from the wasted water at Plain City.

Figures 78 through 80 compare Table 13 recharge simulations and the simulation run without recharge for nodes 86, 90, and 153 respectively. Calculations of cost savings per year total $13,380 and $51,150 for the Gateway and Plain City runs respectively.

To check the effect a large quantity of recharge water would have upon the system, a simulation was made based on the quantities and distribution of recharge as shown in Table 14. The maximum rise in piezometric head at node 90 equaled 150 feet and the cost savings due to reduced pumping lifts totaled approximately $97,500 per year.

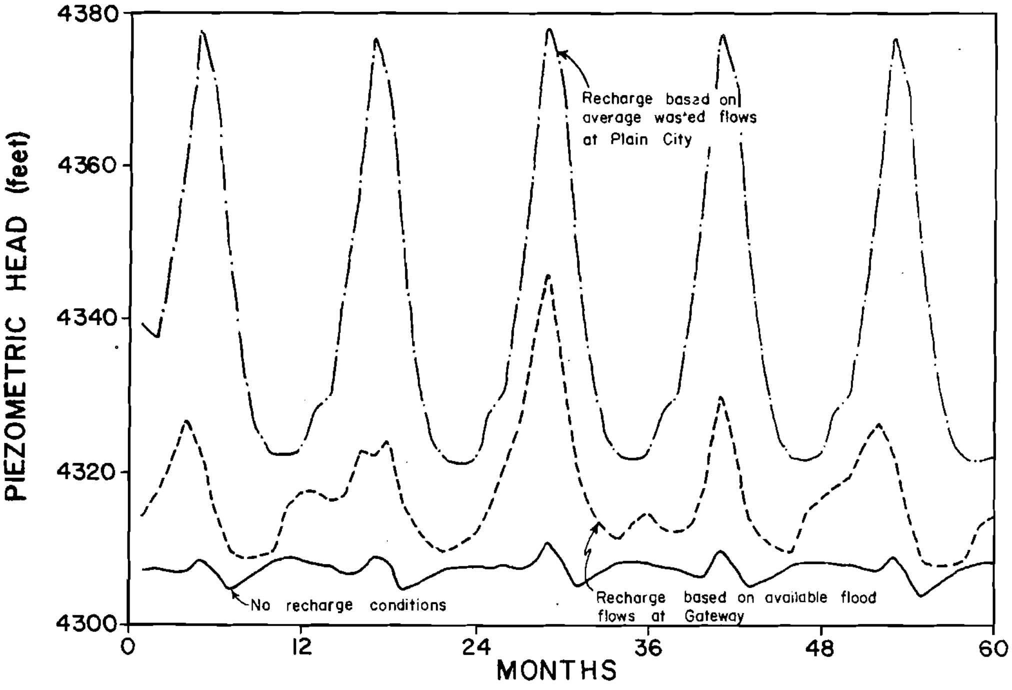


Figure 78. Recharge hydrograph comparisons for node 86 utilizing all available water at Gateway and Plain City.

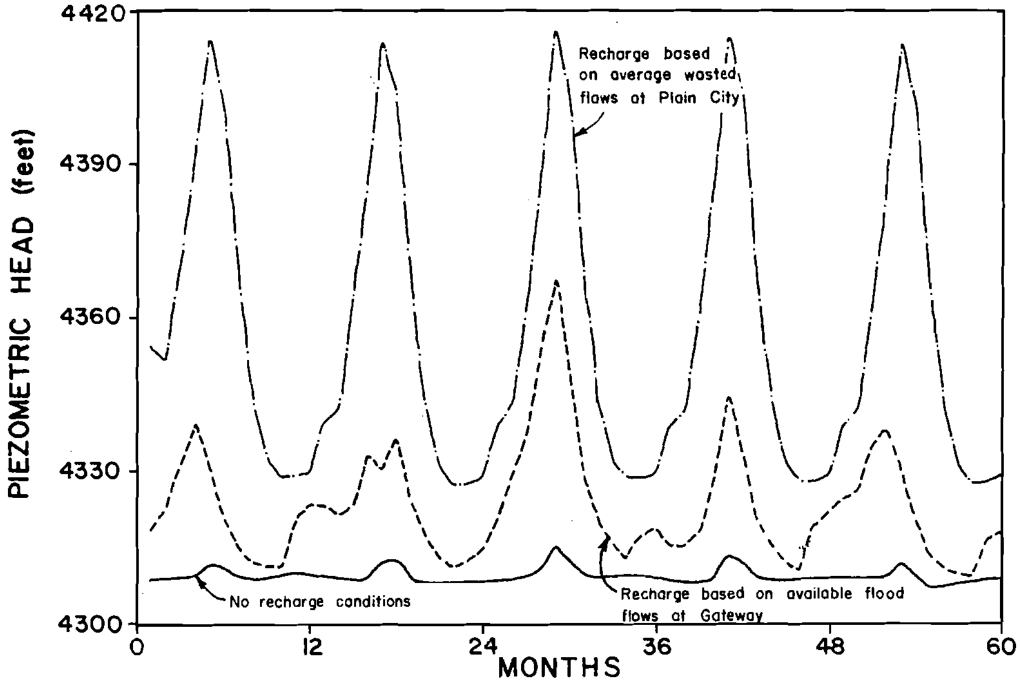


Figure 79. Recharge hydrograph comparisons for node 90 utilizing all available water at Gateway and Plain City.

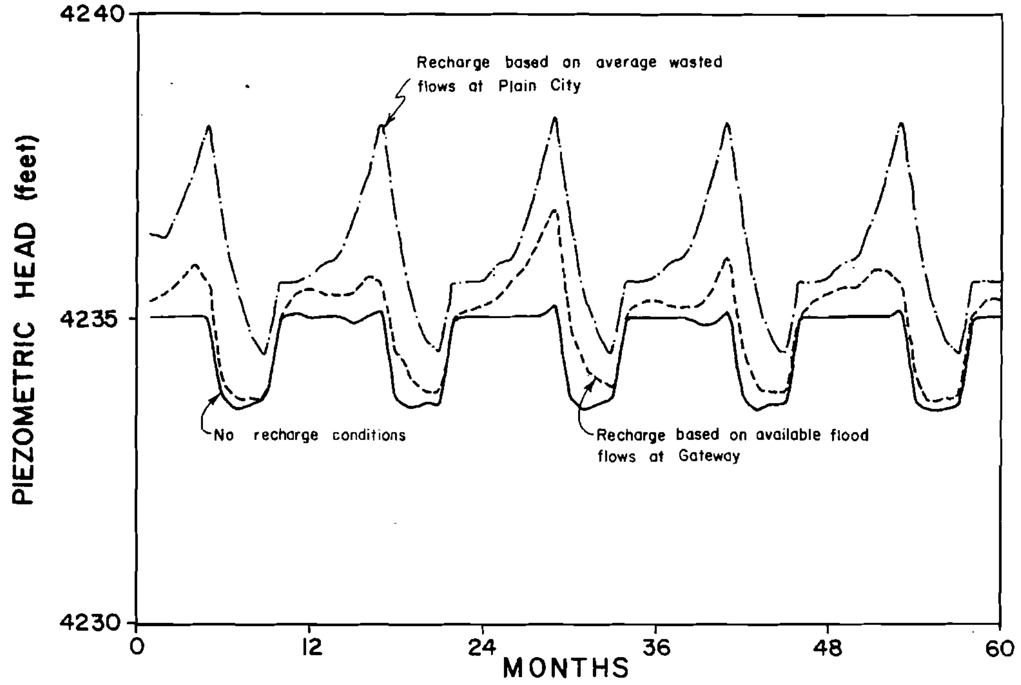


Figure 80. Recharge hydrograph comparisons for node 153 utilizing all available water at Gateway and Plain City.

INSTITUTIONAL AND ECONOMIC CONSIDERATIONS

Water Resources Management

Numerous organizations, both public and private, are involved in the management and use of waters of the Weber and Ogden Rivers. Haws (1973) indicates that there are 63 mutual irrigation companies, 4 water improvement districts, 12 municipalities, and 2 water conservation districts in Weber County; not to mention a number of private water companies which provide culinary water. In addition, there are many irrigation companies and other entities in Morgan and Summit Counties which obtain their water supply from these two rivers.

Federal reclamation projects, including the Weber River project, the Ogden River project, and the Weber Basin project, were built since the late 1920s to impound and distribute surplus water. As a result several large storage reservoirs and distribution systems were constructed and the Weber River Water Users Association, the Ogden River Water Users Association, and the Weber Basin Water Conservancy District were formed to sponsor, operate, and maintain these facilities.

Water Rights

The waters of the Weber River and its tributaries are considered to be fully appropriated, and water rights are administered according to various court decrees and contracts. The Weber River Decree of June 2, 1937, covers rights of the main stem and all major tributaries except the Ogden River, which is covered by a separate decree. Several contracts which have been made between various right holders, such as the water user associations, Utah Power and Light Company, and the federal government, have transferred and otherwise affected these rights. Applications for additional water rights have been filed since the court decrees, and some of these are still pending before the State Engineer.

Distribution of water according to water rights on these rivers is administered by river commissioners appointed by the State Engineer. Operation of the system has been described as follows:

> Waters of the Weber River and tributaries are distributed in accordance with water rights defined in the Ogden River Decree dated April 1, 1948, the Weber River Decree dated June 2, 1937, appropriate contracts and agreements which alter these decrees and other subsequent rights which have been recognized. Storage rights for Weber Basin Project were filed primarily in October 1955 and are junior to the early direct flow rights and thus take effect only after such prior rights are satisfied. The majority of water stored under project water rights is stored during the snowmelt months. Water is withdrawn from storage throughout the year for irrigation, municipal, industrial and fish and wildlife purposes depending upon demands. Municipal and industrial water is released throughout the year from Pineview Reservoir and also from the Weber River Reservoirs except during high

> runoff periods when local sources below the reservoirs are sufficient to apply requirements. Water is released for stream fishery purposes when other releases are inadequate to maintain the stream fishery. Irrigation water is required starting in May and continuing through October. Irrigation releases vary widely depending on runoff patterns during the year and in the case of abnormal and subnormal years. The operation of the reservoirs for conservation purposes greatly reduces the uncontrolled runoff during high flow periods and is compatible with flood control regulations. Evacuation of conservation storage capacity based on runoff forecasts and the flood control diagrams will have only a minor effect on the conservation storage in that the reservoirs are essentially assured of filling in, controlling the potential of high flows. (Stevens et al. 1974, p. VI-30.)

Institutional Arrangements for Groundwater Recharge System

To establish a long-term groundwater recharge system on the Weber River at the location indicated in this study will require some form of organizational arrangement for financing and management. Water rights must be purchased, the abandoned gravel pits to be used for ponding must be acquired, diversion and conveyance facilities must be constructed, the system must be maintained and operated when in place, and the costs of all of these must be properly allocated to and collected from the beneficiaries.

Although large surplus flows in the order of 2000 cfs (56,630 ℓ/sec) pass the recharge site for two to three months during most years, to obtain a year around continuous flow of 5 to 10 cfs (142 to 284 ℓ/sec) for recharge would probably require the purchase of existing direct flow or storage rights. These and other costs outlined above should be passed on to the beneficiaries of the recharge operation. The model of the system developed in this study provides information on the areal extent and magnitude of pumping level improvement resulting from recharge and gives the basis for allocating the costs equitably.

A special improvement district appears to be the most suitable form of institution to finance and manage the recharge system. This is a governmental subdivision with powers to levy taxes on all taxable property within the district, to issue bonds, and collect charges or fees for services rendered. Its powers and authority are limited to the purposes specified in the resolution creating the district. It is created by the board of County Commissioners who can also serve as its board of trustees or they can appoint or arrange for election of other trustees. It could act as the sole manager and operator of the recharge system or it could make arrangements with other organizations such as the Weber Basin Water Conservancy District to supply the water and operate the system.

The details of the method of financing could be patterned after the groundwater replenishment system established and successfully operated for several years in Orange County, California (Crooke 1958). A replenishment assessment for each acre foot of water extracted from the groundwater basin provides the major source of revenue. In the case of the Weber River recharge system being investigated here, it would be appropriate to determine the boundaries of the district to encompass only that part of the groundwater basin benefitted by the recharge operation. This could be done easily from information supplied by the model developed by this project.

Prompt Action to Obtain Land

The principal recharge area in the mouth of Weber Canyon is ideal for recharge purposes. The land surface consists of coarse sand and gravel with little vegetation. Active gravel pits take up part of the area. Most of the center of the valley is still open, but along the sides some scattered houses and subdivisions are being built. In only a few years the opportunity to easily acquire land for a recharge project will be gone. Prompt action by the appropriate public agencies, either local or state, is imperative to retain this recharge resource for public use in the future. In the meantime, as suggested earlier, the land could be utilized for a park, playground, golf course and wetlands habitat. But now is the time for action to set the area aside for its ultimate use as an artificial recharge area.

Recharge Pit Construction and Operation

Costs associated with the construction of a recharge facility are highly variable and dependent upon the recharge method employed and the recharge location. The only recharge method discussed herein is recharge by basins or pits. The best recharge location is the area next to the mouth of the Weber Canyon. The recharge area chosen appears to be ideal because the soil is highly transmissive and numerous active and abandoned gravel pits exist which are ideally suited as recharge basins.

The presence of gravel pits improves the economics of artificial recharge because fewer initial costs would be incurred for pit excavation and preparation. Rough estimates of costs for a recharge facility have been made with the basic assumptions that a recharge basin already exists and that a settling basin would require construction. The cost estimate is found in Table 15.

The actual cost depends on construction conditions and could be decreased below the estimate given if excavation costs could be cut by utilizing more existing basins. The costs of purchase, trade, condemnation, lease, and any other option for obtaining the land required are not included. The repayment of such a project is also highly variable and dependent upon the kind of financing. The cost benefit ratio would vary greatly depending on whether a simple interest loan was obtained, whether a low interest loan was obtained from a state agency or other kinds of innovative financing could be found. The actual economics of pit preparation should be studied further to obtain a better feeling for initial costs and available financing.

Recharge Operation

Each of the three simulation runs based upon utilization of water at Gateway in excess of the used water right appears to be unfavorable in terms of a cost benefit analysis based on pumping lift. Even when the total quantity of available water at Gateway is used the maximum cost savings from reduced pumping lifts total only $13,380. This value barely meets the yearly estimated operating costs shown in Table 15 and does nothing to recover initial construction costs.

If all the available water which passes Plain City and is wasted into the Great Salt Lake were utilized, the average cost savings due to decreased pumping lifts would be approximately $51,000 per year. When operation and maintenance costs are subtracted and the remainder is applied on a $500,000 no interest loan the sum would be cleared within 14 years. In comparison, a 10 percent loan for 30 years would require a yearly payment equal to approximately $53,000 which is again greater than the total yearly savings generated from

Table 15. Cost estimate of recharge system.

Capital Costs	
1. 13 acres @ \$8,000/acre	\$104,000
2. Excavation 168,862 yd^3 @ \$3.00/yd^3	507,000
3. Security Fence 3,140' @ \$3.25/ft	10,000
4. Diversion Works	10,000
5. Contingencies (25%)	158,000
	\$789,000
Annual Operating and Maintenance Costs	
1. Basin Maintenance	\$ 5,000
2. Weed & Algae Control	1,000
3. Misc. Office, Engineering and Legal Expense	2,000
4. Operating Personnel Salary	5,000
	\$ 13,000

recharge under the best assumptions. Direct state support of the recharge project would also greatly affect the economics.

In order to provide a cost benefit ratio of between 1.5 and 2.0 the generated savings should be in the range from \$79,500 to \$106,000. The only recharge simulation (under the limited assumed conditions described above) which falls within the above range is the one utilizing the hypothetical recharge quantities and distribution shown in Table 14.

Other Economic Benefits

When economics is based solely upon the savings realized by a reduction in pumping lifts and fixed construction costs, the value of artificial recharge as calculated herein appears to be marginal. It must be remembered that slight changes in the economic analyses could make a marked difference in the viability of such a project. For example if pumping lifts were to continue to increase in the future, the savings for a given quantity of recharge would be higher. Alternate financing or changing interest rates could greatly affect the ability to repay an initial loan. Rising energy costs would also change the economic worth of recharge.

A complete economic analysis of such a recharge project should include other benefits such as reduced Weber River flooding, delay of flood waters into the Great Salt Lake, protection of groundwater from contamination, reduction of water treatment costs for water used for culinary purposes, and benefit of increased pumping during drought. By including these types of benefits along with others mentioned above, the economic viability of artificial recharge can be changed dramatically thus opening the door to a successful artificial groundwater recharge project.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The piezometric surface of the deep confined aquifer which underlies much of the Weber Delta area has declined from 40 to 50 feet around Hill Air Force Base over the last 30 years. The reason for this decline is twofold: first, there appears to have been a decline in the quantity of subsurface recharge from the mountain front from the mid 1960s to 1981. Second, there has been an increase in pumping demands for municipal and industrial uses which utilize the deeper higher quality water of the Delta Aquifer system. The results from such a combination are that the storage potential of the aquifer has been reduced and that pumping lifts have been increased.

The groundwater computer model presented herein has resulted in a reasonable simulation of yearly historical trends of the piezometric water surface of the Delta Aquifer. A yearly stochastic generation model and a monthly disaggregation model then produced Weber River streamflows to be used as stochastic river recharge into the groundwater model. These same streamflows were also used in conjunction with an estimate of the active water rights on the Weber River to indicate a quantity and distribution of unused available water at the Gateway station. Water was also found to be wasted into the Great Salt Lake based on values of streamflow at the Weber River gaging station near Plain City. Subject to the limitations imposed by the water rights, various quantities and distributions of artificial recharge were then input into the groundwater model and the results were compared with simulations without artificial recharge.

The economic benefit of an artificial recharge project when based solely upon reduced pumping lifts and fixed construction costs appears to be small for all simulations but one. The simulation which had reasonable benefits was a result of utilizing the water currently being wasted into the Great Salt Lake. The calculated benefit was found to be approximately $51,000 per year. The economic analyses performed herein do not include other benefits such as those derived from use of the recharge facilities as a flood control device, reduced water treatment costs of water used for culinary purposes, and savings realized by increasing energy costs. Each of these and other similar questions should be answered by a detailed analysis before a complete economic evaluation can be made.

Conclusions

The results obtained from the computer model indicate that the size of the recharge basin utilized by the Bureau of Reclamation during the 1950s recharge tests is inadequate to capture the maximum economic benefits. To be economically feasible in terms of pumping lift the infiltration capacity would have to be increased either by increasing the driving head or by increasing the recharge basin size.

Total available water at Gateway is highly irregular and unpredictable. The quantity of water is completely dependent upon the management practices of both the upstream and downstream water users. Each user varies his water usage according to past and present climatological conditions. These conditions also affect the quantity of water diverted to, stored in, or released from any one of the instream storage reservoirs. Because water use practices are so highly varied and difficult to predict, it is concluded that water usage for recharge purposes based on computations from water rights is not the best alternative.

The best and most reliable estimates of the available recharge water would be to monitor and then use the available quantity of wasted water which otherwise would enter the Great Salt Lake from the Weber River. There is a substantial amount of wasted water each year which enters the lake which thus could be put to beneficial use for artificial recharge.

Two basic timing options were presented for management of a recharge system. The first was to apply a constant and continuous supply of water for artificial recharge, and the second was to apply a timing technique which applies recharge on an scheduled intermittent basis. Since continuous municipal and industrial use account for the greatest proportion of total use, a continuous supply would give maximum year round pumping cost savings. A continuous supply herein means that the recharge operation would be continued whenever water is available.

The marked decrease in piezometric well head which occurred near the canyon mouth in the mid 1960s might be a good indication of mountain front recharge quantity. Due to the few observation wells in the area, the details of the changes in both water well levels near the canyon mouth and mountain front recharge are uncertain. The fact that the historical piezometric surface declined with the same general pattern as the calibrated mountain front recharge indicates that if natural recharge were to increase once again the piezometric surface would likewise increase.

The overall conclusion reached regarding artificial groundwater recharge, considering the savings realized from reduced pumping lifts, and the fixed construction costs, is that only with ideal management and financing will such a project be economically viable. Changes in the assumptions made or inclusion of other economic benefits could greatly add to the desirability and practicality of recharge.

Recommendations

Further studies should be made of water right patterns for the Weber River. These studies should include the management practices of the various reservoir operators as well as other water users. It is recommended that the studies be done with the overall objective of utilizing any wasted water which presently enters the Great Salt Lake. A study of this nature would result in both the assurance that sufficient water would be available and that the instream users would not be adversely affected by such a recharge project. Such a study should also determine if the economic benefit to any one water user is sufficiently high to warrant voluntary partial allocation of his water right for recharge purposes.

Land acquisition potential should be studied further. Public agencies should act promptly to retain this recharge resource for future public use. The economics of an artificial recharge project are greatly improved when the initial excavation and construction costs can be lowered. Although the potential for recharge into any one of the many present gravel pits is high, the actual sizes and locations might indicate an optimum recharge operation at a minimum initial investment. An added benefit of land acquisition in the recharge area of the Weber Basin would be the future protection of this sensitive area from contamination from urban and industrial sources.

Well B-5-1-36bbb should be found and if possible prepared for further use as an observation well. The quantity of mountain front recharge entering the Delta Aquifer system is important to the maintenance of a proper water balance. Further declines of natural recharge will obviously increase pumping lifts and improve the economics of artificial recharge. On the other hand if mountain front recharge were to start a recovery trend the importance of artificial recharge would be diminished. For this reason it is recommended that well B-5-1-36bbb either be reopened, another adequate well located, or a new well drilled to provide a guide as to the nature of the local subsurface recharge.

During the recharge tests performed by the Bureau of Reclamation several problems such as freezing and basin clogging were encountered which affected the results of the recharge tests. It has also been found that river recharge greatly affects the response of the Delta Aquifer and that some of the effects measured by the Bureau of Reclamation might have been due to natural causes. It is therefore recommended that additional recharge tests be made with careful attention given to avoid some of the same problems previously encountered. It is believed that this could be done with a minimal expense utilizing existing basins and that it should be done before a full scale project is begun.

A more detailed economic analysis should be performed to include other benefits to the recharge project and possible cost trends. Such a study could show the various economic options and possibilities available in terms of both the initial investments and long term operation to better quantify the viability of artificial groundwater recharge.

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APPENDICES

Copies of the Appendices are available on request from the Utah Water Research Laboratory, UMC 82, Utah State University, Logan, Utah 84322.