A MODELING APPROACH FOR ASSESSING THE FEASIBILITY OF GROUNDWATER WITHDRAWAL FROM THE DENVER BASIN DURING PERIODS OF DROUGHT

by

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ABSTRACT

The ground-water resources in the shallow bedrock aquifers of the Denver Basin may be used to supplement water supplies for the expanding Denver metropolitan area. Previous research suggests that large-scale pumping on a continuing basis may deplete the basin's ground-water resources. Short duration pumping, however, designed to meet water deficits during drought periods, may be a feasible method of utilizing the resource without causing long-term ground-water depletion. A pre-existing computer model of the Denver Basin is calibrated and used to predict the decline in aquifer heads and stream baseflows due to drought period pumping from a proposed well field.

The four bedrock aquifers in the upper portion of the section, the Dawson, Denver, Arapahoe, and Laramie-Fox Hills are modeled as separate units along with the major streams and valley fill alluvium in the basin. The MODFLOW computer code is used along with a modified river package, RIVINT, which permits simulation of variable river stage resulting from stream/aquifer interaction during transient simulations. Hydraulic and dimensional parameters for aquifers, alluvium, and streams are taken from several previous studies.

For purposes of modeling drought in the basin, a drought is defined as the period of time when the Palmer

Drought Severity Index for Colorado is -2 or less and the Surface Water Supply Index for the S. Platte River is -2 or less. Using these criteria; 6 drought periods with all but the last having a duration of 2 years, are identified during the 40 year interval 1948 through 1987 and then these historical cycles are imposed on the basin model for drought pumping simulations over the interval 1990 to 2029.

Annual water supply, use, reservoir storage and change in reservoir storage for the city of Denver are examined for the years 1948 to 1987. Pumping rates are specified to eliminate deficits during droughts, such that no negative change in reservoir storage occurs during drought periods, assuming no growth in water use. A satellite well field consisting of 36 wells near Parker, Colorado is designed by using a well field simulator. Well field criteria are established to minimize drawdown at the well field and the maximum pumping rate which meets these criteria from the four aquifers collectively is 38 cfs for a duration of 2 years. At this rate, some negative change in reservoir storage occurs during several modeled droughts.

Drought alleviation pumping simulations are made with basin-wide pumpage estimates for 1978 and are conducted with the assumption that no further aquifer development occurs in the future. Model simulations predict that aquifer heads do not fully recover before the next drought period. Recovery rates for baseflow in streams near the well field are also low and baseflow decline occurs in a stair-step manner. The hydrologic system does not fully approach recovery from moderate drought alleviation pumping before the onset of the next drought, given the scenarios presented herein. A successful drought alleviation pumping scenario may be feasible. Less impact and better recovery may occur for different well field configurations and pumping schedules. In addition, results will be different when model calibration is improved.

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INTRODUCTION

Ground water in shallow aquifers of the Denver Basin in eastern Colorado is a resource with potential for further development. Utilization of this resource on a large scale continues to be questioned, and various strategies for pumping ground water have been suggested and continue to be explored. The impact that development would have on the resource is of concern and raises questions about the complex interrelationship among components of the Denver Basin's hydrologic system. Bedrock aquifer heads and stream baseflows in areas adjacent to a well field would likely be affected by withdrawal of ground water. Previous studies have indicated that pumping from a high discharge well field on a continuing basis would deplete the basin's ground-water resources over time and lead to depressed aquifer potentials in and around the well field (Robson, 1987; Banta, 1989).

Supplemental use of ground water during drought periods, may be a reasonable alternative for management of the ground water resource. The pumped water could be used to augment supplies of the City and County of Denver. Pumping only during drought periods would provide additional water during times when water demand has historically exceeded water supply. Withdrawals from bedrock aquifers during periods of drought induced need, might also lessen the impact of ground water withdrawal on the Denver Basin hydrologic system by allowing recovery of heads and baseflows during the intervening years.

This study was undertaken to assess the technical feasibility of pumping water from the Denver ground-water basin during periods of drought. The way in which the hydrologic system is influenced by current ground water use, future use, and use during periods of drought is evaluated by utilizing a computer model of ground-water flow. The effect produced on the potentiometric surfaces of Denver Basin aquifers due to pumping is numerically calculated for a succession of drought periods. This numerical model incorporates a recently developed river simulation package (Schenk and Poeter, 1990). With this new river package, the simulation of stream/aquifer interaction is improved such that changes in stream stage and flow rate, that result from nearby pumping, can be estimated during transient computer simulations. Reasonable approximations of the magnitude and duration of future drought episodes are made by first defining conditions that exist during a drought, and then reviewing the basin's meteorological record to identify past droughts that are characterized by those conditions. Predictions of basin response to future drought cycles are made by imposing historical drought cycles on the basin model. A satellite well field, which is designed to be productive and efficient at the necessary withdrawal rates, is introduced into the model. Scenarios which combine cyclic variations in recharge with pumpage to meet expected water supply deficits during a drought are then simulated. The affect of cyclic drought pumping on aquifer heads and baseflow in the basin's streams over the course of multiple drought periods is assessed. Finally, an appraisal is made of the time to full recovery of aquifer heads following drought pumping, given drought periods of differing length.

MODEL DEVELOPMENT

Location and Climate of the Study Area

The Denver ground-water basin encompasses a 6,700 square mile area in northeastern Colorado and is part of the larger Denver structural basin that extends from Colorado into eastern Wyoming and western Kansas and Nebraska (Figure 1). Elevations in the basin range from about 4,500 feet along lower reaches of the S. Platte River to over 7,500 feet on the Palmer Divide, a topographic ridge north of Colorado Springs. Most of the basin is part of the S.

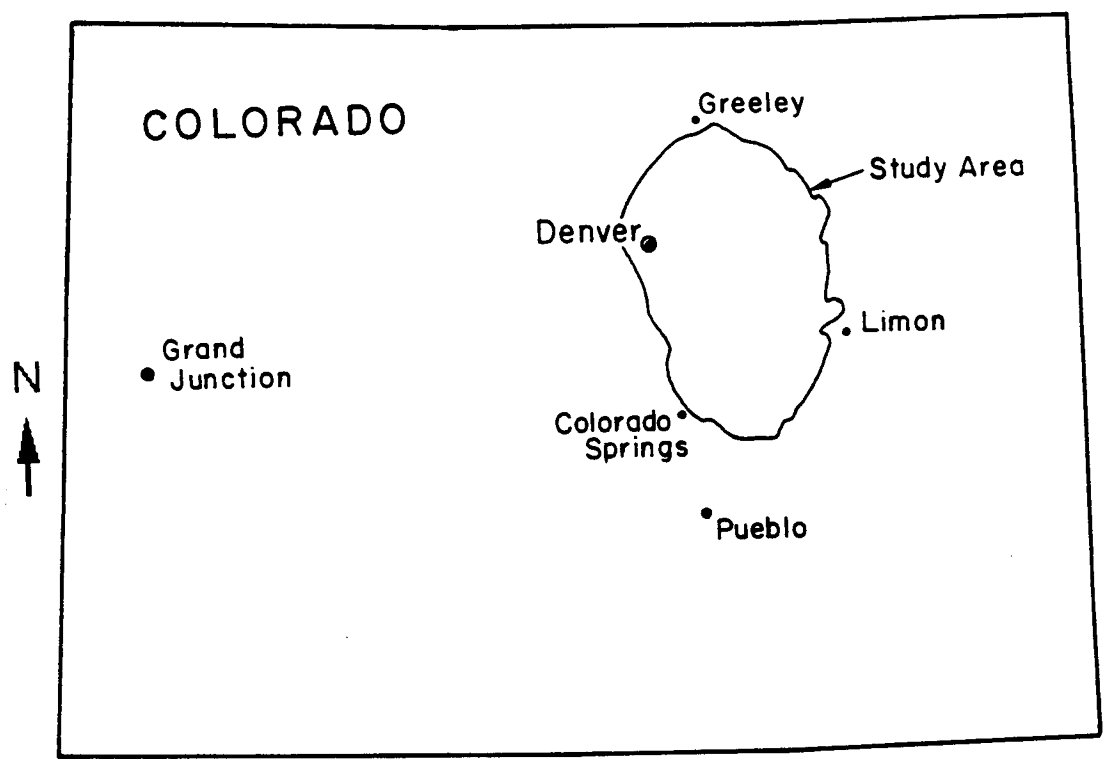

Figure 1. Location of the Denver Basin study area (after Schenk and Poeter, 1990)

Platte River drainage with the extreme southern portion of the basin draining into the Arkansas River.

The basin has a semiarid climate with a mean annual precipitation rate of 14 inches per year (Hansen et al., 1978). Mean annual potential evaporation is 50-70 inches (Robson, 1987). A majority of the precipitation falls from April through September with higher precipitation rates found at higher elevations. An estimated 5.0 million acre-ft of water falls annually on the basin as precipitation. Only 1 percent supplies recharge to bedrock aquifers, the rest being lost through evapotranspiration and runoff (Robson, 1987).

Hydrogeology of the Study Area

The four primary bedrock aquifers in the Denver Basin are the Dawson Arkose of Tertiary age, Denver Formation of Late Cretaceous to early Tertiary age, Arapahoe Formation of Late Cretaceous age, and the Laramie Formation and Fox Hills Sandstone which are grouped together for the purposes of this study and were formed in the Late Cretaceous (Figure 2). The high hydraulic conductivity, water bearing portions of each formation comprise the four primary aquifers. Low hydraulic conductivity portions within each unit act as confining layers. The Pierre Shale forms the base of the shallow ground-water system because of its considerable

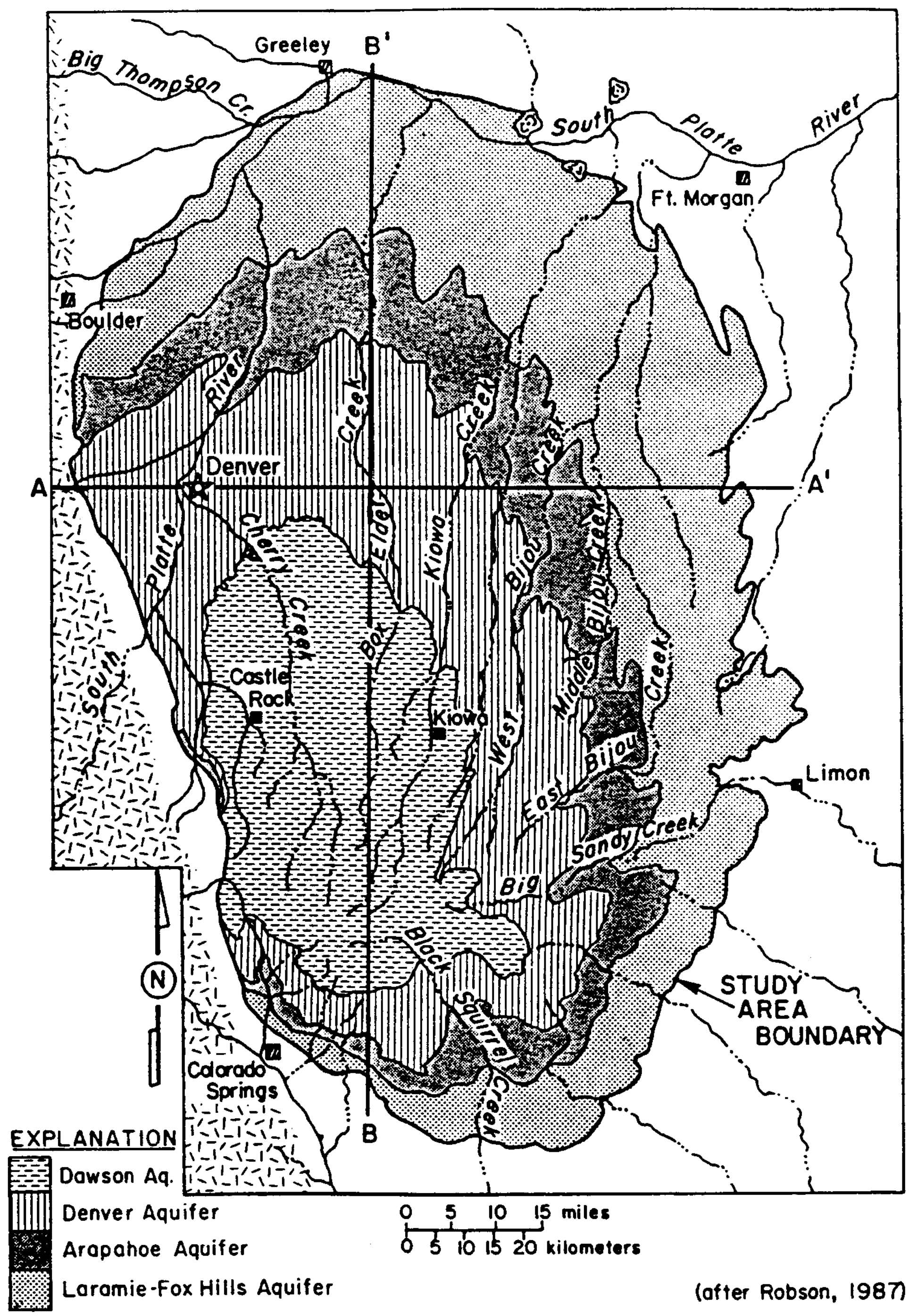

Figure 2. The four principal aquifers in the Denver Basin (after Schenk and Poeter, 1990)

thickness and low vertical hydraulic conductivity (Robson, 1987).

The basin is structurally asymmetrical with low-angle dips on the eastern flank and steeply dipping to overturned beds in the west. Cross-sections in Figure 3 show that the formations of the Denver Basin have a nested bowl-shaped appearance when drawn with vertical exaggeration. Without vertical exaggeration, cross-sections of the basin appear flat and almost featureless.

The Laramie-Fox Hills aquifer is some 200-300 feet thick and is predominantly siltstone and sandstone. Some coarse-grained portions of the underlying Pierre Shale are water-bearing and are included in the Laramie-Fox Hills aquifer. Hydraulic conductivity ranges from 0.05 ft/d along the northwestern margin of the basin to 6 ft/d near Littleton. The highest transmissivity values in the Laramie-Fox Hills aquifer occur near the center of the basin and are over 1,000 ft^2/d (Robson, 1983). The Arapahoe aquifer overlies the Laramie-Fox Hills aquifer and is generally 200-300 feet thick. Water-yielding portions are predominantly conglomerate, sandstone, and siltstone. The Arapahoe aquifer exhibits the basin's highest hydraulic conductivities, with hydraulic conductivity ranging from 0.5 ft/d in central portions of the basin, to 7 ft/d near

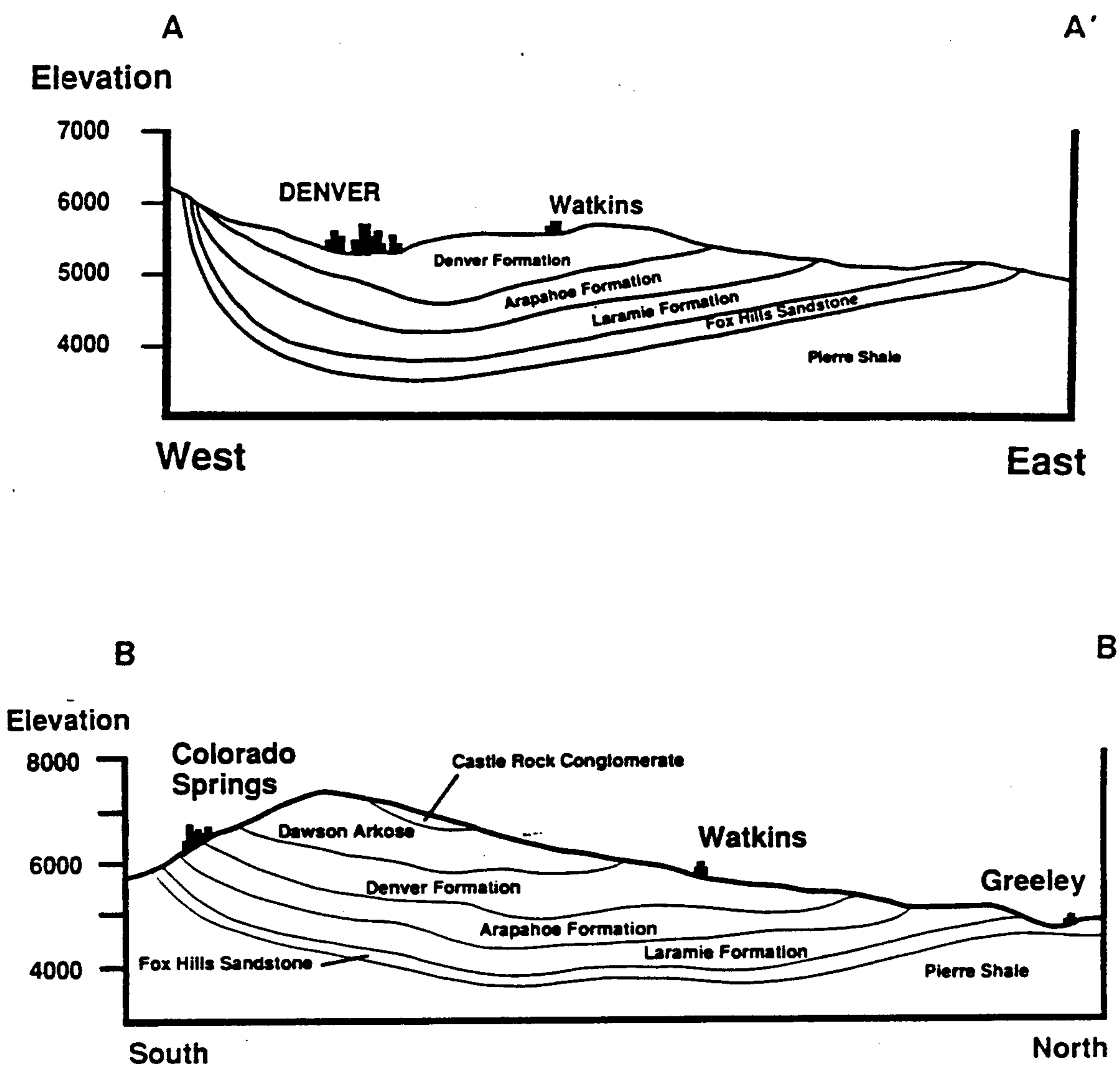

Figure 3. Cross sections of the Denver Basin (after Schenk and Poeter, 1990)

Littleton. Transmissivity values are also highest in the Arapahoe aquifer and are over 2,100 ft^2/d southeast of Littleton (Robson, 1983). Sandstones, siltstones, and interbedded shale in the middle one-third of the Denver Formation make up the 100 to 300 feet thick water-yielding portion of the Denver aquifer. Measured hydraulic conductivity ranges from 0.5 to 1.5 ft/d and the highest transmissivity values are estimated at 400 ft^2/d in the vicinity of Castle Rock (Robson, 1983). Overlying the Denver aquifer is the Dawson Arkose consisting of interbedded conglomerate, sandstone, and shale which form the 100-400 feet thick Dawson aquifer. Hydraulic conductivity in the Dawson has been measured to be from 0.2 to 3.0 ft/d, and transmissivity as high as 1,200 ft^2/d southwest of Elbert (Robson, 1983). All four aquifers are hydraulically connected by leakage through aquitards with vertical hydraulic conductivities on the order of $1x10^{-6}$ ft/d.

The unconsolidated sediments which make up alluvium in the Denver Basin are primarily sands and gravels, however, lenses of silt and clay are found and are important with respect to bulk hydraulic conductivity of these materials. Alluvial aquifers are believed to range in thickness from 10 to 100 feet (Burns, 1980). Hydraulic conductivities reported by Burns (1980) range from 100 to 500 ft/d. Because of heterogeneities in the alluvium, values for hydraulic conductivity and transmissivity vary considerably.

Confined storage coefficient has been estimated at $2x10^{-4}$ to more than $8x10^{-4}$ for those portions of the three lower aquifers where confined conditions commonly occur (Robson, 1983). Robson (1983) made estimates of specific yield for all four Denver Basin aquifers using laboratory analyses. Robson's estimates of specific yield range from 14 to 20 percent. These formations and their corresponding water-yielding units are described in greater detail by Banta (1989) and Robson (1987). Structure of the basin and maps showing hydrologic characteristics of these aquifers can be found in works by Robson and Romero (1981a,b), Robson and others (1981a,b), and Robson (1983).

On a regional scale, water moves away from the topographic high of the Palmer Divide which forms a ground-water divide in the basin. Ground water to the north of the divide moves in a northerly direction; ground water to the south moves in a southerly direction. Movement of ground water also occurs vertically between aquifers, downward in recharge areas and upward in discharge areas. Velocity of vertical leakage is slow, however, it is an important source of recharge for underlying aquifers when the large areal extent of the basin is considered.

As mentioned earlier, only a small portion of precipitation that falls on the basin enters bedrock aquifers as recharge. On the margins of the basin, deep infiltration of precipitation occurs in outcrop areas between stream channels. Recharge from alluvial aquifers also occurs in these areas where heads in the alluvium are higher than in the underlying bedrock aquifers. In the central portion of the basin, ground water moves laterally from areas of recharge to areas of discharge. Movement takes place from highland areas into stream valleys, where ground water discharges into the alluvium or directly into the stream channel. In lower portions of the basin, alluvium in stream valleys acts as a drain for the underlying aquifers.

Ground water pumpage over the last century, particularly since the late 1950's, has effected water levels and patterns of aquifer discharge. Water levels have declined by several hundred feet since development of the Denver area (Robson, 1987). Just since the late 1950s, water levels in all four aquifers have declined in some areas by as much as 200 feet (Schneider, 1980; Romero, 1976). Water withdrawals have influenced ground-water movement, and areas where natural discharge once occurred may no longer exhibit discharge. More than half of the bedrock pumpage in the basin is withdrawn from the Arapahoe aquifer. Rates of withdrawal rose steadily from the late 1950s until the middle 1970s when a marked increase in pumpage occurred. Robson (1987) estimated total pumpage to be 41 cfs in 1978 and Banta (1989) reported total withdrawal rates in 1985 were 56 cfs.

Previous Work

The first attempt to construct a computer model of the basin was undertaken by Robson (1987) at the U.S. Geological Survey. He developed a three-dimensional finite difference model, utilizing the U.S.G.S. ground-water flow code written by Trescott (1975) and Trescott and Larson (1976). He constructed the model using an equal-interval grid consisting of 41 rows by 27 columns and 4 layers which represented the four upper-most aquifers in the Denver Basin. Steady-state simulations were performed in order to estimate a water budget, and to assess if the model could successfully incorporate hypothesized relationships concerning recharge, discharge, and water movement through the basin. Essentially pristine conditions, (conditions where the influence of human activities is considered negligible) were assumed to exist in the basin's hydrologic system until 1958.

Transient-state simulations were run to assess the impact of increased pumping since 1958. Robson used a variably-spaced grid with dimensions 40 rows by 24 columns. These dimensions are somewhat different than in the steady-state model and a greater grid-block density was chosen in the Denver metropolitan area in order to provide greater resolution of head conditions in this area. Pumpage rates for wells producing from the 4 major aquifers in the basin were estimated. Pumping periods beginning in 1959, were defined and pumpage rate during successive periods was increased in a stepped fashion. Robson then had a transient-state model which represented the response of the hydrologic system of the Denver Basin pumping from 1958 through 1978.

Robson used projections of future pumpage to make predictions of hydrologic conditions in the basin for the period 1979-2050, given three possible future pumpage scenarios. The model was used to investigate the feasibility of pumping a 36 square mile satellite well field located in T. 6 S., R. 65 W. in eastern Douglas and western Elbert Counties, in addition to the expected increases in overall basin pumpage. The well field was simulated as pumping at 41 cfs for 72 years starting in 1979.

Robson's study predicted water-level declines on the order of several hundred feet in the vicinity of the satellite well field. Robson suggested that the degree of water-level decline depends on the depth of the aquifer being pumped and the amount of additional pumpage that takes place in the basin. The largest and most widespread declines occurred in deeper aquifers. Declines directly attributable to the well field were smaller when projections of future basin-wide pumpage were higher. Robson pointed out that large, widespread declines would cause some existing shallow wells to go dry and reduce the yield of some deeper wells near the satellite well field. Robson's work suggests that constant pumping at 41 cfs for a long period (72 years) would deplete the basin's ground-water resources and have unfavorable consequences for preexisting wells that tap bedrock aquifers in affected areas.

Research at the U.S.G.S. continued under Banta (1989) who modified the Robson model and used it to assess the impact of ground-water development in the southern portion of the basin near Colorado Springs. Banta changed the grid dimensions to 67 rows by 40 columns, increasing the density of the finite difference grid to provide better resolution of the simulated ground-water system in the southern part of the basin. Hydrologic data that became available subsequent to Robson's work, were also incorporated into the model.

Banta simulated several scenarios of possible aquifer development for the 100-year period from 1985 to 2085. Among these scenarios were two simulations in which pumping took place from a hypothetical well field for 100 years at about 16 cfs and 20 cfs. This well field is located in T. 11 S., R. 65 W. in northern El Paso and southern Douglas Counties. The pumped nodes in this 15.75 square mile well field were arranged in an "I" pattern to avoid problems with excessive drawdown near the center of the field.

Banta showed that pumping was expected to produce relatively large drawdowns in areas adjacent to the well field. Head declines of several hundred feet occurred in the three aquifers that were pumped in the model; the Denver, Arapahoe, and Laramie-Fox Hills. The greatest declines were in the Denver aquifer (over 400 feet near the well field) and the largest cone of depression (in areal extent) developed in the Laramie-Fox Hills aquifer. Several simulations predicted dewatering of aquifers just to the north of Colorado Springs at the southern edge of the basin. Banta's study showed that, even when pumping occurs at lower rates than those simulated by Robson, a well field located in this sensitive area near the edge of the basin could produce significant drawdowns to bedrock aquifers and may result in aquifer dewatering of areas at the edge of the basin where saturated thicknesses are small.

Researchers at Colorado School of Mines wrote a new river module RIVINT (Schenk and Poeter, 1990) to be used with MODFLOW, which allows river stage to vary in reposnse to stream/aquifer interaction. RIVINT simulates a variable river stage and calculates seepage between a river and aquifer based on hydraulic conditions throughout a simulation. Using RIVINT allows prediction of the response of rivers and their associated alluvium to stresses on the ground-water system such as from pumping a well field. A number of parameters which describe each reach of river and alluvium are put into the model. Model output includes river discharge, river stage, seepage rate between river and alluvium, head in the alluvium, and seepage rate between the alluvium and ground-water aquifer (Schenk and Poeter, 1990).

RIVINT was applied to a preliminary model of the Denver Basin by Schenk and Poeter. Their model was based on the model developed by Banta (1989). Data files, which included Banta's grid, material properties, and boundary conditions for the basin, were converted to the proper MODFLOW format.

Parameters for the RIVINT simulation of rivers and alluvium were added to the model. Some minor modifications were made to obtain a working model of the basin.

The RIVINT package used in conjunction with MODFLOW is ideal for monitoring changes in nearby streams and alluvium caused by drought pumping of a satellite well field. In transient-state simulations, effects on river baseflow can be quantitatively appraised during, and immediately following drought pumping. RIVINT provides a tool for assessing the impact of drought pumping on the overall hydrologic system including river stage and baseflow rate, at any point in time during a transient simulation. Therefore, the RIVINT package and the preliminary model of the Denver Basin constructed by Schenk and Poeter, were used in the initial development of a drought pumping model of the basin.

Configuration of the Model

The finite difference model developed by Schenk and Poeter (1990), uses a grid which is overlain across the basin with dimensions 67 rows by 40 columns (Figure 4). The extent of individual aquifers, streams, and alluvium are defined with respect to the gird in Figure 5. The same grid applies to all four aquifers in the model.

Hydraulic and dimensional parameters for bedrock aquifers, are taken from the Banta model, or estimated from

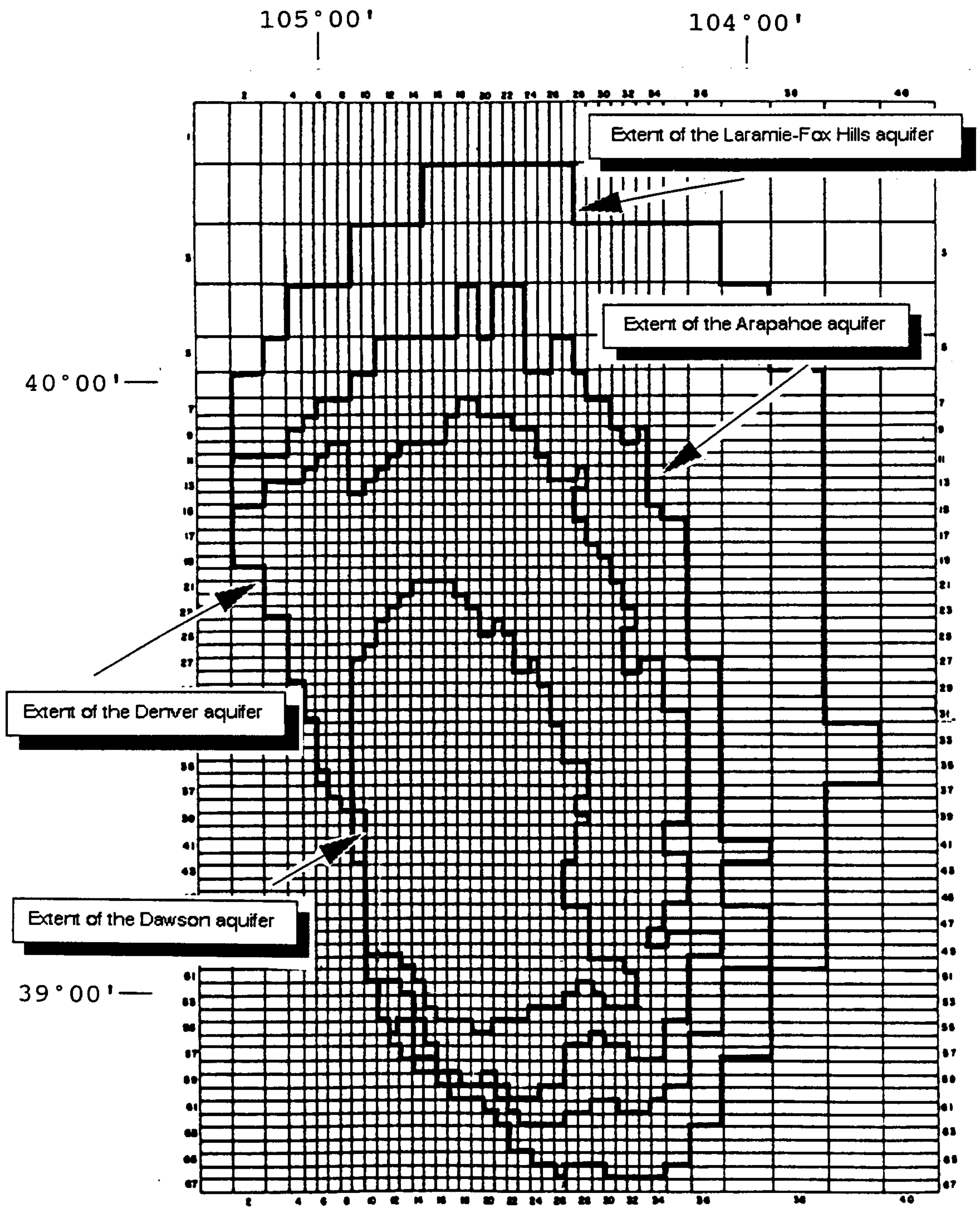

Figure 4. Finite difference grid with outlined Denver Basin bedrock aquifers
(after Schenk and Poeter, 1990)

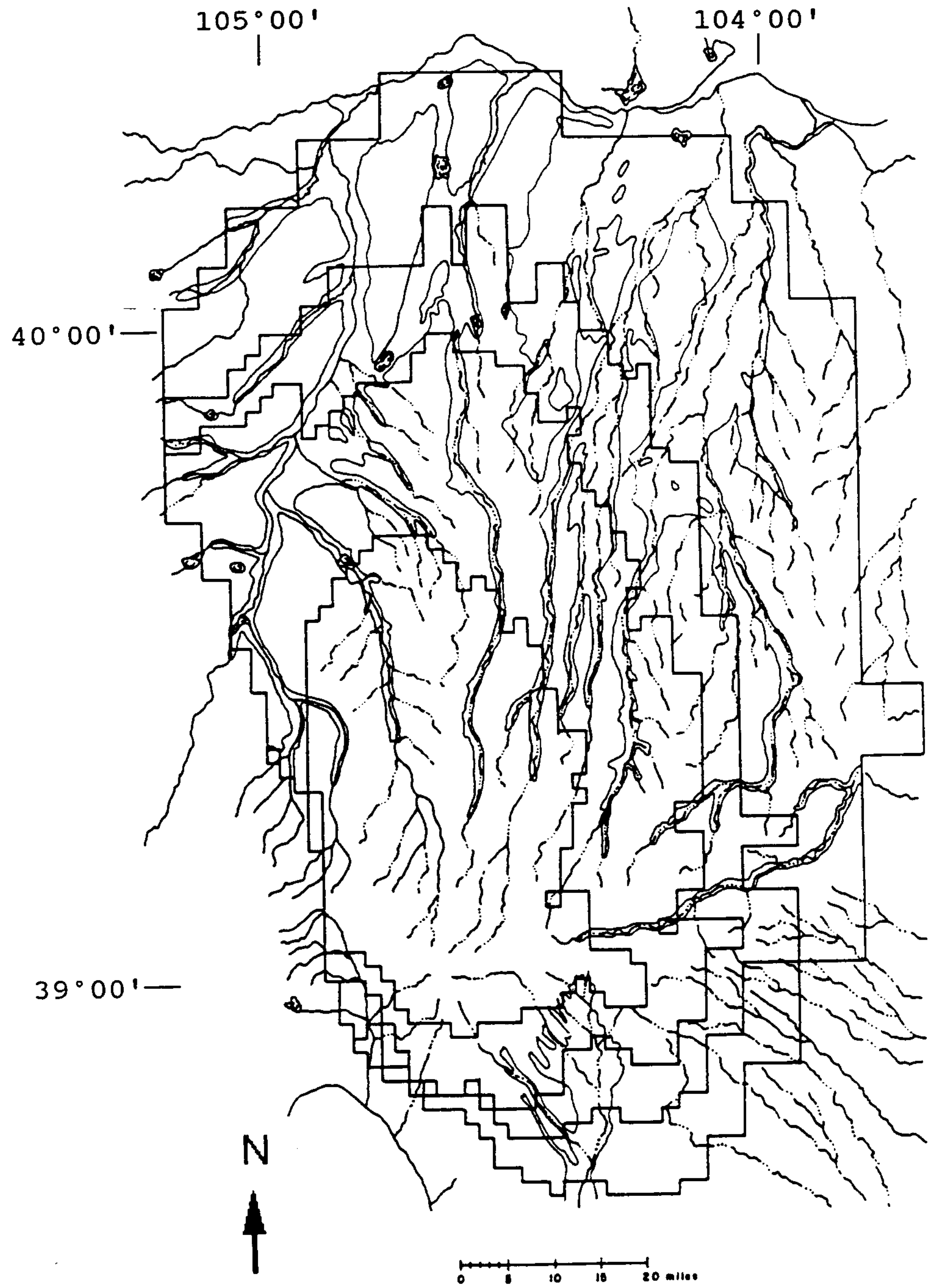

Figure 5. Drainages of the Denver Basin with outlined bedrock aquifers (after Schenk and Poeter, 1990)

published data for each layer and grid block represented in the model. These parameters include thickness, starting head, storage coefficient, specific yield where appropriate, hydraulic conductivity and transmissivity, recharge, and vertical conductance between layers. The same parameters are estimated for alluvial reaches as well. Alluvium in the model is represented explicitly in the RIVINT module, or implicitly by assigning properties representative of alluvium to individual grid cells. River data from published reports on surface water hydrology in the Denver Basin are used to approximate channel geometry, river bed properties, and stream discharge rates for streams modeled in this study. Fixed head grid blocks are used to simulate springs, lakes, and rivers where they are not included in the RIVINT package. The reader is referred to Schenk and Poeter (1990) where details on the method used to approximate the hydrologic system are explained and the complete set of input data are provided. A magnetic disk containing the calibrated input files is contained in this report. Model simulations were performed on an IBM RS 6000 work station. The MODFLOW code was compiled for use in the UNIX (AIX version) environment. The dimensions of the X array were increased to accommodate the large size of this Denver Basin model.

Calibration

The hydraulic parameters used in the Robson and the Schenk and Poeter model, did not yield a satisfactory simulation of the basin. Transient simulations which represented the estimated pumping history of the basin through 1978, predicted aquifer heads that were higher than measured heads by as much as several hundred feet throughout the northern portion of the basin. Discrepancies were most pronounced in the two upper-most aquifers, the Dawson and Denver aquifers. In addition, river discharge rates based on model predicted baseflows were higher than the measured discharge at several gaging stations. Before the model could be used to make reliable predictions of changes in aquifer heads and stream baseflow in response to ground-water withdrawal during droughts, calibration of the model was required to obtain an acceptable representation of initial hydrologic conditions in the basin.

This study began with calibration of the Schenk and Poeter model so that predicted heads and stream flows matched those measured in the field. Predicted heads were calibrated against 1978 potentiometric surface maps for each aquifer. Predicted river baseflows were compared with average stream discharge rates for those streams where data were available. Hydraulic parameters in the model were adjusted to allow more accurate prediction of heads and baseflows. By adjusting hydraulic parameters and comparing predicted results with the measured heads and baseflows in an iterative manner, an acceptable model of the basin's hydrologic system was attained.

<u>Modifications to Recharge</u>. Among the hydrologic parameters in the Banta and the Schenk and Poeter models that were adjusted for this study was the recharge rate applied to the upper-most aquifers. The recharge rate was increased across the northern Dawson and Denver aquifers from zero to approximately 0.05 to 0.1 inches per year because it seems likely that some recharge to bedrock aquifers should occur in these areas. These recharge rates are less than 1% of the precipitation which falls on the area. Increases in the recharge rate of 1% to 2% were made to Banta's original rate in the southern portion of the Dawson aquifer along the Palmer Divide, a topographic high in the southern portion of the basin, in order to bring heads up to measured levels in this localized area. Precipitation is 18 to 20 inches per year (Hansen, Chronic, and Matelock, 1978) in this area and expected recharge to bedrock aquifers is as much as 2 inches per year. Recharge was also added to grid blocks

representing explicit alluvium along streams where none had been previously applied.

Modifications to Rivers and Alluvium. The simulation of streams and associated alluvium was improved by adding explicit alluvium along upper reaches of Plum Creek and Cherry Creek. Explicit alluvium is represented in the RIVINT river simulation package by specifying the exact dimensions and hydraulic parameters of individual reaches of alluvium as described by Schenk and Poeter (1990). Implicit alluvium was added to the model to represent alluvium along lower reaches of Plum Creek, Cherry Creek, and the S. Platte River from Chatfield Reservoir to the confluence with Clear Creek. Implicit alluvium is used in places where alluvium is nearly as wide or wider than the grid block and is simulated by a series of grid blocks in the model. The addition of implicit and explicit alluvium to the model provides a more realistic simulation of the draining effect that alluvium associated with streams has on the underlying bedrock aquifers.

In the earlier version of the model, recharge had been applied to explicit alluvium along stream reaches at rates that ranged from about 11 in/yr to 14 in/yr. This reflected the assumption that with the higher hydraulic conductivities and appreciable overland flow expected with alluvium, recharge rates to alluvium would be among the highest in the basin. An estimation of evapotranspiration rates in these stream valleys, however, had not been introduced into the model. It was hypothesized that because of the presence of phreatophytes along these drainages, there may be considerably less total recharge reaching the saturated zone of the alluvium. Recharge was decreased along stream reaches in areas thought to have high evapotranspiration rates and the results were favorable. In order to simulate the depressed bedrock aquifer potentials along streams, negative recharge was specified for the alluvium in some areas. In summary, the assumptions concerning the nature of alluvial recharge were altered such that the evapotranspiration rate is assumed to be greater than the infiltration rate along some reaches of alluvium. Consequently, in the calibrated version of the model, recharge to alluvium was decreased to a range of -0.03 to -11.3 in/yr along reaches of Plum Creek, Cherry Creek, Box Elder Creek, Kiowa Creek and upper portions of the South Platte River.

Minor changes were also made to streamflow parameters. River flow entering from outside of the model into the headwaters of Cherry Creek and Kiowa Creek was reduced by 1.5 and 0.5 cfs respectively.

<u>Modifications to Bedrock Hydraulic Parameters</u>. The potentiometric surfaces of bedrock aquifers are depressed below streams in the basin. These troughs in the potentiometric surface are most pronounced along the larger streams in the basin such as the S. Platte River, Cherry Creek, and Plum Creek. To obtain these depressed potentials from model predicted heads, hydraulic conductivity of the bedrock aquifers was increased gradationally toward those streams. Increases were made in grid blocks directly under a stream and one grid block to either side, thus producing a band of higher hydraulic conductivity (K) some 4.5 miles wide along major streams (S. Platte River, Plum Creek, and Cherry Creek). This higher K band is only 1.5 to 3.0 miles wide along minor streams (Box Elder Creek, Kiowa Creek, and Sand Creek) and along the headwaters of major streams. Hydraulic conductivity is as much as a factor of 10 above the surrounding value of hydraulic conductivity along reaches of Plum Creek. In other areas hydraulic conductivity below the streams are on the order of 2 to 6 times greater than surrounding hydraulic conductivities.

<u>Results of the Calibrated Model</u>. Predicted heads from the final calibrated version of the model are compared with measured 1978 potentiometric surfaces of Denver Basin bedrock aquifers in Figures 6, 7, 8, 9, and 10 for each of

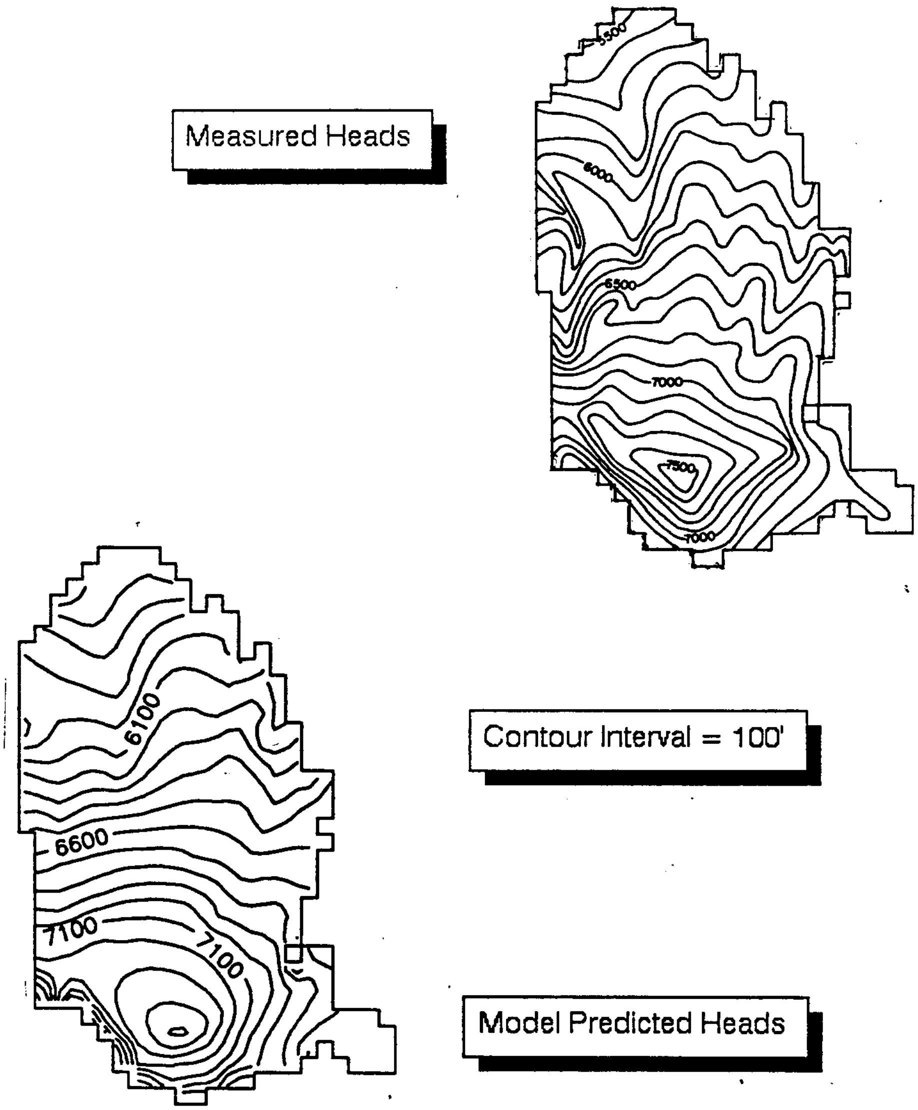

Figure 6. Comparison of measured and model predicted 1978 potentiometric surface of the Dawson aquifer (Location of the aquifer is given in Fig. 4)

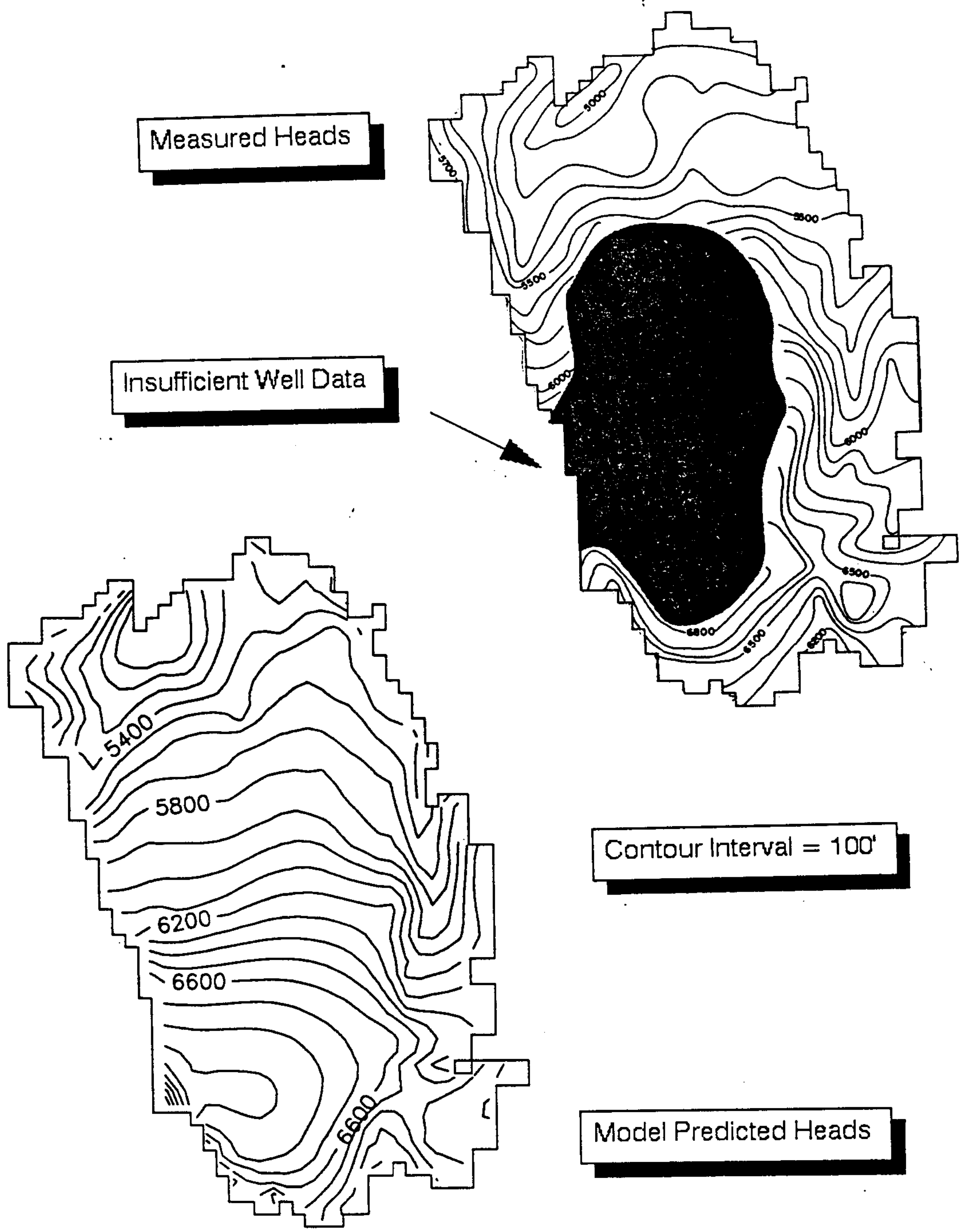

Figure 7. Comparison of measured and model predicted 1978 potentiometric surface of the Denver aquifer (Location of the aquifer is given in Fig. 4)

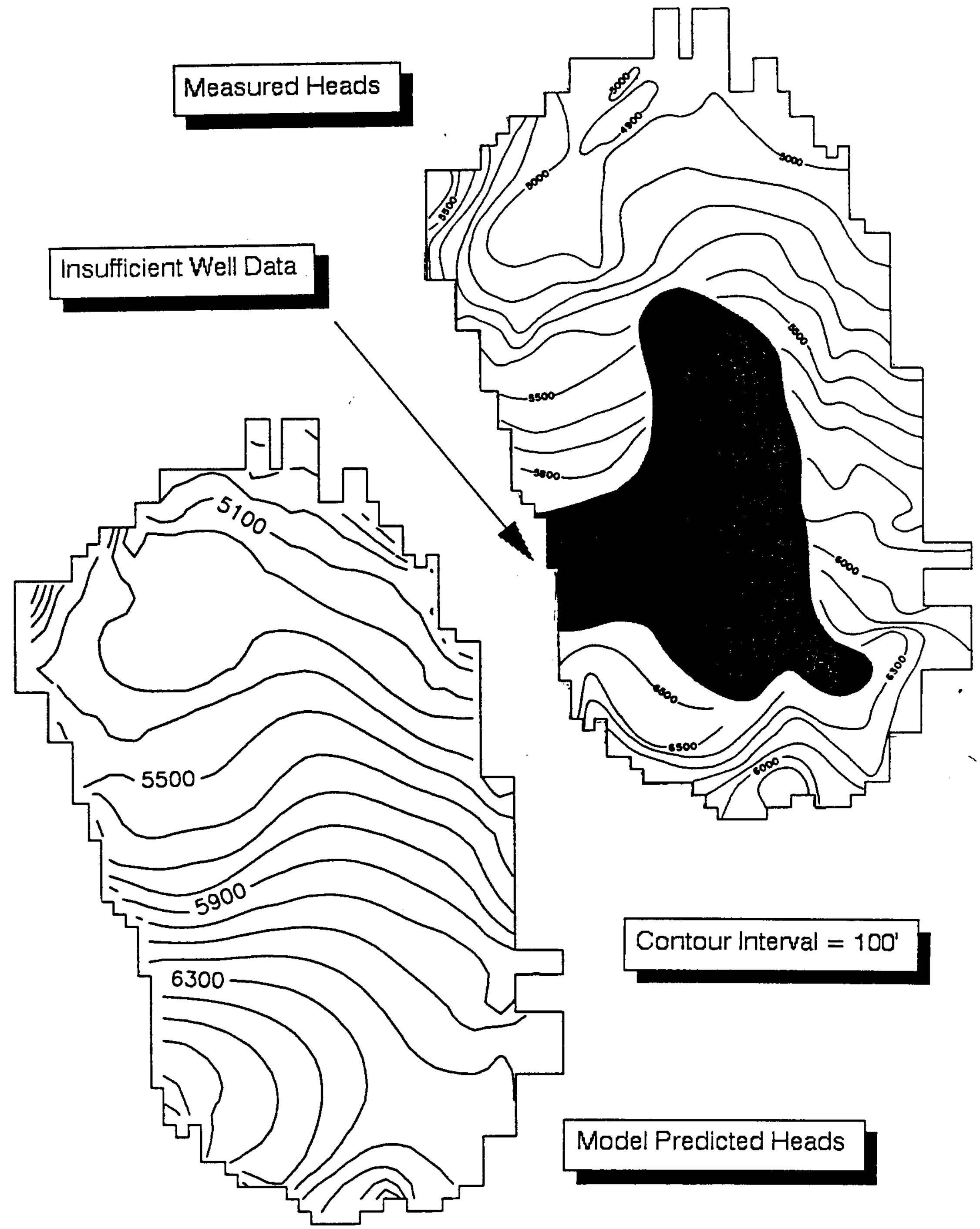

Figure 8. Comparison of measured and model predicted 1978 potentiometric surface of the Arapahoe aquifer (Location of the aquifer is given in Fig. 4)

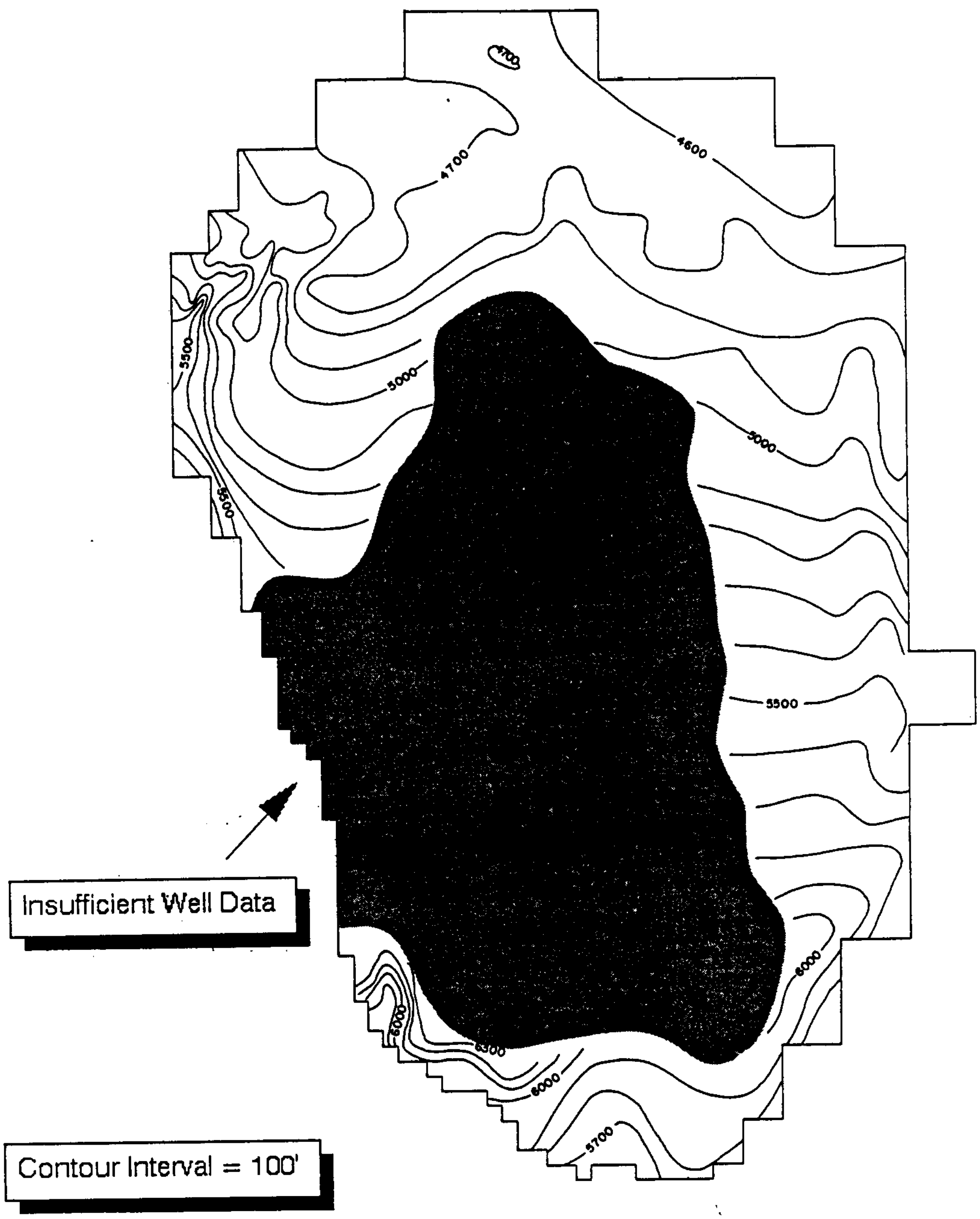

Figure 9. Measured 1978 potentiometric surface of the Laramie-Fox Hills aquifer
(Location of the aquifer is given in Fig. 4)

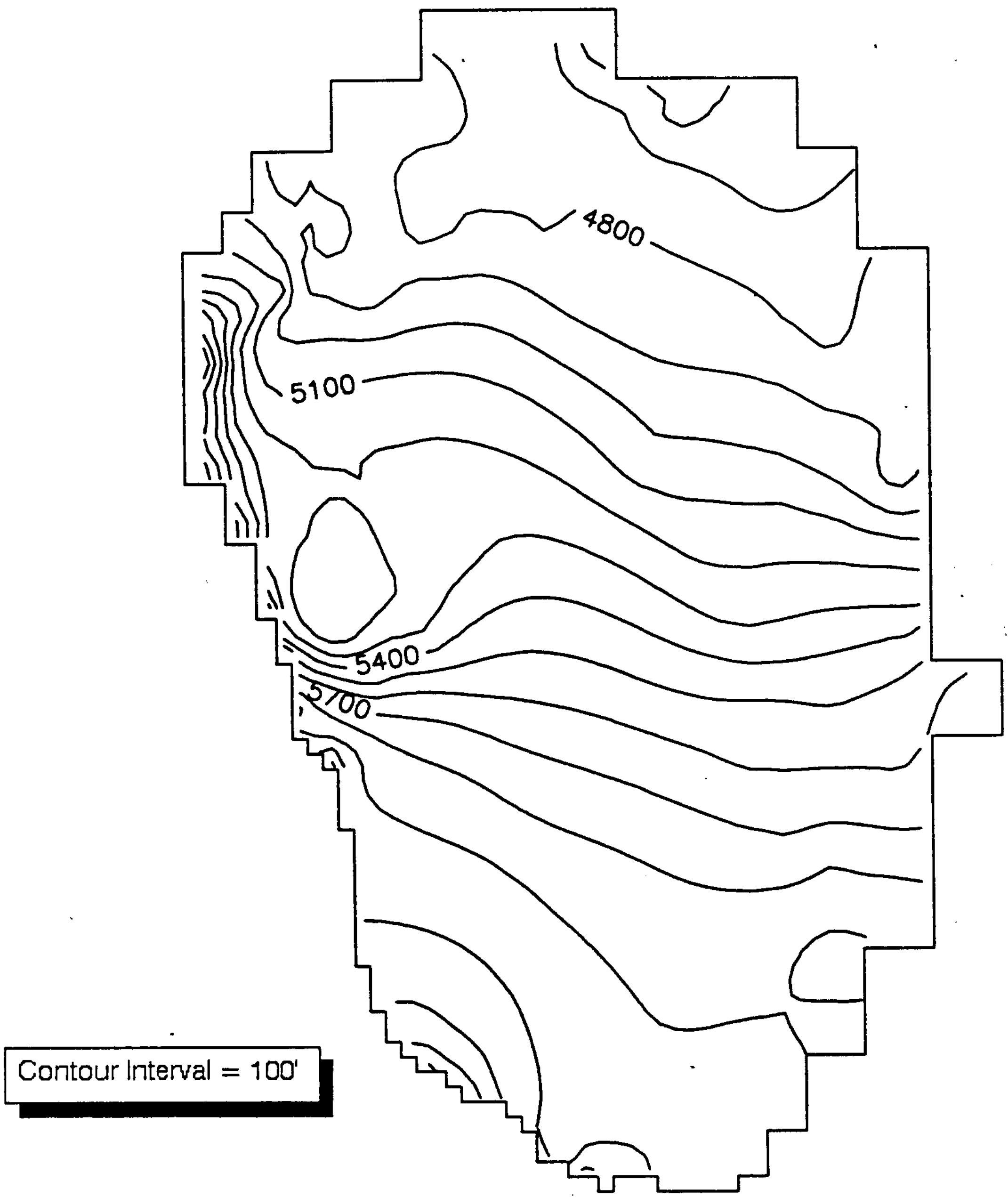

Figure 10. Model predicted 1978 potentiometric surface of the Laramie-Fox Hills aquifer (Location of the aquifer is given in Fig. 4)

the basin's four bedrock aquifers. The calibrated model predicts heads that are closer to observed heads than earlier models, but heads in the northern portion of the basin remain somewhat too high in the Dawson and Denver aquifers. The discrepancy is at most 100 feet in a few localized areas. Definition of the potentiometric surface has been improved, especially along stream channels. The sharp decline in heads along stream valleys exhibited on the 1978 map has not been exactly duplicated by the model, however, some depression of head occurs along trends which follow streams.

Stream baseflows are also lower than those predicted by earlier models. Simulated 1978 average annual stream baseflow after calibration, is compared with average annual measured flow (Petsch, 1979; Norris, et al. 1985) at several gaging stations in Table 1. River reach numbers are those assigned to the associated reach in the model. Prior to calibration, most simulated flows were greater than measured flows. This was particularly evident on Kiowa Creek and West Monument Creek. Although predicted baseflows are somewhat higher than measured flow at some stations, the differences are acceptable for this study. Simulated aquifer heads which are higher than field measurements in

Table 1. Measured and simulated stream discharge rates for select river reaches

River Reach Number	Gaging Station Description	Location on Grid (row,column)	Measured Average Annual Total Stream Flow (cfs)	Simulated Average Annual Base Stream Flow at 20 years (cfs)
30	West Monument Creek at U.S. Air Force Academy	53,13	2.9	4.4
33	West Monument Creek at Pikeview	54,12	0.8	2.0
76	Plum Creek near Sedalia	31,7	32.0	21.2
79	Plum Creek near Louviers	28,5	28.7	21.4
115	Cherry Creek near Franktown	32,15	8.6	9.2
122	Cherry Creek near Melvin	25,13	11.8	10.9
166	S. Platte River at Henderson	10,10	367	289
213	Kiowa Creek at Elbert	43,23	0.9	1.0
223	Kiowa Creek at Kiowa	33,25	3.8	4.75

certain localities are thought to contribute to the elevated baseflow predictions along some stream reaches.

The final calibrated version of the model is a reasonable representation of the natural hydrologic system. However, this configuration is not unique in its ability to represent the system. If the full uncertainty associated with the subsurface parameters were evaluated, numerous different, but feasible, combinations of parameters could yield just as close, or closer, calibration than obtained in this study. Unceratinty analysis is beyond the scope of this study, but should be considered before reaching conclusions on the feasibility of drought alleviation pumping.

In this study, the parameters that are best defined by field data are lateral hydraulic conductivity and specific yield. Values for vertical hydraulic conductivity and recharge are less reliable and were determined during early attempts at calibration. Existing pumpage from the basin and storage coefficient were assessed by estimation techniques. Municipal pumpage was based on pumpage records from municipal agencies; domestic pumpage was estimated based on a per capita use of 175 gal/d and census records for areas served by domestic wells; commercial, industrial, and irrigation pumpage were estimated based on average yield of wells in this category (Robson, 1987). Confined storage coefficient was estimated by relating the compressibility of rocks similar to those in the Denver Basin (Fatt, 1958; Clark, 1966) to the expected release of water from aquifer storage due to compression in Denver Basin aquifers. A discussion on improving the calibration of this model can be found in the "Recommendations For Future Studies" section of this paper.

DROUGHT CYCLES

Drought Definition Criteria

Accurate prediction of drought severity and duration is a difficult task. Considerable disagreement exists concerning the concept of drought among researches in different disciplines. Approaching the problem from a disciplinary perspective, Subrahmanyam (1967) has identified six types of drought: meteorological, climatological, atmospheric, agricultural, hydrologic, and water-management.

In this study, a definition of drought was sought that would delineate the meteorological and hydrologic conditions that lead to a water-management drought.

Drought definitions may be categorized as either conceptual or operational, with conceptual referring to definitions given in general terms to identify the boundaries of the concept of drought (Wilhite and Glantz, 1985). A conceptual definition of drought is "an extended and unusual period of dryness". Operational definitions go further in an attempt to identify the onset, severity, and termination of drought episodes. For this study, an operational definition was sought that would take into account variation in precipitation, evapotranspiration rates, streamflow, snowpack, and reservoir storage.

In Colorado, three methods of forecasting drought are used: the Palmer Drought Severity Index, the Surface Water Supply Index, and snowpack measurements (CWRRI, 1990) Evaluation of these indices provides the best immediate prediction of the onset of drought and its relative severity. The Palmer Drought Severity Index (PDSI), which is a soil moisture budget, is published weekly for each state and is the most widely used drought index in the United States. For wet conditions, the PDSI is positive; for dry conditions index values are negative. The index is accurate only in relative terms and is useful in highlighting drought periods relative to normal periods,when comparisons are made over long intervals. Application of the PDSI is limited because it does not include an assessment of snowpack conditions, nor consider the contributions to recharge of the hydrologic system made in areas where agricultural irrigation takes place.

The Surface Water Supply Index (SWSI), was designed specifically by the State Engineers Office for assessing drought conditions in Colorado's river basins. Using a weighted-probability formula, the effects of snowpack, streamflow, precipitation, and reservoir storage are combined to calculate the SWSI every month for each of Colorado's seven major river basins: the South Platte, Arkansas, Rio Grande, Gunnison, Colorado, Yampa/White, and San Juan and Dolores/Animas. Positive SWSI values denote wet conditions; negative values indicate dry conditions. A disadvantage to using the SWSI is that the relative importance of each factor used in calculating the index is difficult to assess and carry-over moisture in river basin soils is not considered.

Use of only one of these indices to define drought periods in the Denver Basin would be inadequate, since neither index includes an appraisal of all hydrologic and meteorological factors affected by drought in this portion of the state. Therefore both the PDSI and SWSI are used conjunctively. For purposes of modeling droughts in the Denver Basin, a drought is defined as the period of time when the Palmer Drought Severity Index for Colorado is -2 or less and the Surface Water Supply Index for the South Platte River basin is also -2 or less. By using both indices, a measure of soil moisture conditions statewide (PDSI) is coupled with an assessment of hydrologic conditions in the South Platte River basin (SWSI), which makes up a considerable portion of the Denver ground-water basin.

Once the criteria for a drought period had been established, an estimation needed to be made of the frequency and duration of future drought periods. Pumping during droughts could then be realistically simulated by projecting drought periods which met those criteria into the future. A reasonable prediction of future droughts was made by examination of historical records. The 40 year period from January 1948 through December 1987 was chosen for analysis because meteorological data for this period were complete. In addition, one of the most significant droughts from a water management perspective occurred in Colorado during the mid 1950s. The response of the basin to pumping during a drought of this magnitude would be of interest to water planners. Several minor droughts are represented in this 40 year interval as well.

Six drought periods were identified as per the criteria listed above: '53-'54, '62-'63, '71-'72, '76-'77, '80-'81, and '84-'86. All of the drought periods, with the exception of the last, have a duration of 2 years. It was not determined if droughts that meet the specified criteria are most likely to occur with a duration of 2 years, or if this 2 year duration pattern is specific to the 40 year interval chosen. Droughts occurred less frequently in the early portion of the 40 year interval (about once every decade), and more frequently during the last half (about twice every decade). Though the 40 year interval chosen does not contain a severe drought of lengthy duration such as occurred during the 1930s, it does provide a reasonable representation of the mild to moderate droughts that the basin could experience in the next 40 years. This cyclic pattern of drought and non-drought was subsequently imposed on the basin model to represent a possible scenario for the period 1990 to 2029. In Chapter 5, a more detailed explanation is given of how the droughts were simulated with the basin model during the 40 year interval beginning in 1990.

Water Needs During Drought

Reasonable withdrawal rates to supplement the supplies of the City and County of Denver during the modeled drought periods were arrived at by examination of Denver Water Department records (Schmitzer and Waage, 1990). Yearly and monthly records of water use, water supply, reservoir storage, and change in storage were compiled for the 40 year period 1948 to 1987. Analysis of the behavior of these four important factors preceding, during, and following a drought period, allows an assessment to be made of the rate of withdrawal and the duration of pumping required to mitigate the effects of that drought. In a monthly format, these data were used to examine seasonal variations during the 40 year interval. Presentation of data as yearly averages, more clearly delineates drought periods of the previously defined severity and duration. Figure 11 shows the monthly supply of water for the Denver Water Department from 1950 to 1980. Note that seasonal fluctuations are apparent and reflect higher volumes of supply in Spring and Summer months. The change in supply that occurs during a drought is not as evident in Figure 11 as it is in Figure 12 where yearly supply is plotted for the 40 year interval.

During the onset of a drought period, water supplies decrease as runoff from snowpack and precipitation diminish.

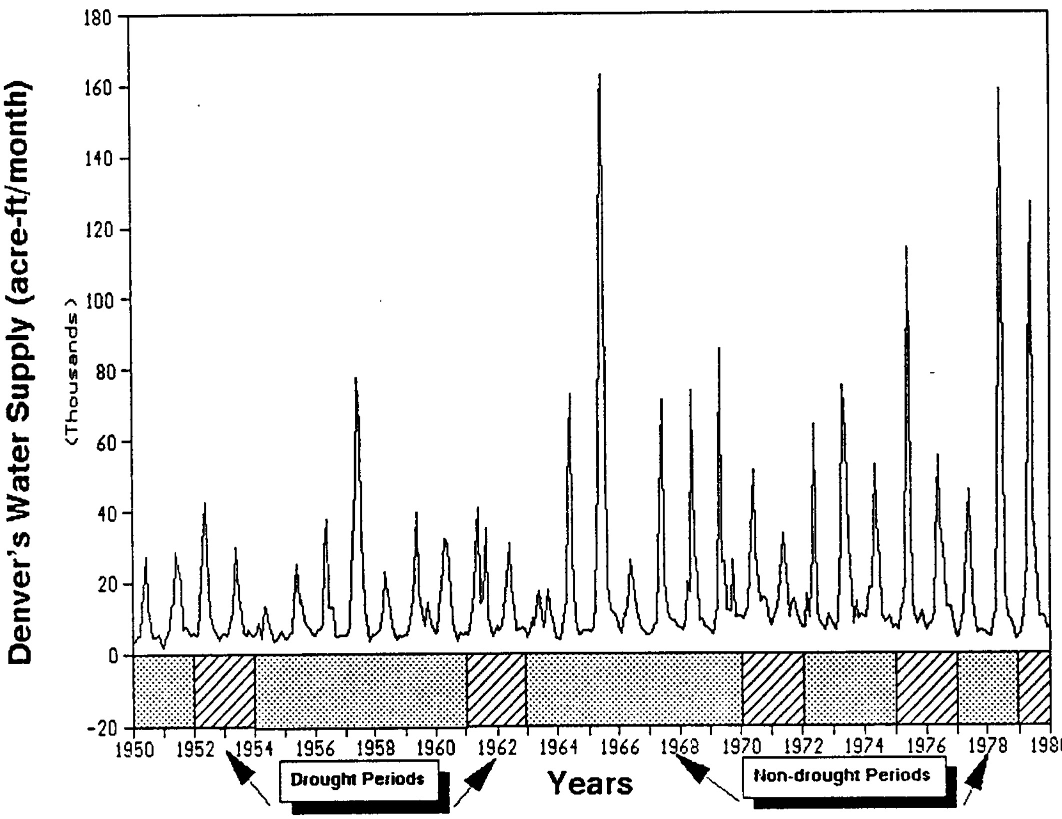

Figure 11. Denver's monthly water supply from 1950 to 1980

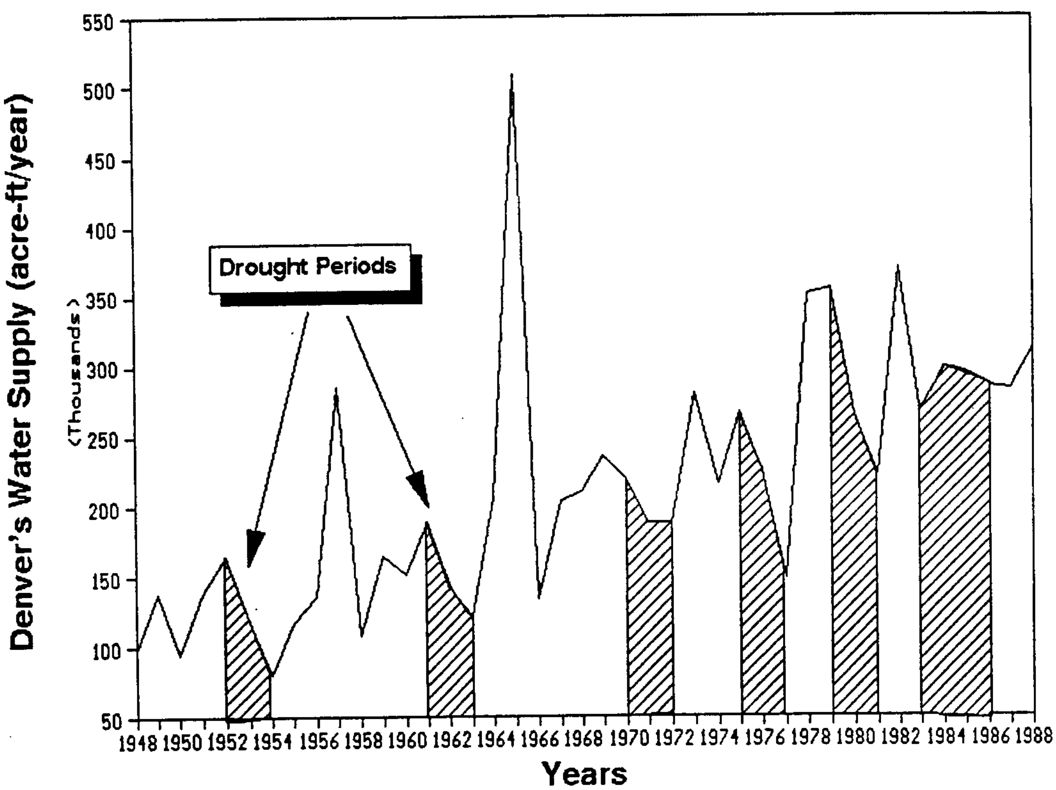

Figure 12. Denver's annual water supply from 1948 to 1988

Figure 12 shows the decline of Denver's water supply in acre-feet/yr for each highlighted drought period. Water supplies plotted in Figure 12 are the yearly volumes of water entering the raw water supply system. Conversely, as show in Figure 13, annual water use in Denver increases during droughts. Elevated use is greatest during summer months when irrigation of lawns in the metropolitan area is common. As would be expected, reservoir storage declines as both increased use and decreased supplies act to drain water stored in the city's reservoirs. The magnitude of decline for each drought is shown in Figure 14.

Over the 40 year interval, supplies have gradually increased as new supplies were acquired through diversions or by other means. Reservoir storage has continually been augmented when new reservoirs have come into operation. Water use has grown steadily with increasing population. Because of these changes over time, assessment of additional water required by the city during drought based on an absolute comparison between water supply and water usage would be misleading. An examination of change in reservoir storage during drought periods is more informative and permits a more useful assessment of water needs during future droughts. The yearly change in reservoir storage for the 40 year interval 1948 to 1987 is presented in Figure 15.

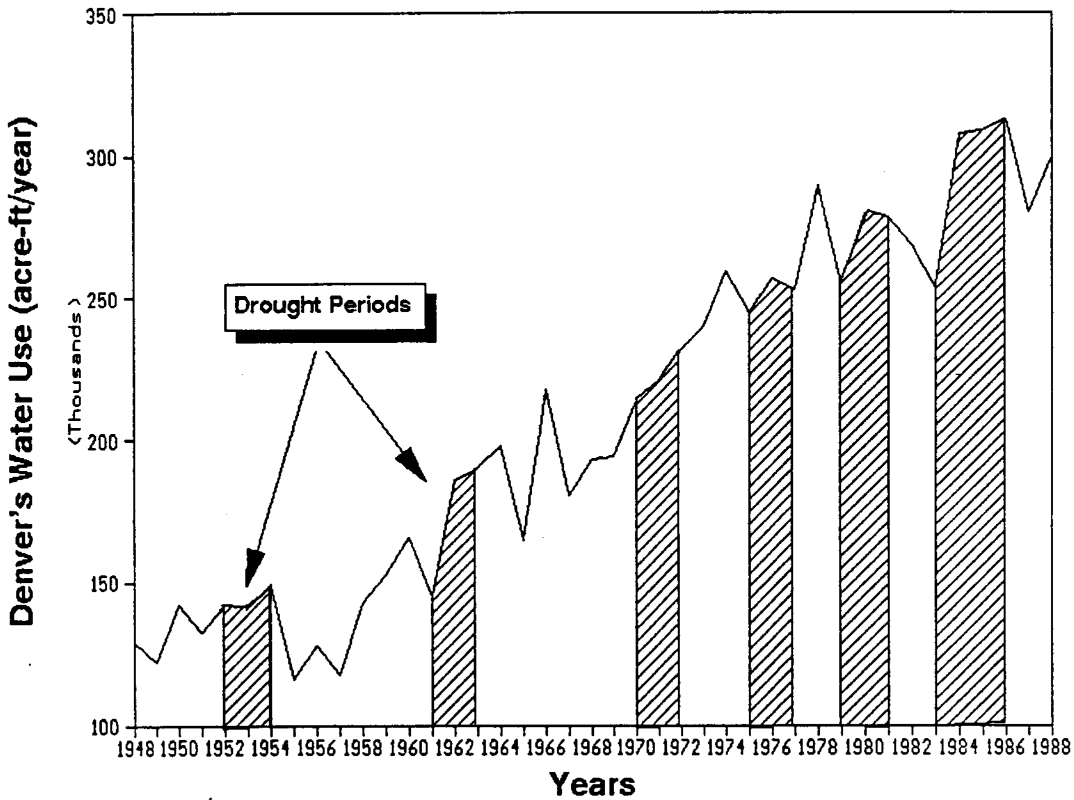

Figure 13. Denver's annual water use from 1948 to 1988

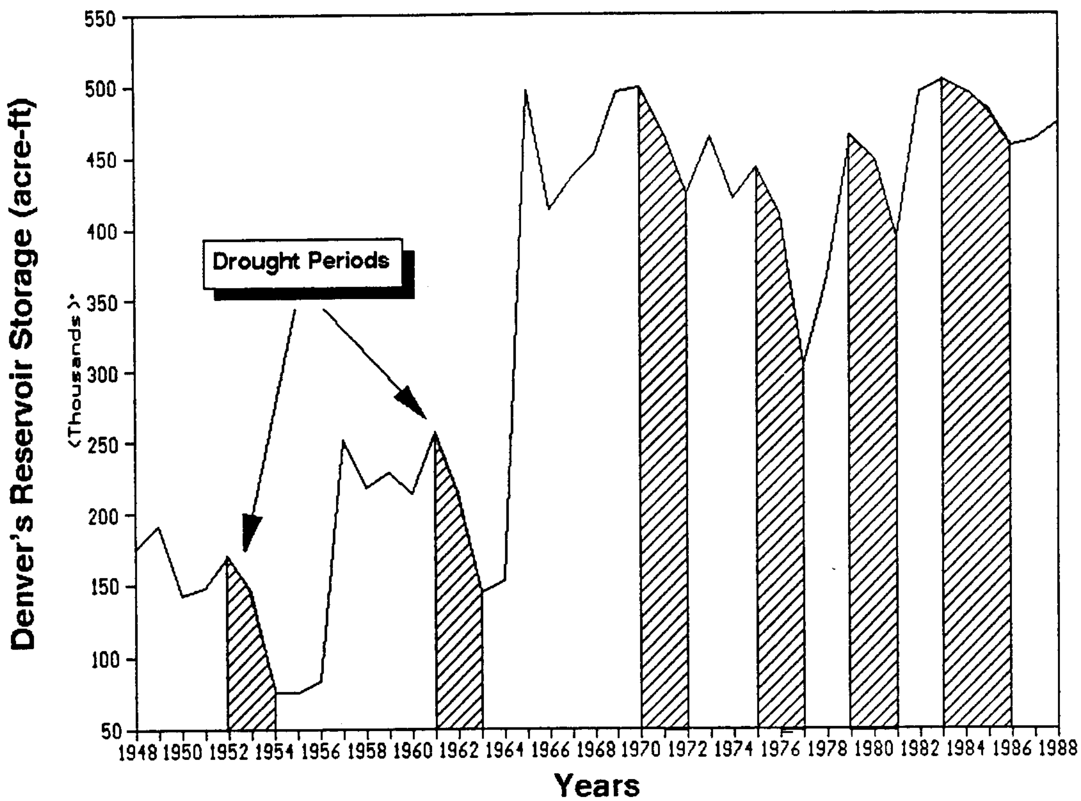

Figure 14. Annual reservoir storage in Denver Water Department reservoirs from 1948 to 1988

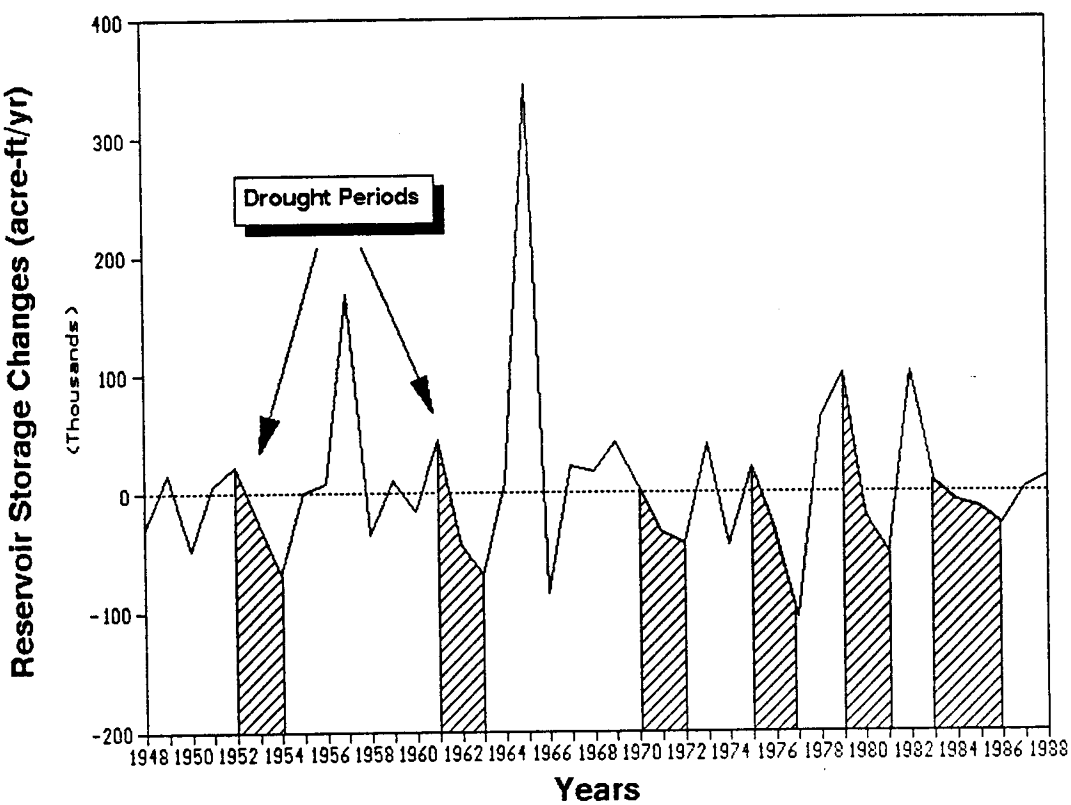

Figure 15. Annual changes in reservoir storage from 1948 to 1988

Change in reservoir storage is the difference between water use and water supply. The cumulative change in reservoir storage over the 40 year period is on the order of +270,000 acre feet. This reflects the fact that increase in storage capacity and available supplies have out-paced usage.

Figure 15 demonstrates that a period of drought always results in a net negative change in reservoir storage. The magnitude of this decline is similar regardless of when, during the 40 year historical period, the drought occurs. Therefore, from a water management viewpoint, a net negative change in reservoir storage for more than one consecutive year could be an indicator of drought. During a drought, storage must be maintained above a minimum acceptable level. Proposed drought alleviation pumping scenarios should meet this requirement. To maintain a reasonable margin of safety during each drought period, it is also desirable to eliminate net negative change in storage during drought years.

Changes in reservoir storage for the six drought periods identified earlier were tabulated. The average annual pumping rate required to maintain reservoir storage during drought periods was calculated. That is, the total water withdrawn during the year would equal the difference between water use and supply for each year in the drought period. Thus there would be no change in reservoir storage throughout the drought.

Recharge Fluctuations

Recharge to the basin's aquifers declines during a drought. In previous model studies of the Denver Basin, a constant average annual recharge was simulated. Using a constant average annual recharge rate is an acceptable manner in which to model recharge when a long term transient simulation is conducted and average impacts at the end of the simulation versus short term variability are of interest.

In this modeling study, however, predicted results during a transient simulation, particularly at the end of a drought period as well as following a non-drought interval, are of great interest. Therefore, incorporation of a reduced recharge rate was simulated during drought periods permitting a more realistic simulation of conditions during those intervals and hence more accurate results. The recharge module in MODFLOW was modified to facilitate input of annual variation of recharge rate. Recharge for drought and non-drought periods is calculated as the average annual recharge multiplied by the annual precipitation for either the drought or non-drought year, divided by the average annual precipitation. The modified recharge module code is provided in Appendix A. The recharge input package contains the average annual recharge array. In addition, the ratio of drought or non-drought interval annual precipitation to average annual precipitation, is input for each stress period as shown in the recharge module input format in Appendix B. By allowing variation of recharge in drought and non-drought periods, the recharge applied throughout the simulation should be the average recharge. Input data for recharge fluctuations during model simulations are provided in the Drought Simulation Input section.

WELL FIELD DESIGN

Site Selection Criteria

A satellite well field was designed to accommodate the withdrawal rates from the Denver Basin bedrock aquifers that had been estimated based on water needs during a drought. The site for the satellite well field was chosen based on four criteria: 1) all four aquifers must occur at the site in order to lessen the impact of pumping on heads in any particular aquifer; 2) saturated thicknesses and available drawdown should be among the greatest in the basin; 3) estimated transmissivities must be acceptable for pumping at these relatively high rates; and 4) the site should be close enough to the Denver metropolitan area to allow delivery of pumped water into the raw water supply system.

The area chosen for the satellite well field is approximately 6 miles southeast of Parker, Colorado as shown in Figure 16. The 36 square mile well field is 1.5 miles east of Cherry Creek and 1.5 miles west of Running (Box Elder) Creek at its closest point. The selected areal extent of the well field is a result of compromising between the needs of minimizing local drawdowns and limiting the distance between wells for construction and management purposes.

Well Field Simulation

To facilitate the design, the well field simulator WESTWEL (Kraeger-Rovey, 1989) is used to estimate drawdowns at the pumping wells for reasonable numbers and spacings of wells. This analytical model, which superimposes numerous Theis solutions, is used to estimate drawdown at the pumping wells because the numerical model does not indicate drawdown at the well bore, rather it represents the average drawdown over a large area (the 2.25 square mile MODFLOW grid block). The desire to limit the number of wells is balanced against the need to minimize drawdown, and still achieve the required pumping rate. Initial results from WESTWEL simulations indicated that 36 wells arranged on the

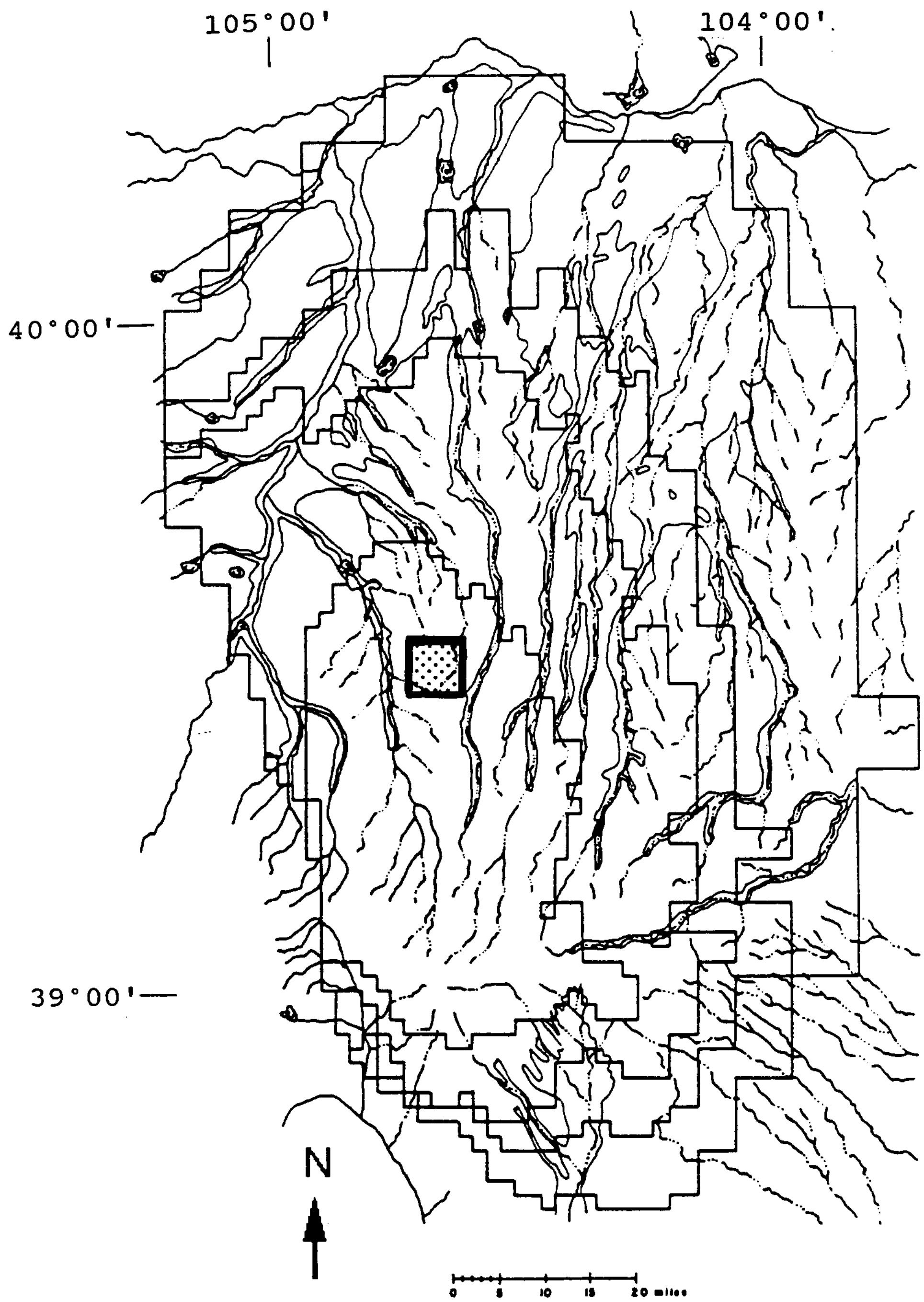

Figure 16. Site of the proposed satellite well field

perimeter of a square pattern would produce acceptable drawdowns in the vicinity of the well field (Figure 17). This pattern, without wells at the center of the field, was chosen to minimize drawdowns at the center of the well field. Wells arranged with wells within the square perimeter produced drawdowns that were 10 percent greater at the center of the well field. Three wells per 2.25 square mile grid block are arranged in an offset pattern as shown in Figure 17. Also provided in Figure 17 are the well field dimensions which show that the closest wells in the field are 0.5 miles apart.

The drawdowns resulting from pumping in the well field, were estimated in separate WESTWEL simulations for each aquifer. Average values for hydraulic conductivity and storativity in the vicinity of the proposed well field were input to the well field simulator for the 3 upper-most aquifers as shown in Tables 2, 3, and 4. Insufficient bottom elevation data from the Laramie-Fox Hills (LFH) aquifer prevented the LFH aquifer from being simulated with WESTWEL. Estimates of available drawdown and transmissivity were used to calculate a maximum withdrawal rate of 6 cfs from the Laramie-Fox Hills aquifer. Approximations of the length of pumping time and total discharge rate needed to alleviate the effects of the six identified drought periods,

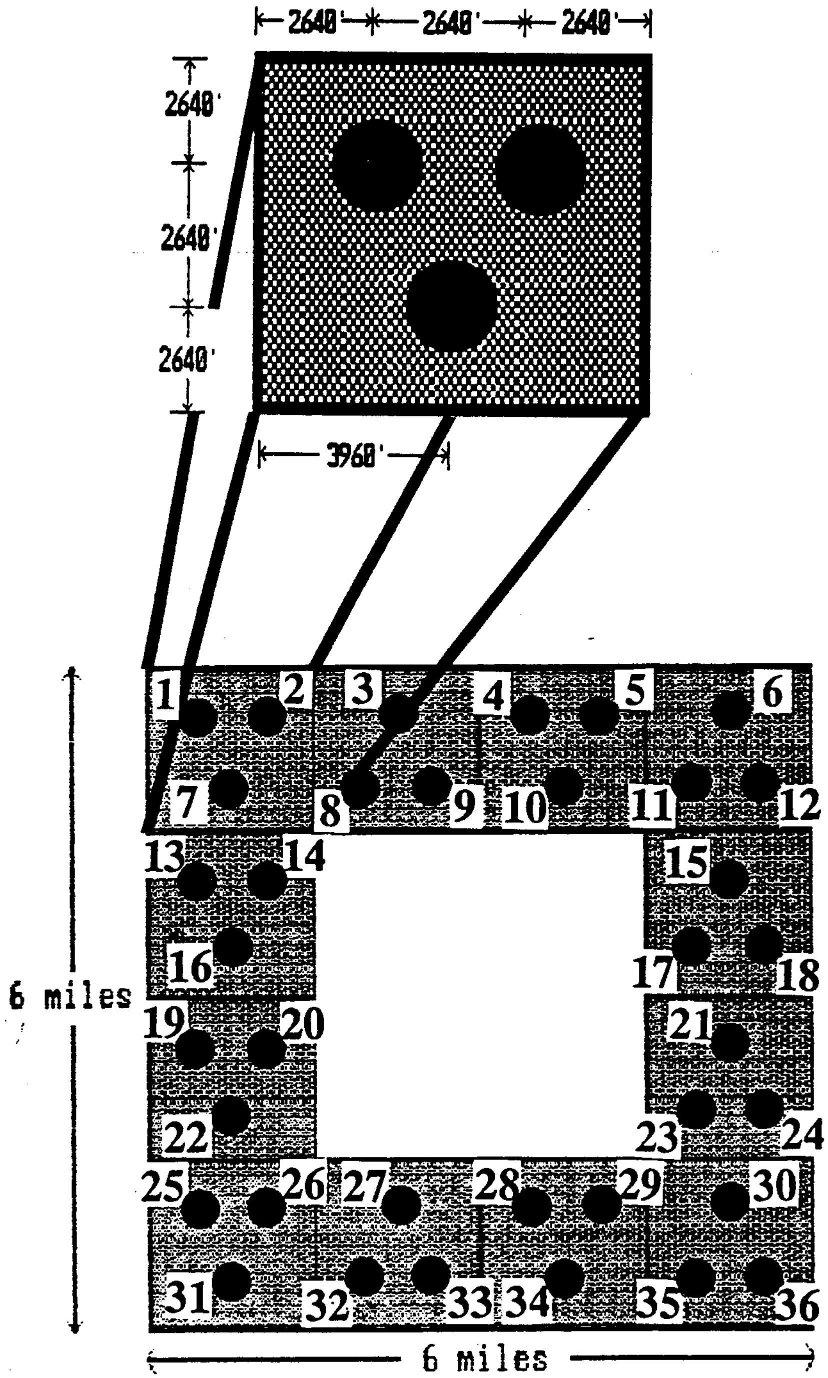

Figure 17. Well field configuration and dimensions

Table 2. Well simulation data for the Dawson aquifer

Storage Coefficient = 0.0005	Total Aquifer Pumping Rate = 7 cfs
Well Radius = 1.0 ft.	Well Discharge Rate = 0.19 cfs
Hydraulic Conductivity = 0.8312 ft./sec.	Pumping Time = 730 days

Well Number	Aquifer Bottom Elevation (ft.)	Potentiometric Surface Elevation (ft.)	Aquifer Top Elevation (ft.)	Potentiometric Surface Drawdown (ft.)	Percentage of Initial Available Drawdown Retained
1	5400.	5918.	5900.	274.	47%
2	5400.	5918.	5900.	294.	43%
3	5409.	6015.	6013.	296.	51%
4	5590.	6084.	6100.	335.	32%
5	5590.	6084.	6100.	335.	32%
6	5710.	6101.	6160.	350.	10%
7	5400.	5918.	5900.	303.	41%
8	5409.	6015.	6013.	311.	49%
9	5409.	6015.	6013.	317.	48%
10	5590.	6084.	6100.	354.	28%
11	5710.	6101.	6160.	388.	1%
12	5710.	6101.	6160.	364.	7%
13	5360.	5950.	5950.	290.	51%
14	5360.	5950.	5950.	309.	48%
15	5697.	6135.	6220.	380.	13%
16	5360.	5950.	5950.	302.	49%
17	5697.	6135.	6220.	392.	11%
18	5697.	6135.	6220.	373.	15%
19	5400.	5995.	6000.	289.	51%
20	5400.	5995.	6000.	307.	48%
21	5756.	6177.	6270.	392.	7%
22	5400.	5995.	6000.	294.	51%
23	5756.	6177.	6270.	395.	6%
24	5756.	6177.	6270.	375.	11%
25	5460.	6048.	6050.	265.	55%
26	5460.	6048.	6050.	284.	52%
27	5552.	6160.	6160.	306.	50%
28	5700.	6198.	6256.	349.	30%
29	5700.	6198.	6256.	352.	29%
30	5764.	6213.	6310.	347.	23%
31	5460.	6048.	6050.	256.	56%
32	5552.	6160.	6160.	286.	53%
33	5552.	6160.	6160.	294.	52%
34	5700.	6198.	6256.	329.	34%
35	5764.	6213.	6310.	331.	26%
36	5764.	6213.	6310.	311.	31%
					34.5% average

Table 3. Well simulation data for the Denver aquifer

Storage Coefficient = 0.00041
Well Radius = 1.0 ft.
Hydraulic Conductivity = 0.265 ft./sec.

Total Aquifer Pumping Rate = 11 cfs
Well Discharge Rate = 0.31 cfs
Pumping Time = 730 days

Well Number	Aquifer Bottom Elevation (ft.)	Potentiometric Surface Elevation (ft.)	Aquifer Top Elevation (ft.)	Potentiometric Surface Drawdown (ft.)	Percentage of Initial Available Drawdown Retained
1	4650.	5840.	5400.	820.	31%
2	4650.	5840.	5400.	885.	26%
3	4700.	5853.	5409.	971.	16%
4	4773.	5868.	5590.	924.	16%
5	4773.	5868.	5590.	899.	18%
6	4852.	5880.	5710.	780.	24%
7	4650.	5840.	5400.	927.	22%
8	4700.	5853.	5409.	1039.	10%
9	4700.	5853.	5409.	1040.	10%
10	4773.	5868.	5590.	968.	12%
11	4852.	5880.	5710.	882.	19%
12	4852.	5880.	5710.	810.	26%
13	4670.	5872.	5360.	991.	18%
14	4670.	5872.	5360.	1055.	12%
15	4850.	5916.	5697.	910.	15%
16	4670.	5872.	5360.	1042.	13%
17	4850.	5916.	5697.	950.	11%
18	4850.	5916.	5697.	888.	17%
19	4720.	5904.	5400.	1015.	14%
20	4720.	5904.	5400.	1074.	9%
21	4869.	5962.	5756.	903.	17%
22	4720.	5904.	5400.	1034.	13%
23	4869.	5962.	5756.	919.	16%
24	4869.	5962.	5756.	855.	22%
25	4780.	5943.	5460.	922.	21%
26	4780.	5943.	5460.	992.	15%
27	4813.	5965.	5552.	1012.	12%
28	4837.	5989.	5700.	947.	18%
29	4837.	5989.	5700.	927.	20%
30	4869.	6010.	5764.	816.	28%
31	4780.	5943.	5460.	881.	24%
32	4813.	5965.	5552.	950.	17%
33	4813.	5965.	5552.	954.	17%
34	4837.	5989.	5700.	875.	24%
35	4869.	6010.	5764.	784.	31%
36	4869.	6010.	5764.	722.	37%
					18.6% average

Table 4. Well simulation data for the Arapahoe aquifer

Storage Coefficient = 0.00057
Well Radius = 1.0 ft.
Hydraulic Conductivity = 0.139 ft./sec.

Total Aquifer Pumping Rate = 14 cfs
Well Discharge Rate = 0.39 cfs
Pumping Time = 730 days

Well Number	Aquifer Bottom Elevation (ft.)	Potentiometric Surface Elevation (ft.)	Aquifer Top Elevation (ft.)	Potentiometric Surface Drawdown (ft.)	Percentage of Initial Available Drawdown Retained
1	3790.	5543.	4650.	1298.	26%
2	3790.	5543.	4650.	1414.	19%
3	3851.	5562.	4700.	1536.	10%
4	3904.	5576.	4773.	1532.	8%
5	3904.	5576.	4773.	1506.	10%
6	3959.	5604.	4852.	1308.	20%
7	3790.	5543.	4650.	1479.	16%
8	3851.	5562.	4700.	1645.	4%
9	3851.	5562.	4700.	1649.	4%
10	3904.	5576.	4773.	1610.	4%
11	3959.	5604.	4852.	1495.	9%
12	3959.	5604.	4852.	1369.	17%
13	3800.	5567.	4670.	1501.	15%
14	3800.	5567.	4670.	1608.	9%
15	3969.	5637.	4850.	1551.	7%
16	3800.	5567.	4670.	1569.	11%
17	3969.	5637.	4850.	1609.	4%
18	3969.	5637.	4850.	1513.	9%
19	3820.	5599.	4720.	1468.	17%
20	3820.	5599.	4720.	1561.	12%
21	3968.	5674.	4869.	1548.	9%
22	3820.	5599.	4720.	1497.	16%
23	3968.	5674.	4869.	1578.	8%
24	3968.	5674.	4869.	1473.	14%
25	3840.	5632.	4780.	1290.	28%
26	3840.	5632.	4780.	1405.	22%
27	3883.	5643.	4813.	1510.	14%
28	3923.	5675.	4837.	1551.	11%
29	3923.	5675.	4837.	1548.	12%
30	3969.	5721.	4869.	1423.	19%
31	3840.	5632.	4780.	1230.	31%
32	3883.	5643.	4813.	1411.	20%
33	3883.	5643.	4813.	1434.	19%
34	3923.	5675.	4837.	1443.	18%
35	3969.	5721.	4869.	1358.	22%
36	3969.	5721.	4869.	1248.	29%
					14.5% average

were input to WESTWEL. In order to determine maximum allowable pumping rates the following criteria were established: 1) a majority of wells in the field must retain approximately 20 percent of the initial available drawdown by the end of a drought pumping period, and 2) no wells should go dry over the course of a drought. WESTWEL simulations were made by varying the discharge rate on successive simulations and assessing whether the well field criteria were met. In this manner, a maximum permissible pumping rate was calculated for each of the 3 upper-most aquifers. Those pumping rates were: 7 cfs in the Dawson aquifer, 11 cfs in the Denver aquifer, and 14 cfs in the Arapahoe aquifer. When combined with the earlier estimate for maximum permissible pumping from the Laramie-Fox Hills aquifer of 6 cfs, the total maximum allowable pumping rate from the well field during a two year drought was 38 cfs. Each well, drawing from all four aquifers, pumps at a rate of about 475 gpm. The drawdown and percentage of initial drawdown retained for each well, are presented in Tables 2, 3, and 4 for the Dawson, Denver, and Arapahoe aquifers respectively.

Results of the analytical model revealed that the well field criteria could not be met at the pumping rate required to prevent loss of reservoir storage during drought. During a number of the identified drought periods, the annual change in reservoir storage was less than -27,454 acre-ft, the yearly volume of water that would be replaced by pumping the well field at 38 cfs. Figure 15 shows that in 1977 there was a change in reservoir storage of about -106,000 acre-ft (a volume that could only be replaced by pumping at about 146 cfs for one year). Adopting a pumping rate of 38 cfs meant that reservoir storage would decline during some drought years. However, this rate will provide a significant contribution to water supplies during drought. The adjusted change in reservoir storage that results from adding the water pumped from the well field at 38 cfs to Denver's water supply, is presented for each drought year in the following section.

DROUGHT SIMULATIONS

Hydrologic input parameters were the same as in the Schenk and Poeter (1990) model except for the hydraulic property modifications outlined in the calibration section. Previous models of the Denver Basin assumed pristine hydrologic conditions at the beginning of 1958, steady basin-wide pumping at rates specified by Robson (1987) until 1978, and an increase in pumping thereafter. The simulations presented herein are structured in the same manner with the simulation beginning in 1958, however, in 1990 the 40 year interval with the six identified drought periods begins.

<u>Drought Alleviation Pumping Simulation #1 (DAPS1)</u>

The first of two drought pumping simulations was done with an annual pumping rate of approximately 38 cfs. The initial intent was to pump at a rate sufficient to eliminate net negative change in reservoir storage during a period of drought. Several drought periods involved large net negative changes in reservoir storage and given the well field criteria, a satellite well field could not withdraw ground water at the rate required to maintain reservoir storage levels. Thus in Drought Alleviation Pumping Simulation #1 (DAPS1), a constant pumping rate of about 38 cfs was adopted. This rate remains constant through each drought year, and pumping continues during successive drought years for the full duration of those years.

Pumping rates were not varied on a seasonal schedule. Pumping was assumed to commence on January 1st of drought years and cease on December 31st of the last year in the drought period. This pumping schedule may present difficulties from a water management perspective. The model does not address the protocol that would be observed by water management agencies in specifying exactly when pumps are to be turned on, once a drought period has been identified and is proceeding. To effectively implement a drought alleviation plan, a formal decision tree which includes drought pumping is required. This might follow the format of drought response arrangements that are already well established in Colorado.

Table 5 presents the DAPS1 pumping schedule. The simulated years 1990-2029 are matched with the historical reservoir storage changes that occurred from 1948 to 1987. During the first year of the 1953-54 drought simulated as occurring in 1995-96, pumping begins at 27,322 acre-ft/year (AFY) producing a net increase in storage of 2085 AF. The following year, drought alleviation pumping reduces the net negative change in storage by about 40 percent to -41,131 AF. Drought pumping follows the outlined schedule until 2029 when the simulation ends.

In most drought years, the effects are mitigated considerably but a net negative change in reservoir storage still occurs. Some years experience a positive change in storage. During these years, which are frequently at the beginning of a drought, pumping at the maximum allowable rate of approximately 38 cfs permits early mitigation of a drought that is still in its initial phase. This is a

Table 5. Input data for Drought Alleviation Pumping Simulation #1; (DAPS1)

Simulated Years	Historical Years	Yearly Storage Changes (acre-ft.)	Drought Periods (*)	Pumpage Rate (cfs) [acre-ft./year]	Recharge; Percentage of Average Annual	Yearly Storage Changes Adjusted For Pumping (acre-ft.)
1990	1948	-30719		--	100%	-30719
1991	1949	+16058		--	100%	+16058
1992	1950	-47948		--	100%	-47948
1993	1951	+4635		--	100%	+4635
1994	1952	+22555		--	100%	+22555
1995	1953	-25237	*	37.7 [27322]	97%	+2085
1996	1954	-68453	*	37.7 [27322]	47%	-41131
1997	1955	+66		--	111%	+66
1998	1956	+7614		--	111%	+7614
1999	1957	+167851		--	111%	+16785
2000	1958	-34960		--	111%	-34960
2001	1959	+11203		--	111%	+11203
2002	1960	-15133		--	111%	-15133
2003	1961	+44049		--	111%	+44049
2004	1962	-42853	*	37.7 [27322]	61%	-15531
2005	1963	-69755	*	37.7 [27322]	87%	-42433
2006	1964	+7971		--	109%	+7971
2007	1965	+344167		--	109%	+344167
2008	1966	-84194		--	109%	-84194
2009	1967	+22874		--	109%	+22874
2010	1968	+17194		--	109%	+17194
2011	1969	+42336		--	109%	+42336
2012	1970	+4742		--	109%	+4742
2013	1971	-31865	*	37.7 [27322]	78%	-4543
2014	1972	-43441	*	37.7 [27322]	74%	-16119
2015	1973	+40111		--	117%	+40111
2016	1974	-44072		--	117%	-44072
2017	1975	+21990		--	117%	+21990
2018	1976	-32309	*	37.7 [27322]	92%	-4987
2019	1977	-105731	*	37.7 [27322]	71%	-78409
2020	1978	+61377		--	107%	+61377
2021	1979	+100358		--	107%	+100358
2022	1980	-16574	*	37.7 [27322]	94%	+10748
2023	1981	-55892	*	37.7 [27322]	86%	-28570
2024	1982	+101360		--	116%	+101360
2025	1983	+8807		--	116%	+8807
2026	1984	-7542	*	37.7 [27322]	95%	+19780
2027	1985	-12205	*	37.7 [27322]	95%	+15117
2028	1986	-26257	*	37.7 [27322]	95%	+1065
2029	1987	+3494		--	100%	+3494

conservative approach to drought management as it curbs the effects of drought during the initial portions of the drought period.

Recharge to the basin's bedrock aquifers was varied during drought and non-drought periods as explained previously in the Recharge Fluctuations section. This was done to better simulate the effects of drought on the hydrologic system. Precipitation records from Denver Basin weather stations (Hansen, Chronic, and Matelock, 1978) were used to predict the percentage of average annual recharge during these periods. The recharge rate that is applied over the course of the simulation averages out to the mean recharge rate, that was applied in earlier models of the Denver Basin ground water flow.

DAPS1 Simulation Results

To assess the effects of drought period pumping, two identical simulations were conducted with the exception that the first simulation included drought alleviation pumping (DAPS1), and the second did not include drought alleviation pumping (DAPS1WO). Direct comparison of the output from each simulation allows delineation of the effects on the hydrologic system of pumping the satellite well field.

Bedrock Aquifer Heads. Potentiometric surface maps were examined for bedrock aquifers at simulation times following each drought, as well as after every normal precipitation interval. Considerable fluctuation was observed in heads throughout the drought cycles. Changes were most pronounced in the lower aquifers and near the well field.

Aquifer heads never fully recovered after a non-drought interval. Percentage recovery was estimated by measuring head in an area immediately after a non-drought period from DAPS1, and comparing it with predicted head from DAPS1WO for the same simulation time. Upper aquifers were found to have a nearly steady decline in head, throughout the simulated period. The model predicted recovery for the Arapahoe and Laramie-Fox Hills aquifers as high as 85% near the center of the well field. Percentage recovery decreased outward from the cone of depression where total drawdown was smaller. Along the edge of the cone in both lower aquifers, consistent declines occurred throughout the entire simulation.

Potentiometric surface maps of bedrock aquifers from DAPS1 and DAPS1WO were used to create water level decline maps to illustrate the impact of drought alleviation pumping. Maps of each aquifer for the end of the final simulated drought period in 2028, are shown in Figures 18, 19, 20, and 21. Position of the well field is indicated by the dot. Deeper aquifers exhibit larger cones of depression than shallow aquifers. Maps of conditions in 2028 represent the lowest heads of the entire simulation.

Stream Discharge Rates. Specific reaches of streams within the basin were selected for examination. Once again data from DAPS1 and DAPS1WO were compared to allow appraisal of the impact drought alleviation pumping has on stream discharge rates. Baseflow was lower for most streams in the basin at all times in scenario DAPS1. Streams far from the well field experienced no change in baseflow (e.g. the entire modeled length of the S. Platte River). Cherry Creek and Box Elder Creek, which are 1.5 to 2 miles from the well field, exhibited small declines of 1 or 2 percent.

Over the entire DAPS1 simulation, baseflow declines were greatest along Cherry Creek with a 3% loss in upper reaches and 9% decline just above Cherry Creek Reservoir. Baseflow decline on Cherry Creek near Parker, Colorado is presented for DAPS1 in Figure 22. Drought alleviation pumping clearly had an effect on streams in the immediate vicinity of the well field.

Baseflow declines of approximately 1% occurred during individual drought periods in DAPS1 simulations of Cherry

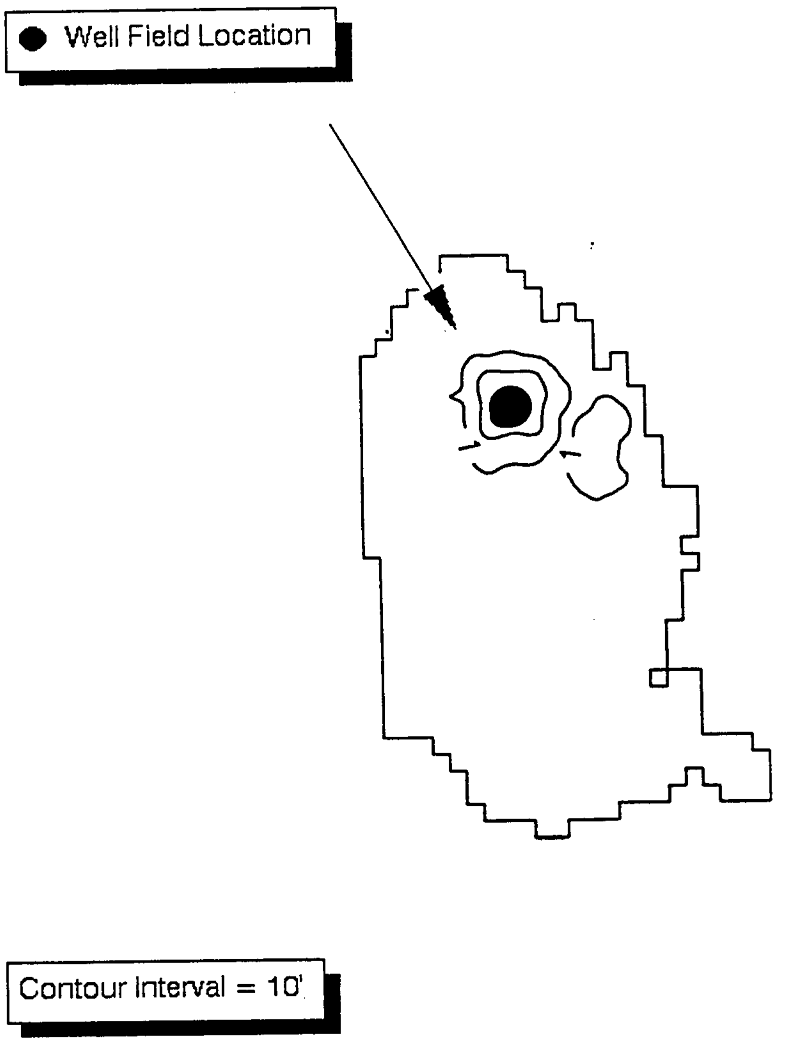

Figure 18. Water level decline in the Dawson aquifer after the 6th drought period in DAPS1 (Location of the aquifer is given in Fig. 4)

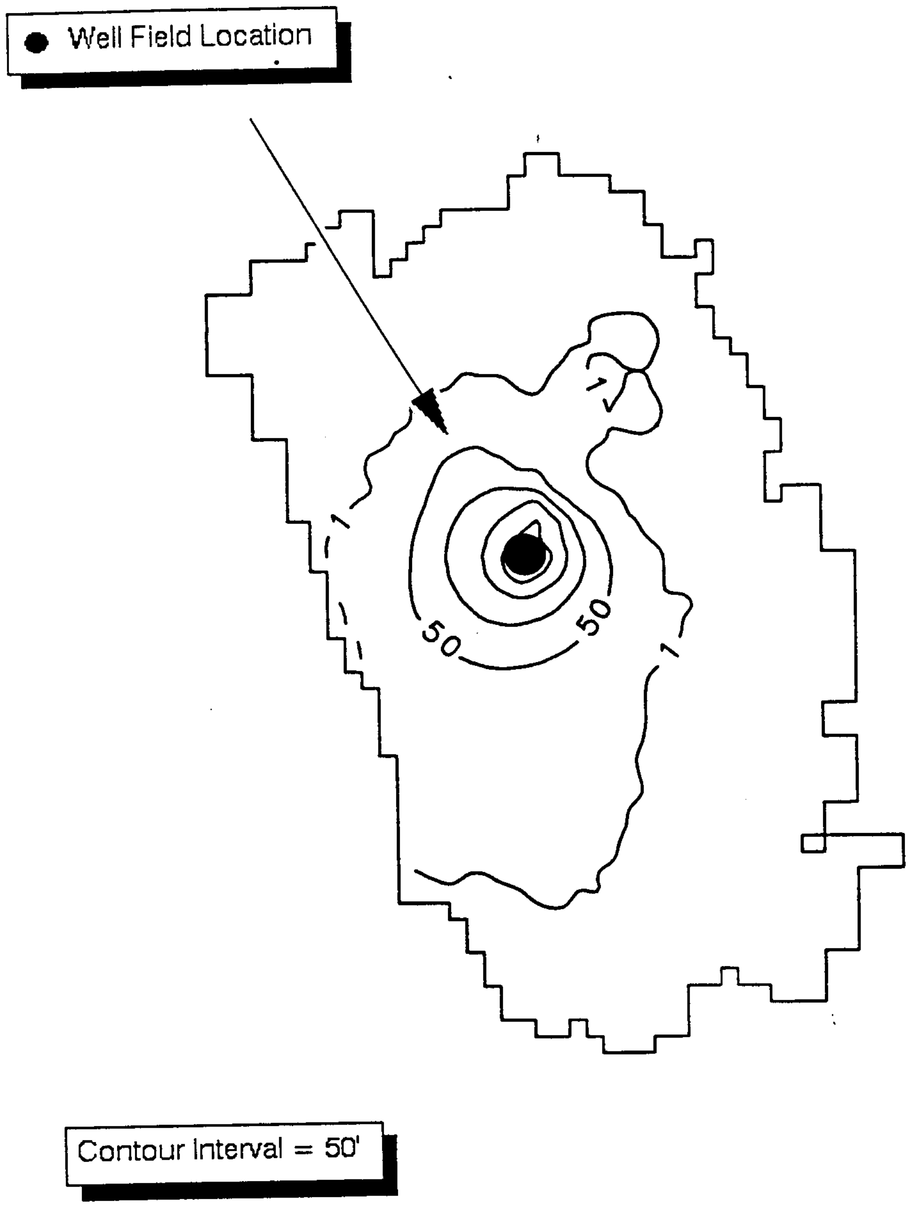

Figure 19. Water level decline in the Denver aquifer after the 6th drought period in DAPS1 (Location of the aquifer is given in Fig. 4)

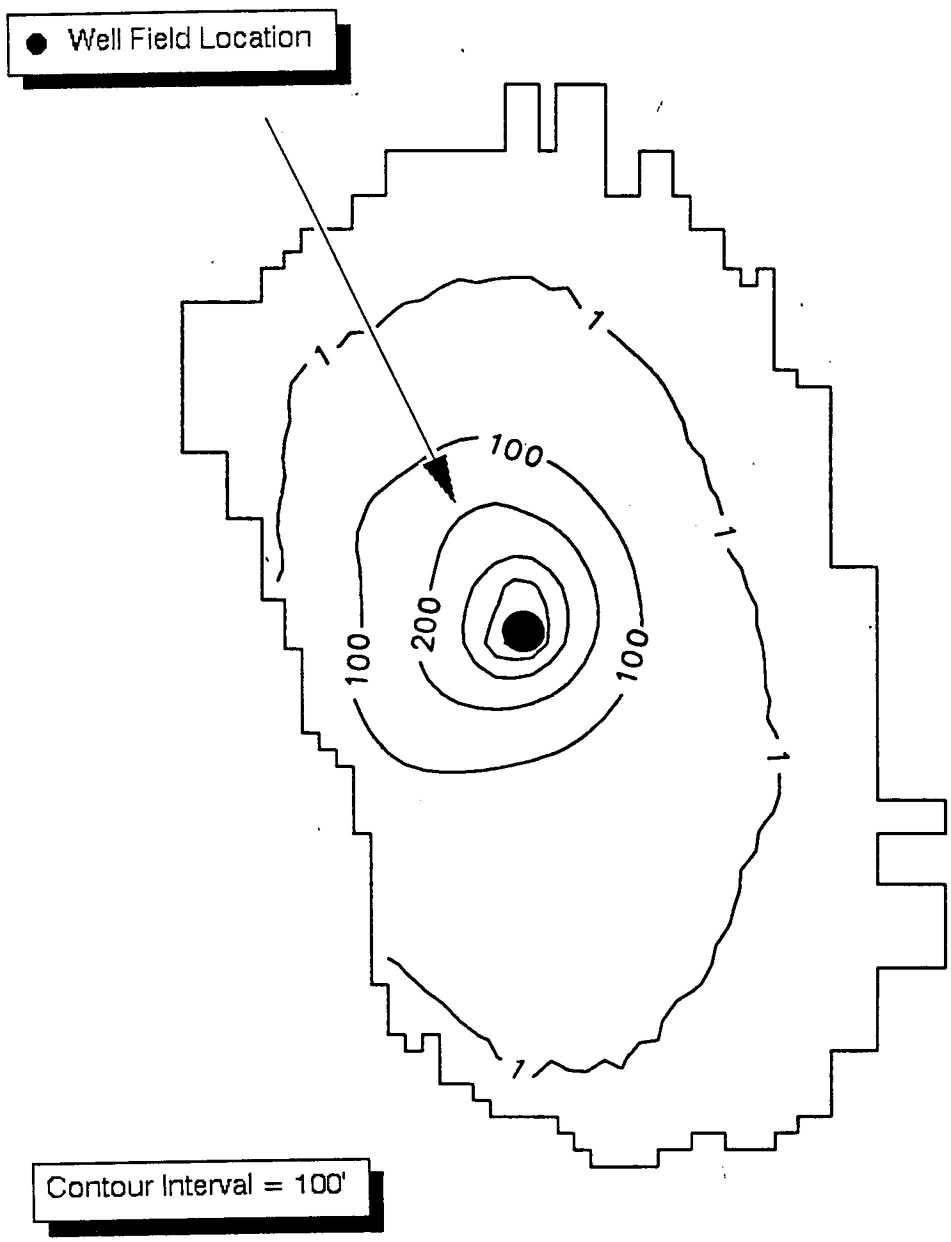

Figure 20. Water level decline in the Arapahoe aquifer after the 6th drought period in DAPS1 (Location of the aquifer is given in Fig. 4)

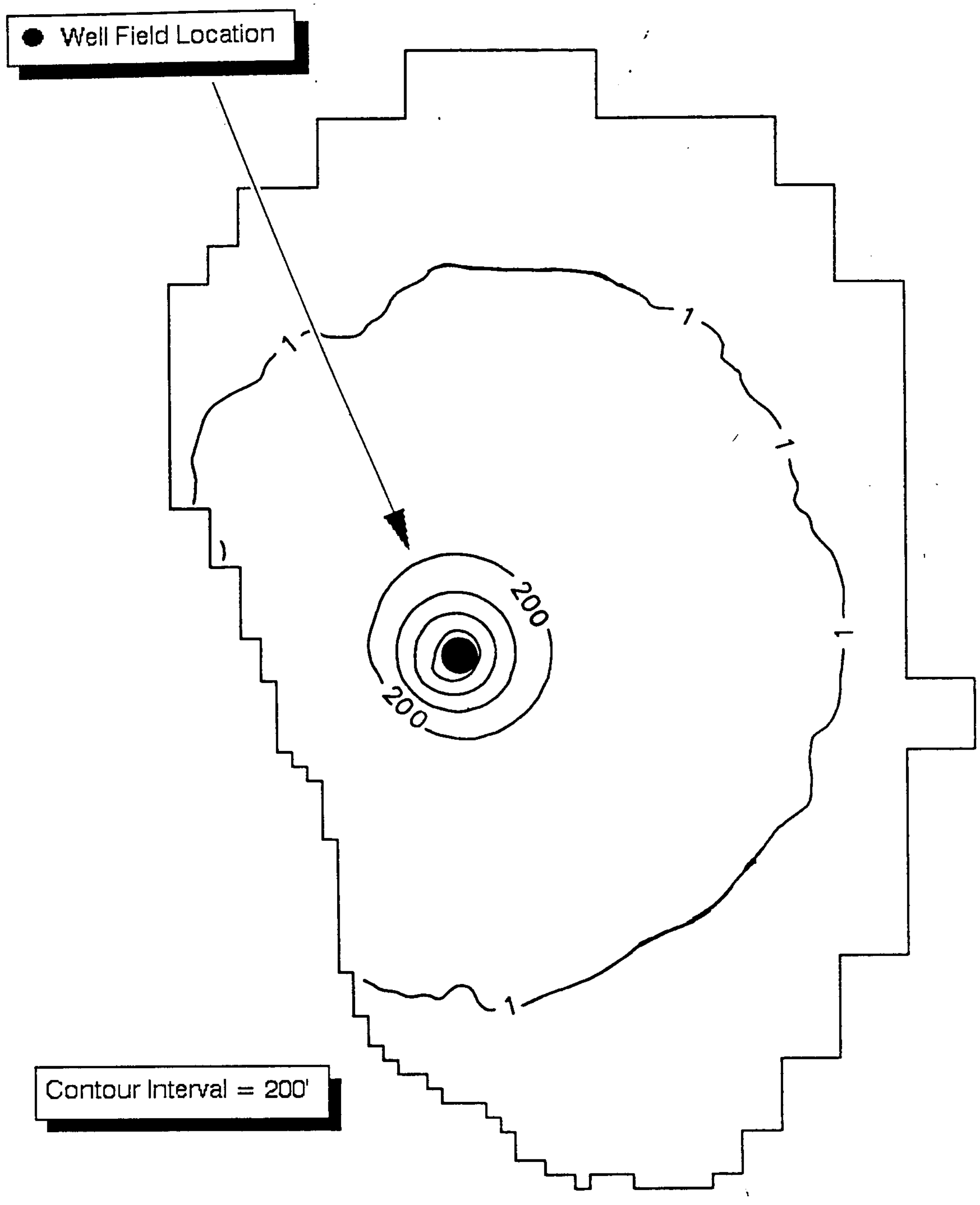

Figure 21. Water level decline in the Laramie-Fox Hills aquifer after the 6th drought period in DAPS1 (Location of the aquifer is given in Fig. 4)

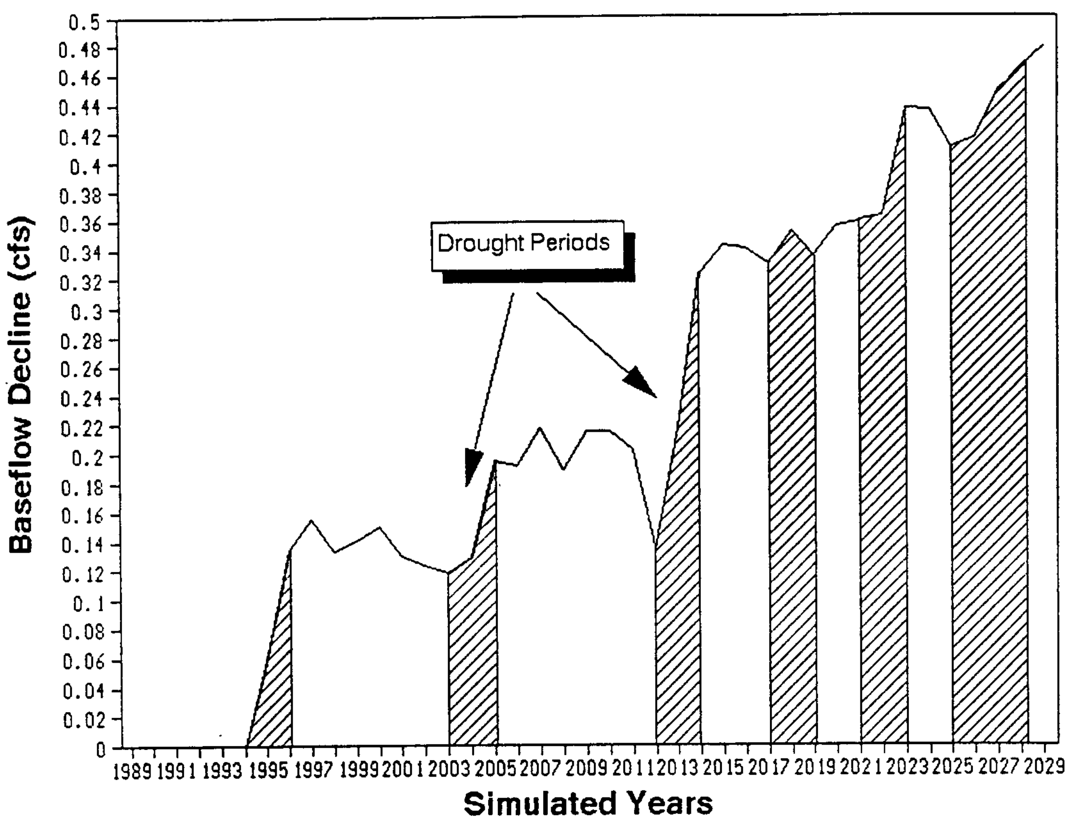

Figure 22. Baseflow decline on Cherry Creek near Parker, Colorado during DAPS1

Creek and baseflow recovery was negligible (Figure 22). Behavior of Cherry Creek in the DAPS1 simulation is best described as a stair-step decline in baseflow with reduction in baseflow during drought periods and relatively no change in non-drought periods. This decline is calculated by taking the difference in baseflow between simulations of the same model but with varied recharge and no pumping so that the baseflow decline is directly attributable to pumping the well field. As illustrated in Figure 22, the trend over the course of the simulation is a baseflow decline of greater than 0.1 cfs per decade, at this reach of Cherry Creek.

Drought Alleviation Pumping Simulation #2 (DAPS2)

Results from DAPS1 suggested that the basin would not recover from drawdown caused by drought pumping at DAPS1 withdrawal rates during non-drought periods. The DAPS2 pumping scheme was designed to be less stressful to the hydrologic system, yet still provide reasonable abatement of the effects of the most serious drought periods in the 40 year simulation interval. Pumping rates were reduced to 19 cfs, one-half the original rate. Drought alleviation pumping was modeled only during the three most severe drought periods as measured in terms of drought indices. These periods were '53-'54, '62-'63, and '76-'77. The reduced stress of DAPS2 provides greater opportunity for aquifer head and stream baseflow recovery. The pumping schedule for DAPS2 is presented in Table 6.

DAPS2 Simulation Results

Model results from DAPS2 simulations predict declines of aquifer heads and stream baseflows that are smaller than DAPS1. In Figures 23, 24, 25, and 26 the water level declines from the four aquifers are shown to cover a smaller area and are smaller near the well field than those from DAPS1. These water level declines are simulated for the end of the third drought period in 2019 and represent the lowest water levels of this simulation.

Note that head declines are greatest in the lower aquifers. In DAPS1, head declines in the Laramie-Fox Hills aquifer were on the order of over 800 feet near the well field. In DAPS2 the head decline has been reduced by an order of magnitude to about 80 feet. This impressive reduction in decline of heads is also found in the Arapahoe aquifer. Differences between the two simulations are less dramatic in the two upper aquifers, and there is virtually no deviation in head declines in the Dawson aquifer. The contrast in head declines between DAPS1 and DAPS2 suggest that the lower two aquifers in the section are considerably more sensitive to changes in aquifer stresses than the

Table 6. Input data for Drought Alleviation Pumping Simulation #2; (DAPS2)

Simulated Years	Historical Years	Yearly Storage Changes (acre-ft.)	Drought Periods (*)	Pumpage Rate (cfs) [acre-ft./year]	Recharge; Percentage of Average Annual	Yearly Storage Changes Adjusted For Pumping (acre-ft.)
1990	1948	-30719		--	100%	-30719
1991	1949	+16058		--	100%	+16058
1992	1950	-47948		--	100%	-47948
1993	1951	+4635		--	100%	+4635
1994	1952	+22555		--	100%	+22555
1995	1953	-25237	*	19 [13759]	97%	-11478
1996	1954	-68453	*	19 [13759]	47%	-54649
1997	1955	+66		--	111%	+66
1998	1956	+7614		--	111%	+7614
1999	1957	+167851		--	111%	+16785
2000	1958	-34960		--	111%	-34960
2001	1959	+11203		--	111%	+11203
2002	1960	-15133		--	111%	-15133
2003	1961	+44049		--	111%	+44049
2004	1962	-42853	*	19 [13759]	61%	-29094
2005	1963	-69755	*	19 [13759]	87%	-55996
2006	1964	+7971		--	109%	+7971
2007	1965	+344167		--	109%	+344167
2008	1966	-84194		--	109%	-84194
2009	1967	+22874		--	109%	+22874
2010	1968	+17194		--	109%	+17194
2011	1969	+42336		--	109%	+42336
2012	1970	+4742		--	109%	+4742
2013	1971	-31865		--	78%	-31865
2014	1972	-43441		--	74%	-43441
2015	1973	+40111		--	117%	+40111
2016	1974	-44072		--	117%	-44072
2017	1975	+21990		--	117%	+21990
2018	1976	-32309	*	19 [13759]	92%	-18550
2019	1977	-105731	*	19 [13759]	71%	-91972
2020	1978	+61377		--	107%	+61377
2021	1979	+100358		--	107%	+100358
2022	1980	-16574		--	94%	-16574
2023	1981	-55892		--	86%	-55892
2024	1982	+101360		--	116%	+101360
2025	1983	+8807		--	116%	+8807
2026	1984	-7542		--	95%	-7542
2027	1985	-12205		--	95%	-12205
2028	1986	-26257		--	95%	-26257
2029	1987	+3494		--	100%	+3494

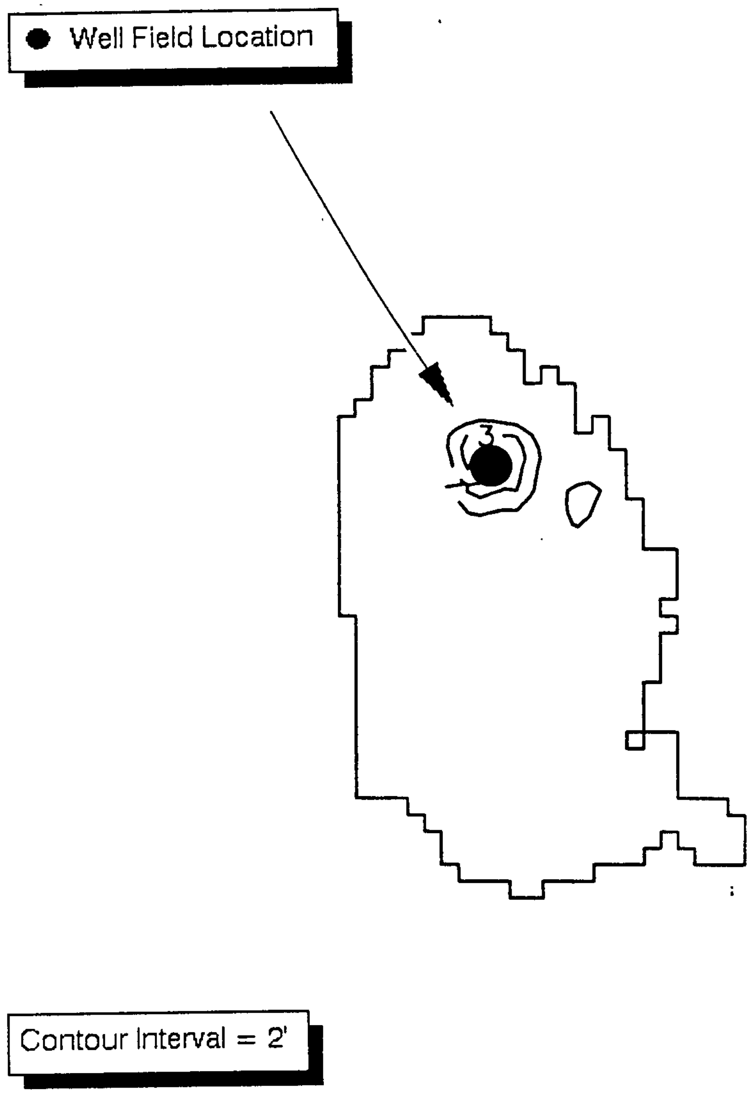

Figure 23. Water level decline in the Dawson aquifer after the 3rd drought period in DAPS2
(Location of the aquifer is given in Fig. 4)

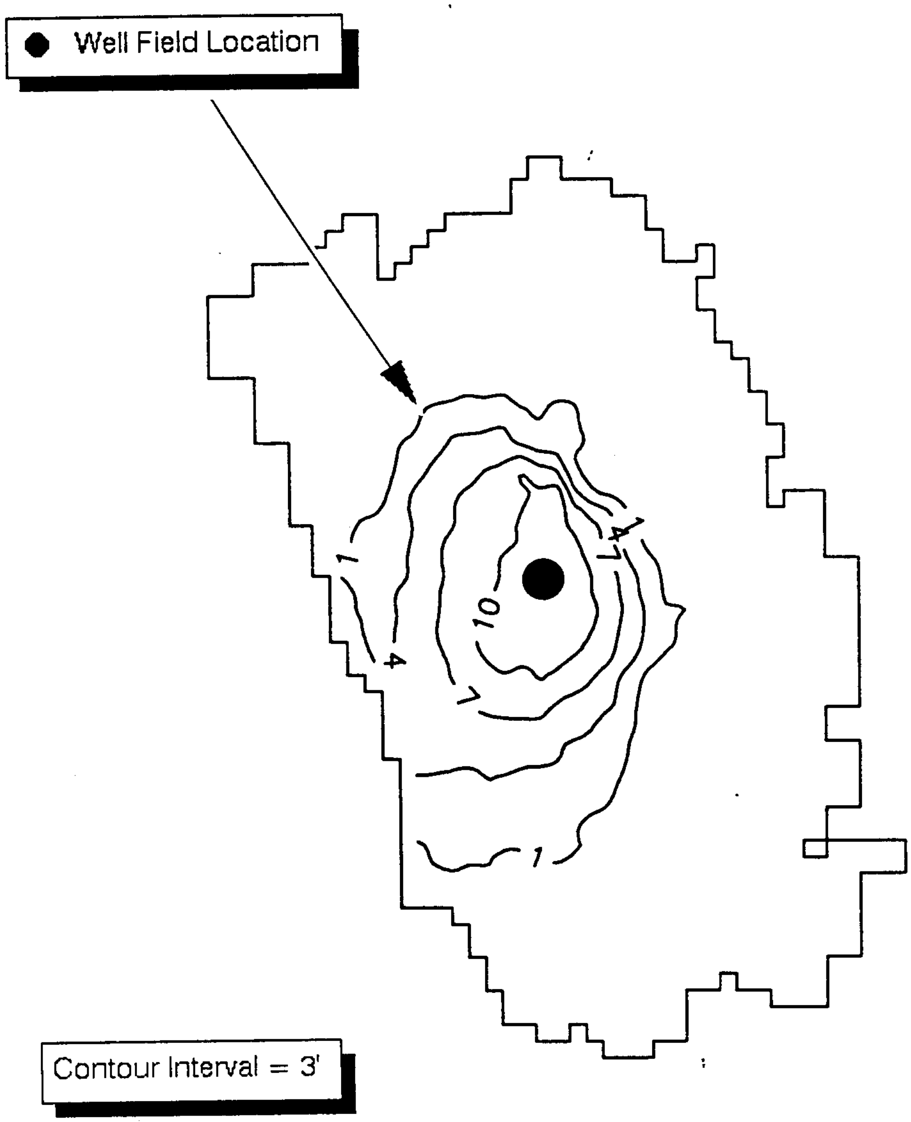

Figure 24. Water level decline in the Denver aquifer after the 3rd drought period in DAPS2
(Location of the aquifer is given in Fig. 4)

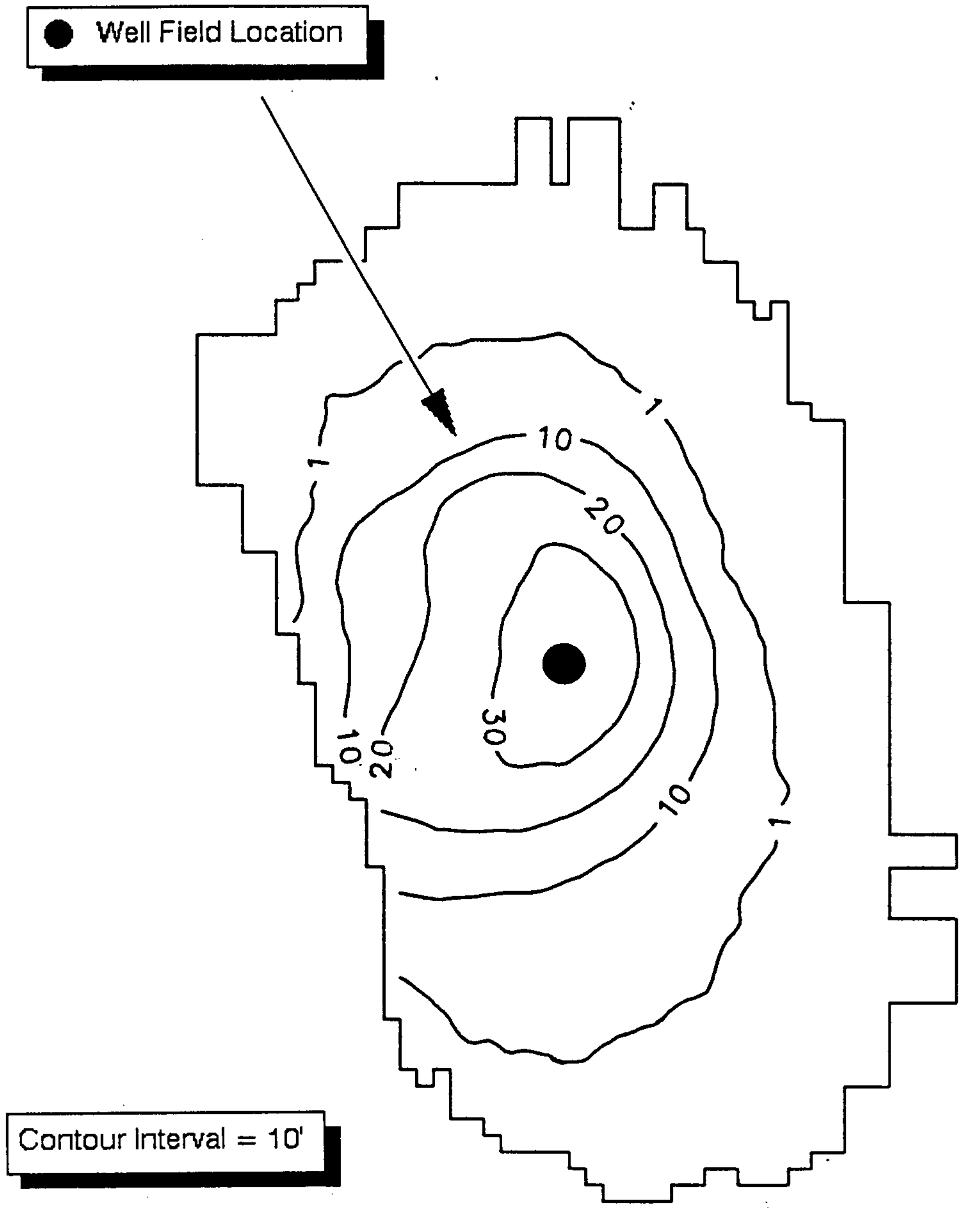

Figure 25. Water level decline in the Arapahoe aquifer after the 3rd drought period in DAPS2 (Location of the aquifer is given in Fig. 4)

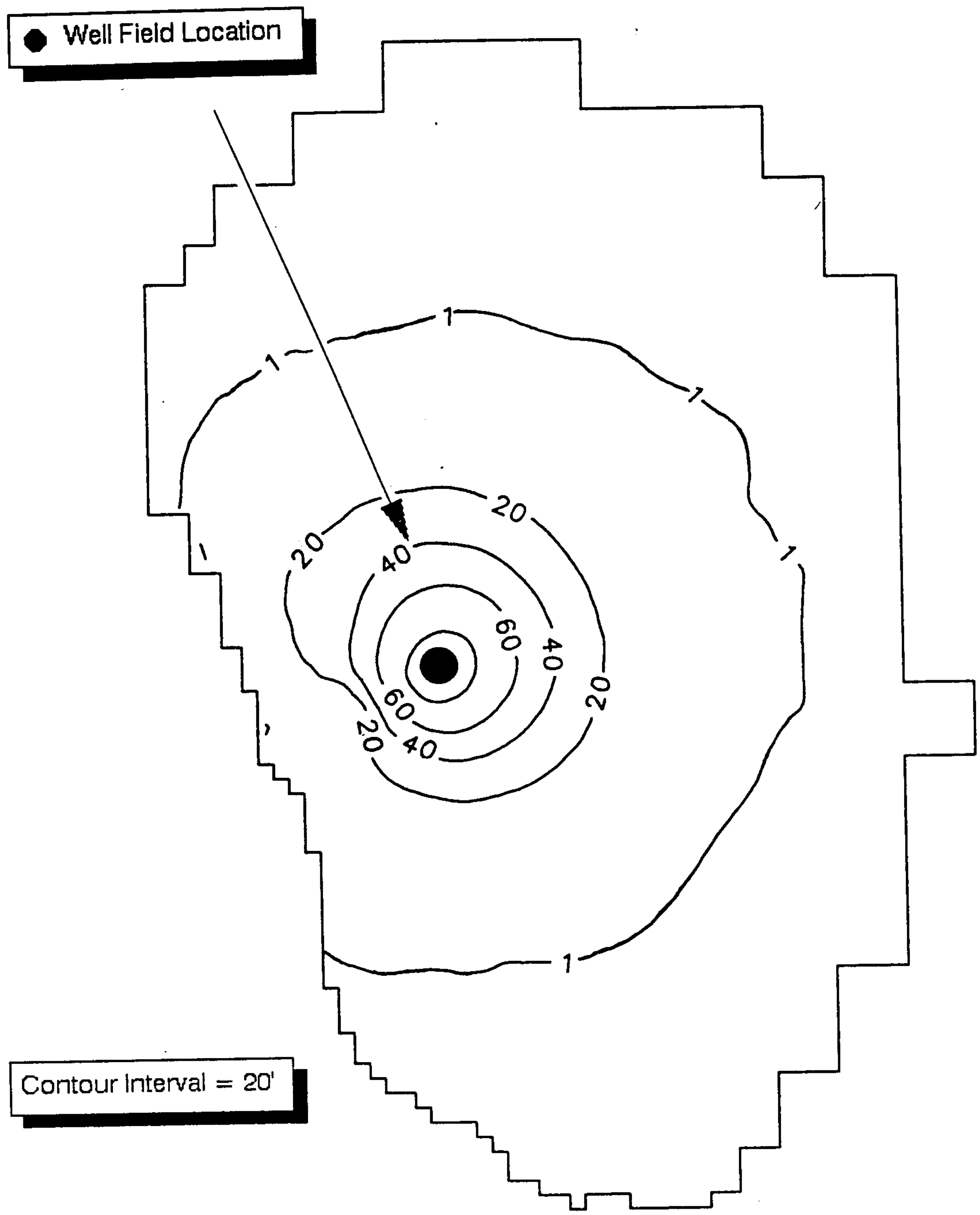

Figure 26. Water level decline in the Laramie-Fox Hills aquifer after the 3rd drought period in DAPS2 (Location of the aquifer is given in Fig. 4)

Dawson. The Denver aquifer exhibits modest sensitivity to these changes.

Baseflow declines on Cherry Creek at Parker, Colorado (Figure 27) are also less severe in DAPS2 than in DAPS1. Recovery after each drought period, before the start of the next period, was improved to better than 50 percent. In DAPS2 the baseflow decline trend is about 0.04 cfs per decade, contrasted with the DAPS1 trend of 0.1 cfs per decade. This more than 50 percent difference is reasonable considering that only 23 percent of the volume pumped during DAPS1 was withdrawn during DAPS2 (357,640 AF for DAPS1 and 82,532 AF for DAPS2). Given the greatly reduced volume withdrawn by pumping over the course of the simulation, this degree of baseflow decline suggests that streams near the well field are sensitive to pumping and baseflow recovery is slow, irrespective of the rate of pumping.

Recovery of Aquifer Heads after Drought Pumping

Subsequent to the DAPS1 and DAPS2 simulations, the model was used to assess the time required for full recovery of heads in each bedrock aquifer. The satellite well field was pumped for 2 consecutive years at 38 cfs and 19 cfs, just as if a drought were being simulated. This pumping was simulated as occurring in 1995 and 1996. The water level in each aquifer was monitored at grid block 30,16 on the

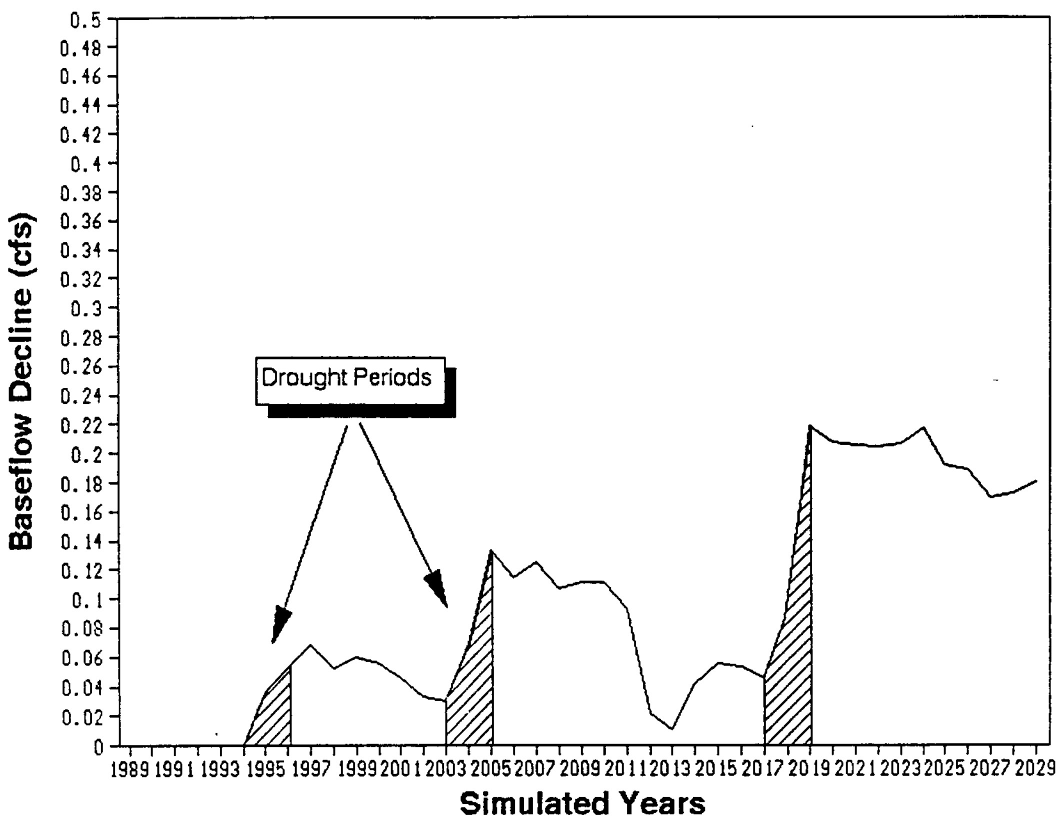

Figure 27. Baseflow decline on Cherry Creek near Parker, Colorado during DAPS2

western edge of the well field for the remainder of the simulation without drought alleviation pumping.

Heads that resulted from drought alleviation pumping were plotted along with heads that would have resulted without drought alleviation pumping. Water level recovery curves for the Dawson, Denver, Arapahoe, and Laramie-Fox Hills aquifers are presented in Figures 28, 29, 30, and 31 respectively. In each aquifer, the potentiometric surface without pumping is not static over the remaining 34 years of the simulation, but is steadily declining due to the projected basin-wide pumping. Figure 31 shows that the greatest declines in the potentiometric surface for simulations without pumping are about 10 ft/yr and occur in the Laramie-Fox Hills aquifer. This is reasonable when compared with the findings of Robson (1987) who has reported that water level declines in portions of the Laramie-Fox Hills aquifer were measured as greater that 200 feet from 1958 to 1978 (about 10 ft/yr).

In the Dawson aquifer, where drawdown was small, there is virtually no recovery of water levels. Where greater drawdowns were observed, such as in the Arapahoe and Laramie-Fox Hills aquifers, the rate at which water levels recover is higher than the two upper aquifers, yet drawdown as a result of pumping remains appreciable for a number of

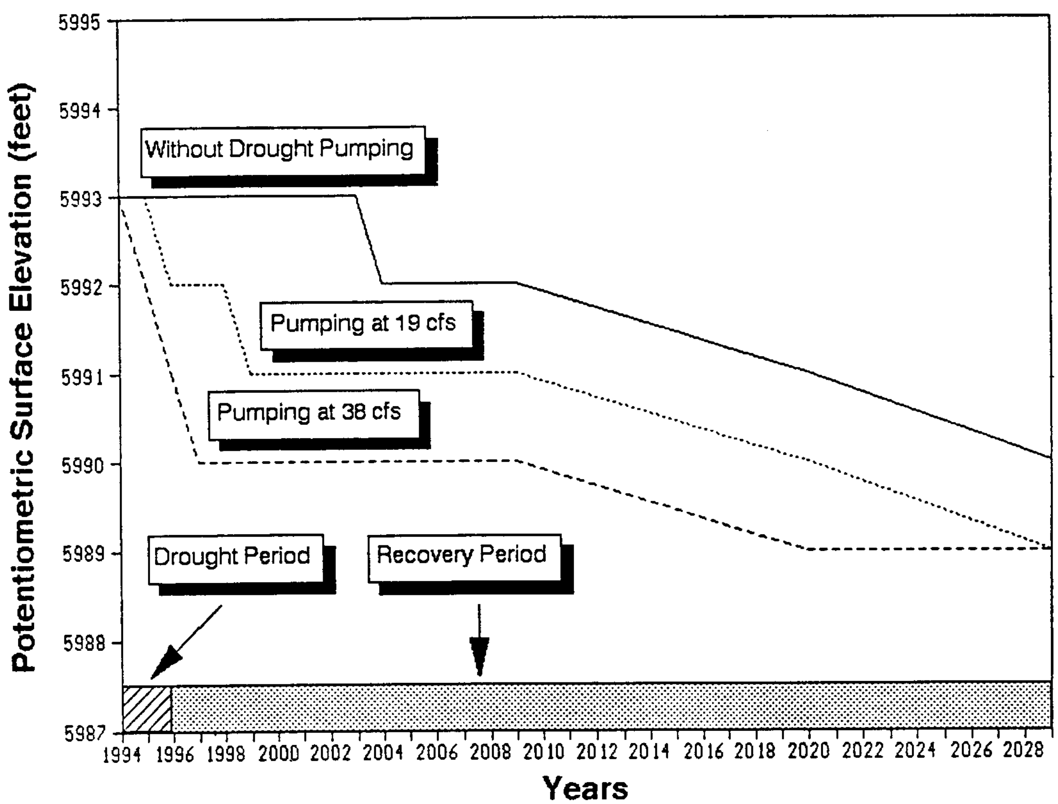

Figure 28. Recovery of the Dawson aquifer's potentiometric surface at the well field, following a 2 year drought

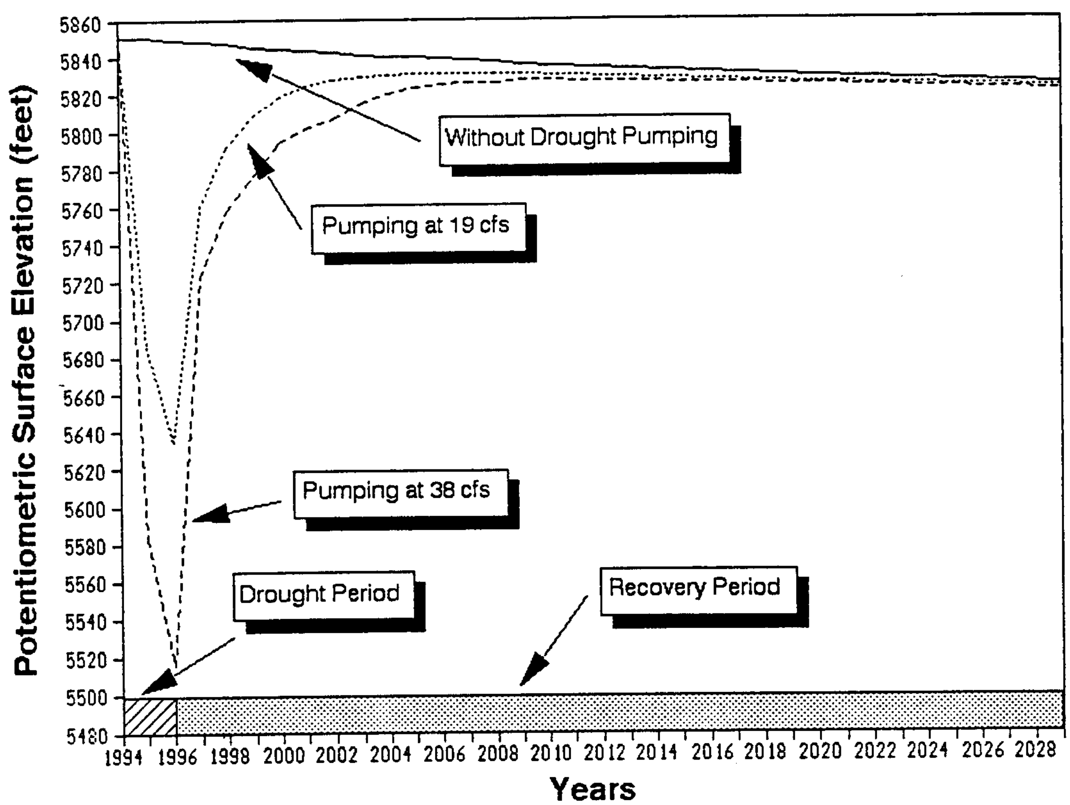

Figure 29. Recovery of the Denver aquifer's potentiometric surface at the well field, following a 2 year drought

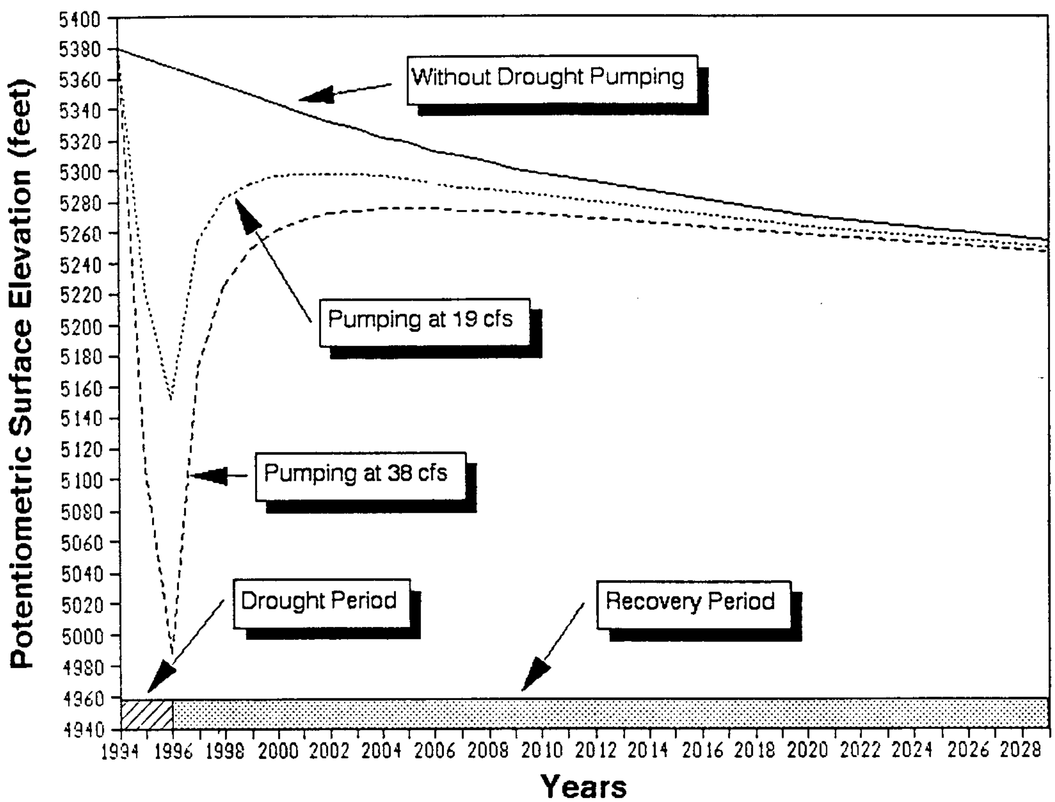

Figure 30. Recovery of the Arapahoe aquifer's potentiometric surface at the well field, following a 2 year drought

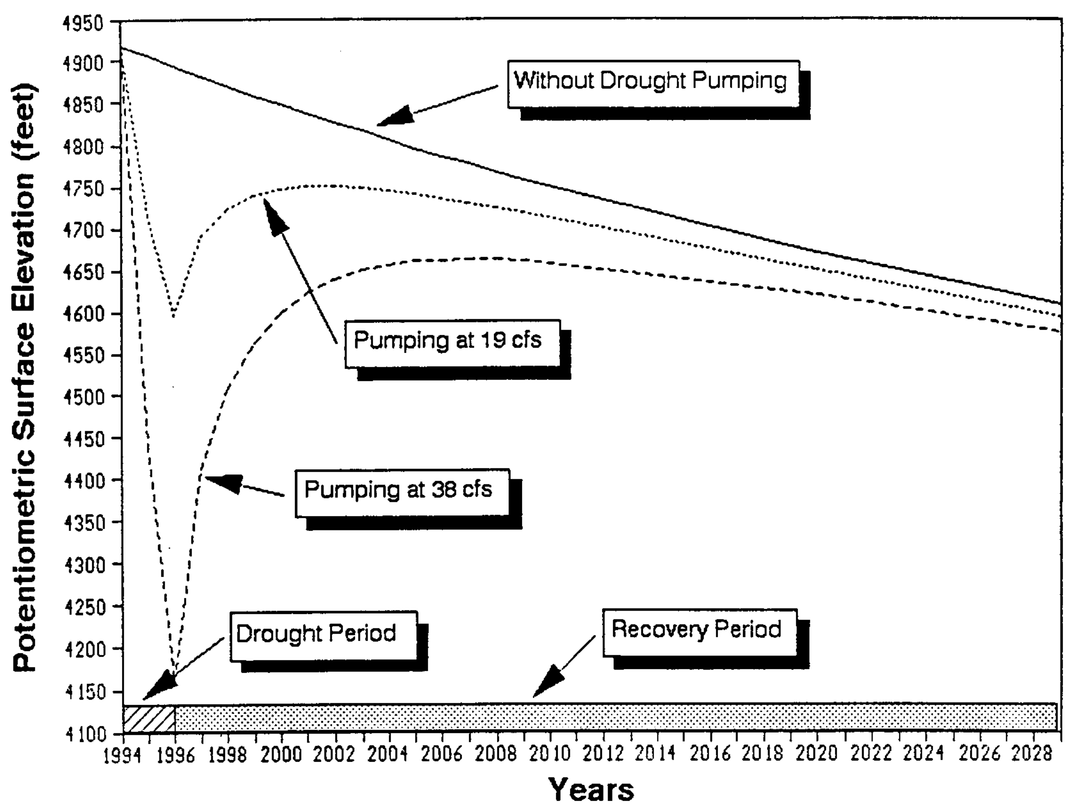

Figure 31. Recovery of the Laramie-Fox Hills aquifer's potentiometric surface at the well field, following a 2 year drought

years following cessation of pumping. One hundred percent recovery never occurs in any of the aquifers within the simulated period. Rather, water levels increase for a time, then decrease as the recovery curve approaches the declining water level curve predicted for a scenario without drought alleviation pumping.

With these poor recovery rates, it is understandable that numerous drought periods would precipitate the stair step decline in aquifer heads predicted during the drought cycle simulations. Simulated natural recharge, is insufficient to bring aquifer heads back up to pre-pumping levels in a timely manner. The two deepest aquifers continue to exhibit substantial drawdown for a number of years following drought pumping, while in the Dawson and Denver aquifers only a few feet of drawdown remain.

SUMMARY AND CONCLUSIONS

The Denver Basin model which utilizes the RIVINT river simulation package was calibrated so that predicted aquifer heads and stream baseflows better matched field measurements than they did in previous modeling projects. Calibration was carried out by adjusting bedrock aquifer, alluvial aquifer, and stream parameters. Aquifer heads are somewhat too high in some portions of the Dawson and Denver aquifers.

A review of Denver Basin meteorological records was used as a basis for identifying conditions which define a moderate drought. Water requirements were assessed during drought periods and pumping rates required to meet the need were estimated. A satellite well field was designed to permit withdrawal at the maximum permissible rate while also meeting specified criteria intended to maintain reasonable well efficiency. Drought period pumping was simulated by imposing an historical record containing numerous drought cycles on the basin model.

Results of this modeling study indicate the Denver Basin bedrock aquifers cannot fully recover from moderate drought alleviation pumping before the onset of the next drought period. Reducing stress to the system by less frequent drought alleviation pumping or by specifying smaller pumping rates decreases the drawdowns. Baseflow reduction is confined to streams near the well field. No appreciable recovery of baseflow is predicted before the onset of a subsequent drought period. Pumping at reduced rates and less frequently, resulted in decreased head and baseflow declines in the basin. However, the ground-water resource would still be depleted over the course of numerous drought cycles.

Conclusions drawn from this study must be tempered by consideration of this model as one of many possible representations of the hydrologic system in the Denver Basin. Different, equally valid, models of the Denver Basin will yield both greater and lesser drawdowns and baseflow declines. Full assessment of the uncertainty associated with prediction of drawdowns and baseflow declines resulting from drought alleviation pumping requires that the pumping be simulated within the range of possible representations of the basin. Additional data which better defines the nature of the basin will reduce the uncertainty associated with the model and, in turn, reduce the uncertainty related to the predictions.

RECOMMENDATIONS FOR FUTURE STUDIES

A ground-water model is simply a numerical approximation of hydrologic field conditions. As such, the reliability of predictions is a function of how accurately field conditions are represented. Where simplifications of the system are made, or field data are unreliable or non-existent, errors occur. In terms of this Denver Basin model, future research is needed to better delineate hydrologic parameters such as recharge rates and parameters associated with simulating rivers. During calibration of the model, questions arose about recharge into alluvial aquifers. Calibration was facilitated by acting on the assumption that evapotranspiration in some alluvial areas was high and little or no recharge entered the alluvium. Further work could be performed to estimate evapotranspiration and recharge during wet and dry periods over alluvial aquifers of the basin. Parameters which describe stream geometry and stream hydraulics could be measured along important river reaches. This would allow the capabilities of the RIVINT river simulation package to be more fully employed.

Estimates of historical pumpage could also be improved. The estimates used in this study were those made by Robson (1987). Robson reports that because of incomplete or erroneous data, the approximations of municipal and domestic pumpage are accurate to within 20 to 30 percent. Robson adjusted pumpage to more closely model water level changes observed in the field, under the assumption that other input parameters were better defined and thus discrepancies were due to erroneous pumpage estimates. Robson's original pumpage estimates could be obtained and re-evaluated within the framework of the model as calibrated in this study.

Calibration of the model could be improved by utilizing an inverse ground water flow code. The inverse version of MODFLOW will be released this year (1991). Application of this inverse version of MODFLOW to the Denver Basin model should improve the parameter estimation and the closeness of the calibration.

Finally, the RIVINT river simulation package cannot execute a steady-state simulation when alluvium is modeled explicitly. To obtain an initial steady-state configuration of the flow system, the model must be run in transient mode until heads in explicitly modeled alluvium and stream baseflows remain constant though several iterations. The resulting explicit alluvial heads from this simulation are then used as input for a transient simulation where stresses to the flow system are simulated such as aquifer pumping. The required transient simulation time to achieve steady-state flow conditions may be considerable, depending on the complexity of the model. A steady-state version of the RIVINT code could be developed. This new version would permit simulation of pristine flow conditions without performing a lengthy and unwieldy transient simulation to obtain steady-state flow conditions.

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APPENDIX A

MODIFIED RECHARGE MODULE COMPUTER CODE

```
      SUBROUTINE RCH1RP(NRCHOP,IRCH,RECH,DELR,DELC,NROW,NCOL,
C                    NLAY,IN,IOUT)
C
C-----VERSION 1513 22DEC1982 RCH1RP
C     ******************************************************************
C     READ RECHARGE RATES
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
        DIMENSION       IRCH(NCOL,NROW),RECH(NCOL,NROW),DELR(NCOL),DELC(NROW)
C
CF66
C     DIMENSION ANAME(6,2)
CF66
CF77
      CHARACTER*4 ANAME(6,2)
CF77
      DATA ANAME(1,1),ANAME(2,1),ANAME(3,1),ANAME(4,1),ANAME(5,1),
     1  ANAME(6,1) /'    ','RECH','ARGE',' LAY','ER I','NDEX'/
      DATA ANAME(1,2),ANAME(2,2),ANAME(3,2),ANAME(4,2),ANAME(5,2),
     1  ANAME(6,2) /'    ','    ','    ','    ','RECH','ARGE'/
C     ------------------------------------------------------------------
C
C1------READ FLAGS SHOWING IF DATA IS TO BE REUSED.
      READ(IN,4)INRECH,INIRCH,INFLAG,REFACTOR
    4 FORMAT(3I10,G10.3)
C
C-------TEST INFLAG TO SEE IF SAVREFAC SHOULD BE SET TO 1.0
      IF(INFLAG.LE.0)SAVREFAC = 1.0
C
C2------TEST INRECH TO SEE WHERE RECH IS COMING FROM.
      IF(INRECH.GE.0)GO TO 32
C
C-------TEST INFLAG TO SEE IF THERE IS A NEED TO CHANGE RECH.
      IF(INFLAG.GT.0)GO TO 33
C
C2A-----IF INRECH<0 THEN REUSE RECHARGE ARRAY FROM LAST STRESS C     PERIOD
      WRITE(IOUT,3)
    3 FORMAT(1H0,'REUSING RECH FROM LAST STRESS PERIOD')
      GO TO 55
C
C3------IF INRECH=>0 THEN CALL U2DREL TO READ RECHARGE RATE.
   32 CALL U2DREL(RECH,ANAME(1,2),NROW,NCOL,0,IN,IOUT)
      GO TO 49
C
C     IF INFLAG>0, MULTIPLY RECH BY CORRECTED RECHARGE FACTOR C    (CRF)
   33 CRF = REFACTOR/SAVREFAC
      SAVREFAC = REFACTOR
      WRITE(IOUT,6)CRF
    6 FORMAT(1H0,'RECH FROM LAST STRESS PERIOD IS MULTIPLIED BY:  ',G10.3,'(CORRECTED RECHARGE
      FACTOR)')
      WRITE(IOUT,7)
    7 FORMAT(1H0,'IF REFACTOR IS <1.0, A DROUGHT IS BEGINNING')
      WRITE(IOUT,8)
    8 FORMAT(1H0,'IF REFACTOR IS 1.0, NORMAL PRECIP. IS CONTINUING')
      WRITE(IOUT,9)
    9 FORMAT(1H0,'IF REFACTOR IS >1.0 THEN A PERIOD OF HIGHER PRECIP.      &        IS COMMENCING')
      DO 34 IR=1,NROW
      DO 34 IC=1,NCOL
      RECH(IC,IR)=RECH(IC,IR)*CRF
```

```
   34 CONTINUE
      GO TO 55
C
C4------MULTIPLY RECHARGE RATE BY CELL AREA TO GET VOLUMETRIC C      RATE.
   49 DO 50 IR=1,NROW
      DO 50 IC=1,NCOL
      RECH(IC,IR)=RECH(IC,IR)*DELR(IC)*DELC(IR)
   50 CONTINUE
C
C5------IF NRCHOP=2 THEN A LAYER INDICATOR ARRAY IS NEEDED.
   55  IF (NRCHOP.NE.2)GO TO 60
C
C6------IF INIRCH<0 THEN REUSE LAYER INDICATOR ARRAY.
      IF(INIRCH.GE.0)GO TO 58
      WRITE(IOUT,2)
    2 FORMAT(1H0,'REUSING IRCH FROM LAST STRESS PERIOD')
      GO TO 60
C
C7------IF INIRCH=>0 CALL U2DINT TO READ LAYER IND ARRAY(IRCH)
   58 CALL U2DINT(IRCH,ANAME(1,1),NROW,NCOL,0,IN,IOUT)
C
C8------RETURN
   60 RETURN
      END
```

APPENDIX B

MODIFIED RECHARGE MODULE INPUT FORMAT

Modified Recharge Module Input Format

Input to the Recharge Module is read from the unit specified in IUNIT(8).

FOR EACH SIMULATION

1.	Data:	NRCHOP	IRCHCB		
	Format:	I10	I10		

FOR THE FIRST STRESS PERIOD

2.	Data:	INRECH	INIRCH	INFLAG	REFACTOR
	Format:	I10	I10	I10	G10.3
3.	Data:	RECH(NCOL,NROW)			
	Module:	U2DREL			

IF THE RECHARGE OPTION IS EQUAL TO 2

4.	Data:	IRCH(NCOL,NROW)			
	Module:	U2DINT			

FOR EACH ADDITIONAL STRESS PERIOD

5.	Data:	INRECH	INIRCH	INFLAG	REFACTOR
	Format:	I10	I10	I10	G10.3

Explanation of Additional Input Terms in Modified Recharge Module

INFLAG — This flag is set when values in the recharge array RECH are to be multiplied by some factor: REFACTOR.

If INFLAG $\leq$ 0 — reuse the recharge values in the array RECH

If INFLAG > 0 — the array RECH is multiplied by a factor REFACTOR

REFACTOR — This is the factor which will be used to multiply the recharge array, RECH. It must be a real number expressed in the G10.3 format. If, for example, the recharge rate during a stress period is 90% of that in the array RECH, then REFACTOR would be 0.9.

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