GROUNDWATER CONDITIONS AT THE HAYES CREEK TEMPORARY CONTROLLED GROUNDWATER AREA

MONTANA DEPARTMENT OF NATURAL RESOURCES AND CONSERVATION

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Abstract

A two-year, temporary controlled groundwater area was established in most of the Hayes Creek drainage basin, which encompasses about 2500 acres, in 1996. Hayes Creek is a tributary to the Bitterroot River, with its headwaters on the east side of Blue Mountain, about 10 miles southwest of Missoula. A permanent controlled groundwater area already exists for approximately 51 acres underlying the Woodlands Heights and Woodland Park subdivisions area, at the lower end of the basin. In this area, groundwater withdrawals for summer lawn irrigation have caused severe seasonal declines in groundwater levels. While the groundwater system typically recovers over winter months, residents are concerned about a variety of problems including the possibility of water shortages during especially dry summers and the threat of new groundwater developments in surrounding areas. The Montana Department of Natural Resources and Conservation (DNRC) was directed to commence studies to decide if the temporary controlled groundwater area needs to be designated as a permanent controlled groundwater area.

University of Montana graduate student Dana S. Bayuk conducted a detailed study of groundwater conditions in the Woodlands Heights and Woodland Park subdivisions during 1985 and 1986. Bayuk collected an impressive amount of information concerning the hydrogeology of the area. The hydrogeology, groundwater budget, and observed reaction of the bedrock aquifer underlying the subdivisions area is reevaluated in this report using Bayuk's extensive information and new groundwater level data collected in 1996 and 1997.

The Woodlands Heights and Woodland Park subdivisions area is underlain by a fractured bedrock aquifer. The observed response of groundwater levels in the aquifer to seasonal pumping for lawn irrigation is an expected condition for this rock type and geographic setting.

The water budget at the subdivisions area remains uncertain, although the approximate range of many components can be estimated. Since pumping withdrawals for lawn irrigation are a major component of the water budget, and have bearing on estimating recharge from the surface, the measurement of these withdrawals would provide an important constraint in the water budget that would improve our understanding of the system.

The recurrent groundwater problems are a result of pumping groundwater from a concentrated area in the Woodlands Heights and Woodland Park subdivisions during dry summers. Because of the low transmissivity of the bedrock, the immediate source of water is largely groundwater in storage in the aquifer. This water is slowly replaced over the seasons by natural groundwater flow through the aquifer and whatever recharge is available from precipitation, excess irrigation water, and drain fields at the surface. Recharge from Hayes Creek is probably not a major component of the water budget as previously thought.

The principal source of water at the subdivisions area is believed to be groundwater moving into the area from the west. Available data indicates that the current level of development has not impacted groundwater inflow to the subdivisions area to any detectable degree. Groundwater development in areas west of the subdivision at modest levels with one well serving perhaps a 5-acre lot, *and* with withdrawals in about the same range as existing wells in the subdivisions would not be expected to significantly impact the subdivisions. The location of additional wells, and the new information gained from additional wells would have to be evaluated to determine what threat specific developments would have. Some new wells might have almost no impact to the subdivisions, while others may be in more threatening positions. Because of the limited amount of private land where further development can be expected that is upgradient of the subdivisions area, the threat to substantial changes in groundwater flow from the west is limited.

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Montana Department of Natural Resources and Conservation
February 1998

Introduction

A permanent controlled groundwater area was established in May 1995 for the Woodland Heights and Woodland Park subdivisions north of Hayes Creek. The permanent controlled groundwater area encompasses approximately 51 acres in Section 10, T12N, R20W (Figure 1). The controlled groundwater area was established because excessive groundwater level declines occurred during summer months due to groundwater withdrawals for irrigation.

A second petition for a controlled groundwater area that includes most of the Hayes Creek drainage basin was filed by area residents in 1996. Area residents noted that shortages still occur during dry summers, some wells had been deepened, and there was concern that additional groundwater developments upgradient of the subdivisions could cause additional problems. A two-year, temporary controlled groundwater area was established in July 1996 for this 2465-acre area. The eastern portion of this temporary controlled groundwater area is shown in Figure 1. The temporary controlled groundwater area extends west of the area shown in Figure 1 to include the entire Hayes Creek drainage basin, but this area is largely undeveloped US Forest Service property. The Montana Department of Natural Resources and Conservation (DNRC) was directed to commence studies to decide if the temporary controlled groundwater area needs to be designated a permanent controlled groundwater area. There are no known wells within the Hayes Creek drainage basin west of the area shown in Figure 1, so the study area is essentially limited to the east end of the designated temporary controlled groundwater area shown in the figure. This report presents the results of the study conducted by DNRC during 1996 and 1997.

Previous Work

Dana S. Bayuk conducted a detailed study of groundwater conditions at the Woodland Heights and Woodland Park subdivisions in the mid-1980's. This work was published as an M.S. Thesis in geology at the University of Montana (Bayuk, 1989). A separate report, entitled "A Hydrogeologic Investigation of the Lower Hayes Creek Drainage Basin, Western Montana" was also prepared by Bayuk (1986) for the Woodland Heights Homeowners Association. These two reports are similar in content, but have some differences. Notably, the mass balance, or groundwater budget, equation presented in the 1986 report was different from that presented in the 1989 M.S. thesis. As a result, some water budget figures in the two reports differ. These reports provide static groundwater levels measured monthly in 43 wells during the period June 1985 to June 1986, and a variety of other work such as aquifer tests, geologic cross-sections, and water-level maps and cross-sections.

Methods

The approach used in conducting this study was to reevaluate the groundwater conditions and water budget in the study area using available groundwater data. This included collecting additional groundwater-level data and developing a computer model used to test how the aquifer might react to seasonal pumping for irrigation. Bayuk (1989) provides much of the basic

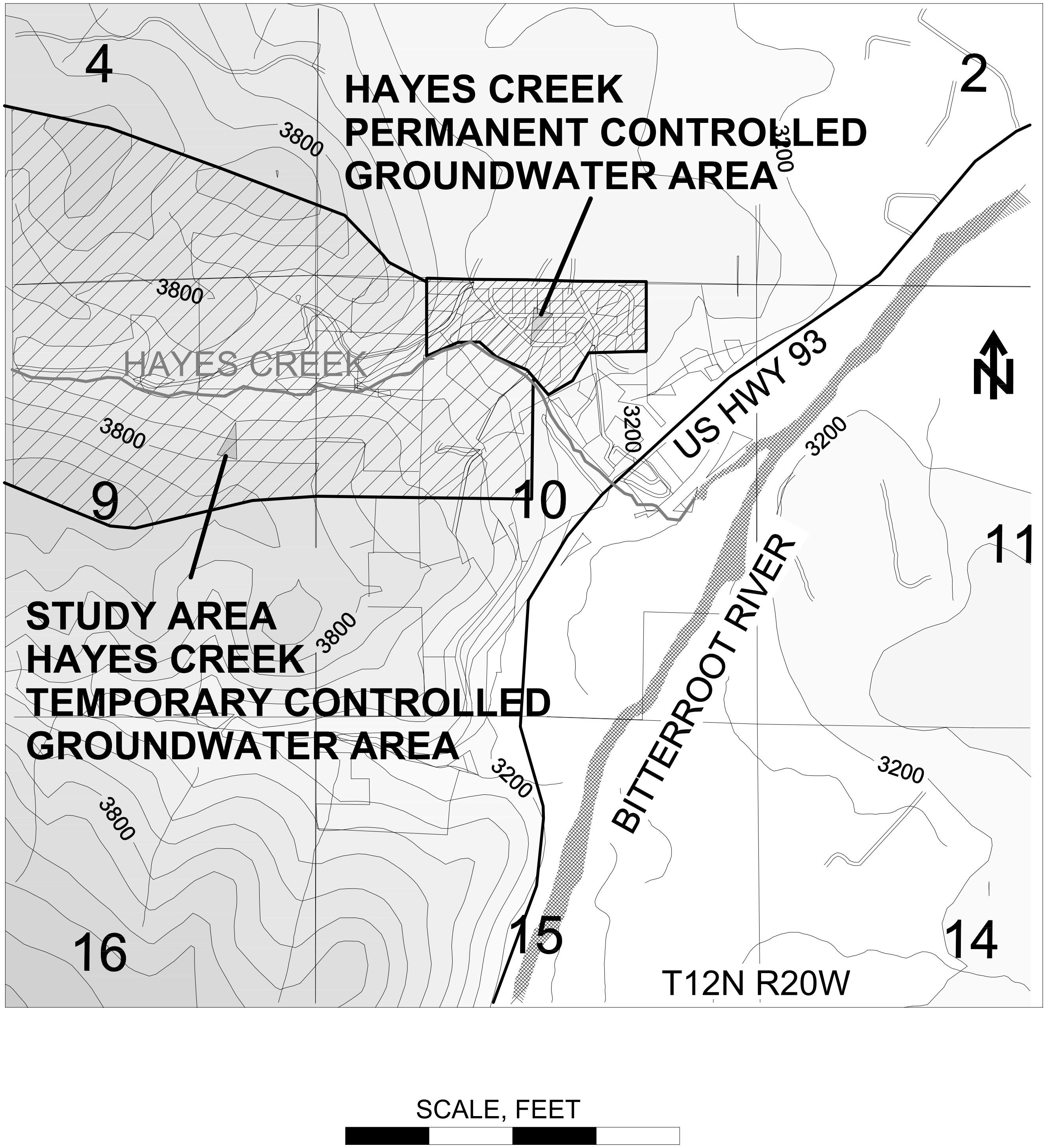


Figure 1. Location map

geologic and hydrogeologic data needed to assess conditions in the study area. DNRC staff at the Missoula Water Resources Regional Office measured groundwater levels in 19 area wells during the period September 1996 to October 1997. Most of these wells are within the Woodland Heights and Woodland Park subdivisions. However, three wells are west and southwest of the subdivisions, and one well is east of the subdivisions. Figure 2 shows the locations of most of the wells monitored in the area by Bayuk in 1985 and 1986 and all of the wells monitored by DNRC in 1996 and 1997. The wells monitored by Bayuk not shown on the map are HC-35, in SW1/4, NW1/4, SE1/4 Section 3, and wells HC-42 and HC-43, which are both in Section 2. Table 1 lists the wells that DNRC monitored in 1996 and 1997.

Geologic Conditions

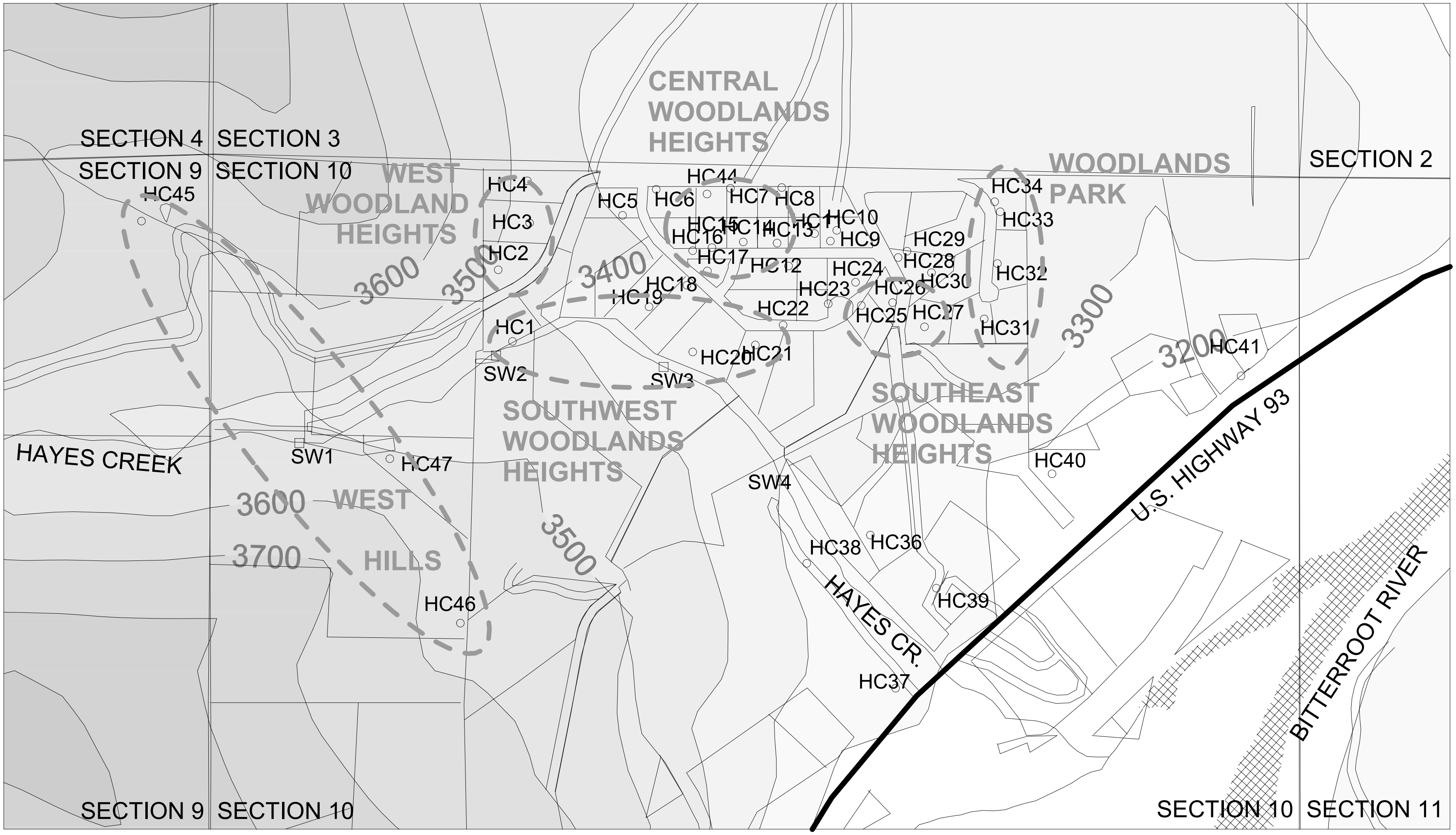
Bayuk (1989) provides a detailed discussion of the rock types near the Woodland Heights and Woodland Park subdivisions, along with geologic cross sections showing the distribution of rock formations in the subsurface. The area is underlain by bedrock, covered in some areas with a thin veneer of poorly sorted gravel or landslide deposits. The bedrock consists of red and green argillite, siltite, and quartzite of the Precambrian Missoula Group. The upper part of the bedrock has weathered to a mixture of clay and bedrock in some areas, based on well log descriptions and observations by Bayuk during the drilling of four wells in the area. The thickness of the weathered zone ranges from a few feet to 170 feet near the subdivisions. According to Bayuk, none of the area wells are perforated in the clay-rich weathered bedrock, but draw water from the deeper unweathered bedrock.

The unweathered bedrock is Mount Shields Formation member 3 beneath most of the Woodland Heights and Woodland Park subdivisions. This member is described by Bayuk as predominantly interbedded red and green argillites and siltites. The Mount Shields Formation member 2 is present near the surface at the west end of the Woodland Heights subdivision. Member 2 is described as reddish-orange quartzite. According to Bayuk, the finer grained rock of member 3 has more abundant and smaller fractures or jointing than the coarser quartzite of member 2. From Bayuk's Geologic Cross Section W-E and Bayuk's Plate 1, the contact between member 2 and the overlying member 3 strikes roughly north-south and dips about 25 to 30 degrees east.

The argillites, siltites, and quartzites that form the bedrock aquifer are metasedimentary rocks that have virtually no primary porosity, and groundwater is expected to occur principally as water occupying joints or fractures in the rock. Bedrock aquifers of this nature typically produce modest amounts of water, usually adequate for house or stock wells. The abundance of fractures probably diminishes with depth, as shown by Bayuk's analysis of specific capacity and well depth, and as is common for fractured crystalline rocks (Freeze and Cherry, 1979). Bayuk noted that specific capacities of wells decrease in the study area by a factor of 4 below 250 feet.

Potentiometric Surface

Bayuk (1989) presented potentiometric maps for three sets of groundwater-level measurements



HAYES CREEK CONTROLLED GROUNDWATER AREA
MONITORING WELL NETWORK - 1997
CONTOUR INTERVAL 100 FEET

SCALE - FEET

0 500 1000

HC33 1985-86 MONITORING WELL & ID (BAYUK, 1986)

HC15 1997 DNRC MONITORING WELL & ID

WOODLANDS PARK GROUPING OF GROUNDWATER LEVEL GRAPHS IN FIGURES 6, 7, AND 8

Figure 2. Locations of Wells Monitored in the Hayes Creek Area

Table 1. Wells Monitored by DNRC - 1996 and 1997

WELL	NAME	LOCATION	DEPTH (FEET)	MEASURING POINT ELEVATION (FEET)	WATER DEPTH (FEET)	MBMG ID	DNRC WATER RIGHT
HC-1	LANGENDERFER	12N20W10BACB	140	3369[1]	125		C091250
HC-2	SWARTLEY	12N20W10BABC	100	3460[1]	100		C091268
HC-3	BODDY	12N20W10BABB	100	3445[1]	80		C017199
HC-13	WOODWORTH	12N20W10ABBC	175	3397[1]	90		C091251
HC-15	KAST	12N20W10BAAD	120	3386[1]	51	M:67132	C064601
HC-19	KNUDSEN	12N20W10BADB	220	3401[1]	130	M:144640	C091343
HC-20	WHALEY	12N20W10BADA	23	3304[1]	23	M:145875	C091247
HC-21	MCCOOL	12N20W10BADA	180	3371[1]	60	M:67149	C092175
HC-25	VACURA	12B20W10ABBD	320	3387[1]	100	M:67153	C057780
HC-27	FLATEN	12N20W10ABDB	180	3340[1]	35		C057815
HC-31	LAVERY	12N20W10ABDA	250	3382[1]	125	M:67148	C053896
HC-32	MYERS	12N20W10ABAD	160	3381[1]	111		UNUSED
HC-33	DATSOPOULOS	12N20W10ABAA	280	3379[1]	91	M:67155	C053969
HC-34	DATSOPOULOS	12N20W10ABAA	180	3380[1]	70		
HC-41	SHAFFNER	12N20W10AADA	55	3165[1]	21		C025195
HC-44	RENEAU	12N20W10BAAA	220	3393[2]	95	M:67144	C083684
HC-45	CRONYN	12N20W09AAAA	300	3593[2]	60	M:126232	C098058
HC-46	GRAY	12N20W10BCDA	320	3542[2]	88	M:67179	C075259
HC-47	GARRICK	12N20W10BCAB	165	3498[2]	55	M:124620	C081027

NOTES:
1. MEASURING POINT ELEVATION FROM BAYUK (1989)
2. MEASURING POINT ELEVATION ESTIMATED FROM MAP ELEVATION OF WELL

made during his research. The maps are for July 26 and December 31, 1985 and for April 8, 1986. New maps were created using Bayuk's data tables for these same times to ease comparisons with the groundwater level measurements made in 1996 and 1997. Since the only available storage coefficient (0.004, from Bayuk's Test 5) suggests confined conditions, the "Groundwater Surface" maps in this report are potentiometric surface maps.

Figure 3 is the groundwater surface map generated using Bayuk's data from December 1985. The groundwater surface slopes about 50 feet vertically per 1000 feet horizontally beneath the central and west part of the Woodland Heights and Woodland Park subdivisions, similar to the land surface. The groundwater surface is about twice as steep southeast of the subdivisions along the edge of the bedrock bench on which the subdivisions are built. This appears as the closely spaced groundwater contours labeled 3140 to 3260 in Figure 3. The inset surface plot of the groundwater map is helpful in visualizing the nature of the groundwater surface in the area mapped. The left edge of the surface plot is about where Hayes Creek is found, as can be seen on the map where the groundwater contours end. Note that the groundwater table is at about the same elevation as Hayes Creek, and tends to slope toward the creek rather than away from it.

Another groundwater surface map is shown in Figure 4. This map shows groundwater elevations measured in wells in April 1997. The additional wells west of the Woodland Heights and Woodland Park subdivisions allow a rough definition of the shape of the potentiometric surface in a larger area than was previously possible.

Seasonal Groundwater-Level Fluctuations

Surface plots of similar data for the three times that Bayuk mapped for 1985 and 1986 are shown in Figure 5. Note the depression of the groundwater surface that occurs due to pumping wells in the subdivision as shown in the July 1985 plot. The extent of the depression is limited, occurring in the central parts of the subdivisions. The depression recovers during winter months.

Available groundwater-level data for all of the wells monitored by DNRC in 1996 and 1997 are shown in Figures 6, 7 and 8. Most of these wells were monitored by Bayuk during 1985 and 1986, and for these wells the earlier measurements are also shown for comparison. The locations of the named areas on the graphs are shown in Figure 2. In these graphs, the influence of pumping is apparent as falling groundwater levels in most wells during the summer months and rising groundwater levels at other times of the year. Note that groundwater depths in nearly all of the wells are in about the same range in 1996 and 1997 as they were 1985 and 1986. The water level measurements for these wells are listed in Appendix A.

The impact of pumping is most evident in the Woodlands Park, Southeast Woodland Heights, and Central Woodland Heights areas. Water levels in these wells vary seasonally by 40 to 80 feet, creating the cones of depression illustrated in Figure 5. At some wells, the graphs suggest that the groundwater-level recovery may be incomplete at the onset of the next irrigation season. For example, water levels in the Woodland Park area wells (Figure 6 Graphs A and B) appear to

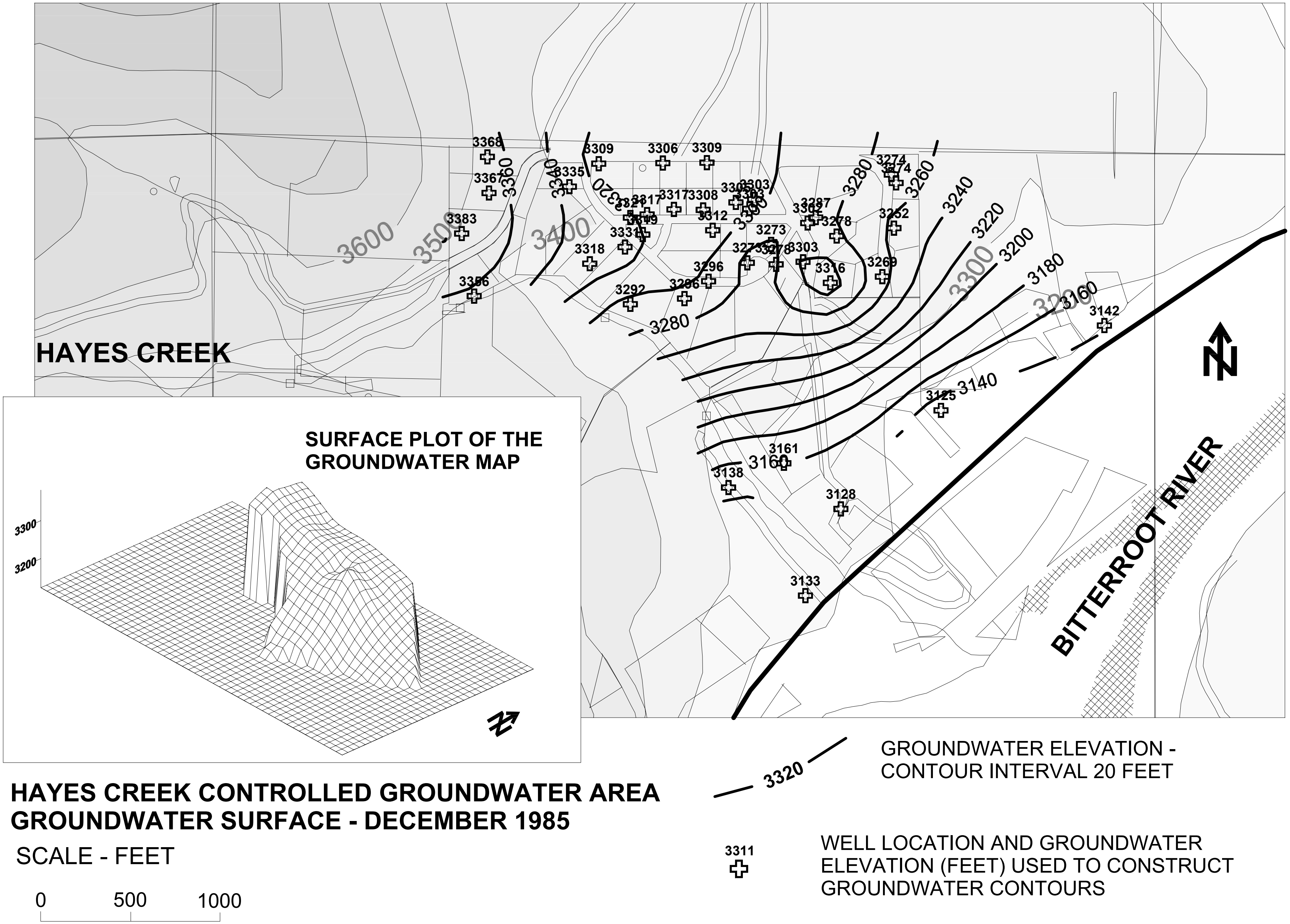


Figure 3. Groundwater Surface December 1985 (data from Bayuk, 1989)

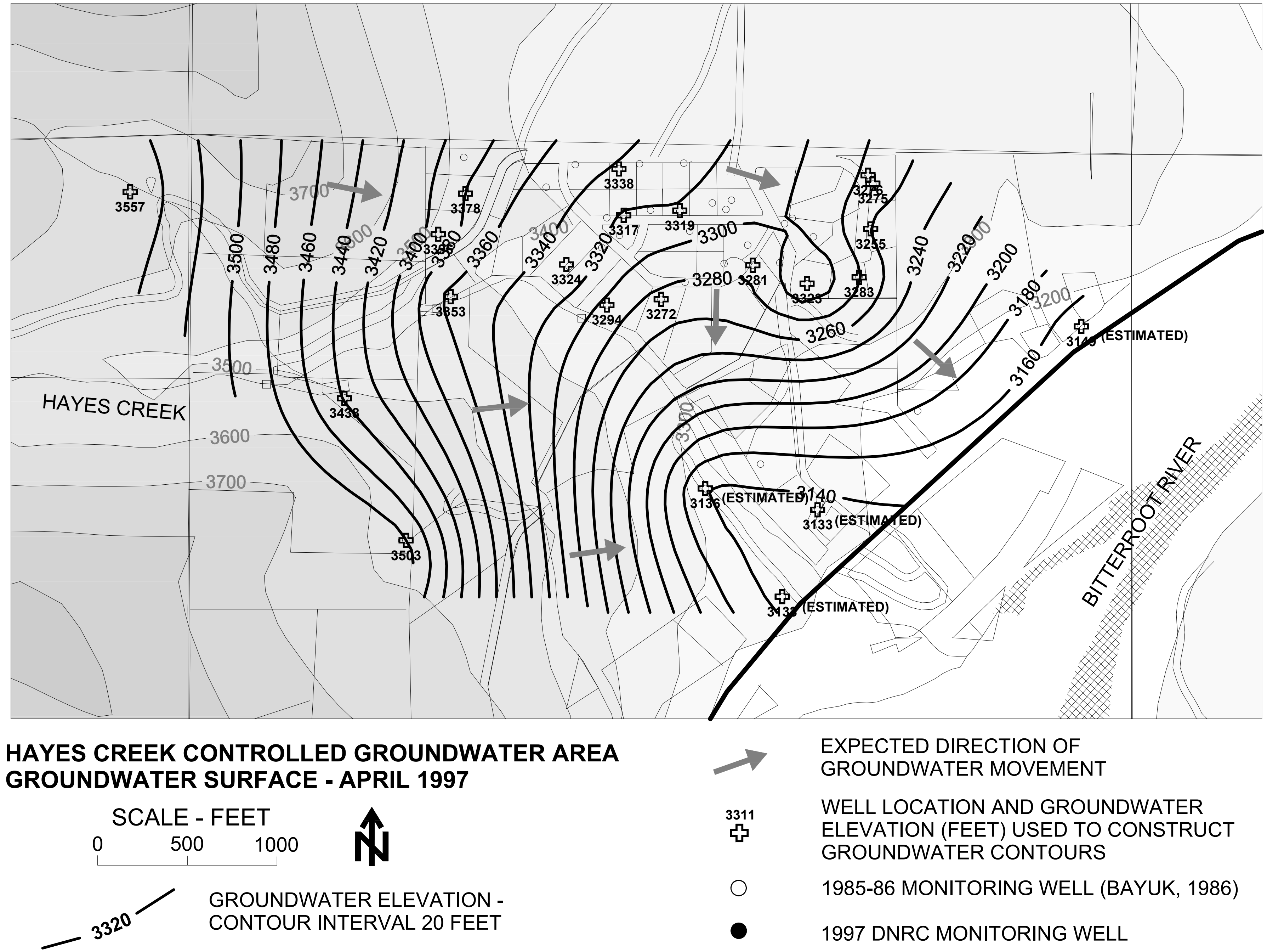


Figure 4. Groundwater Surface - April 1997

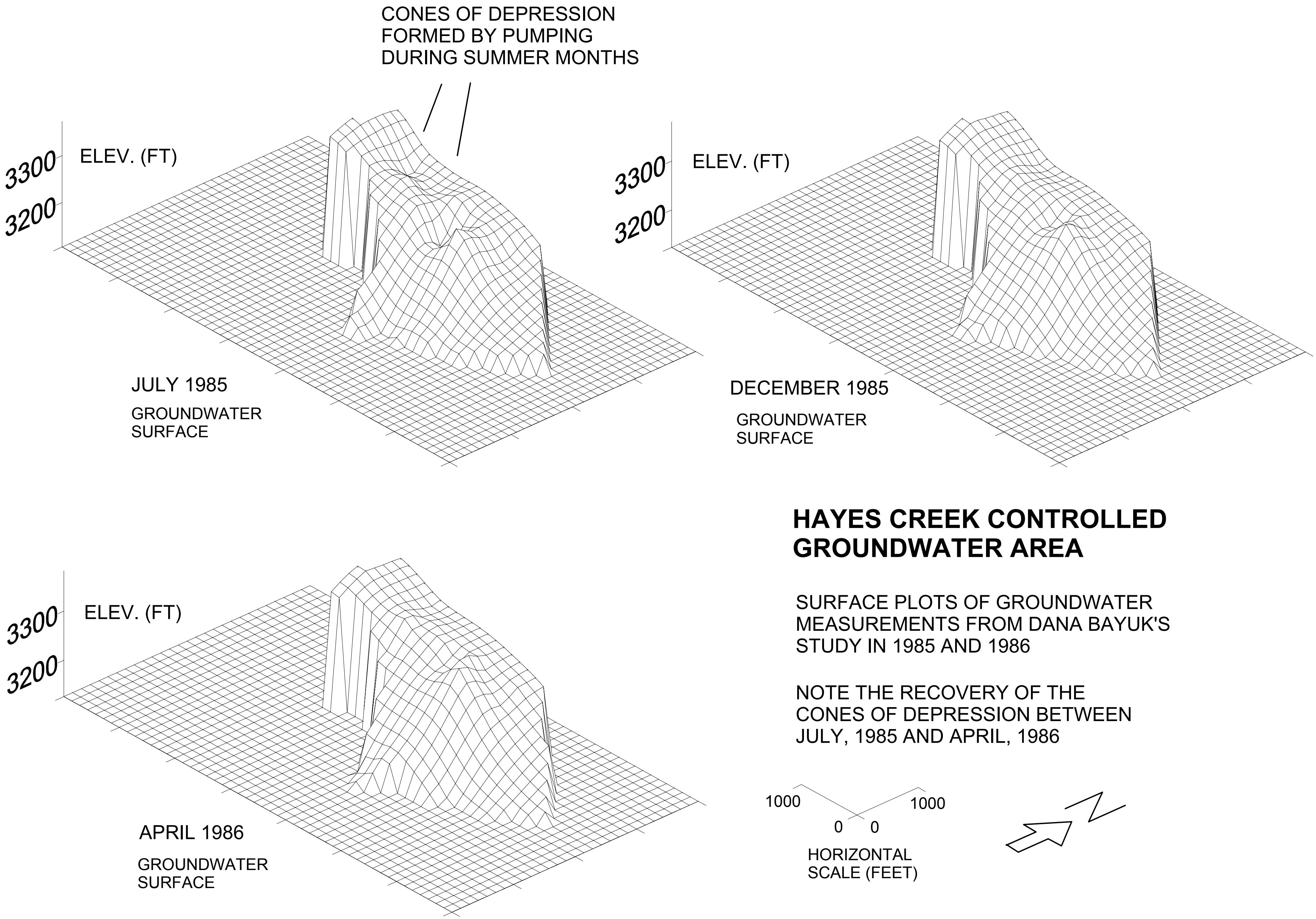


Figure 5. Surface Plots of Groundwater Measurements in 1985 and 1986 (data from Bayuk, 1989)

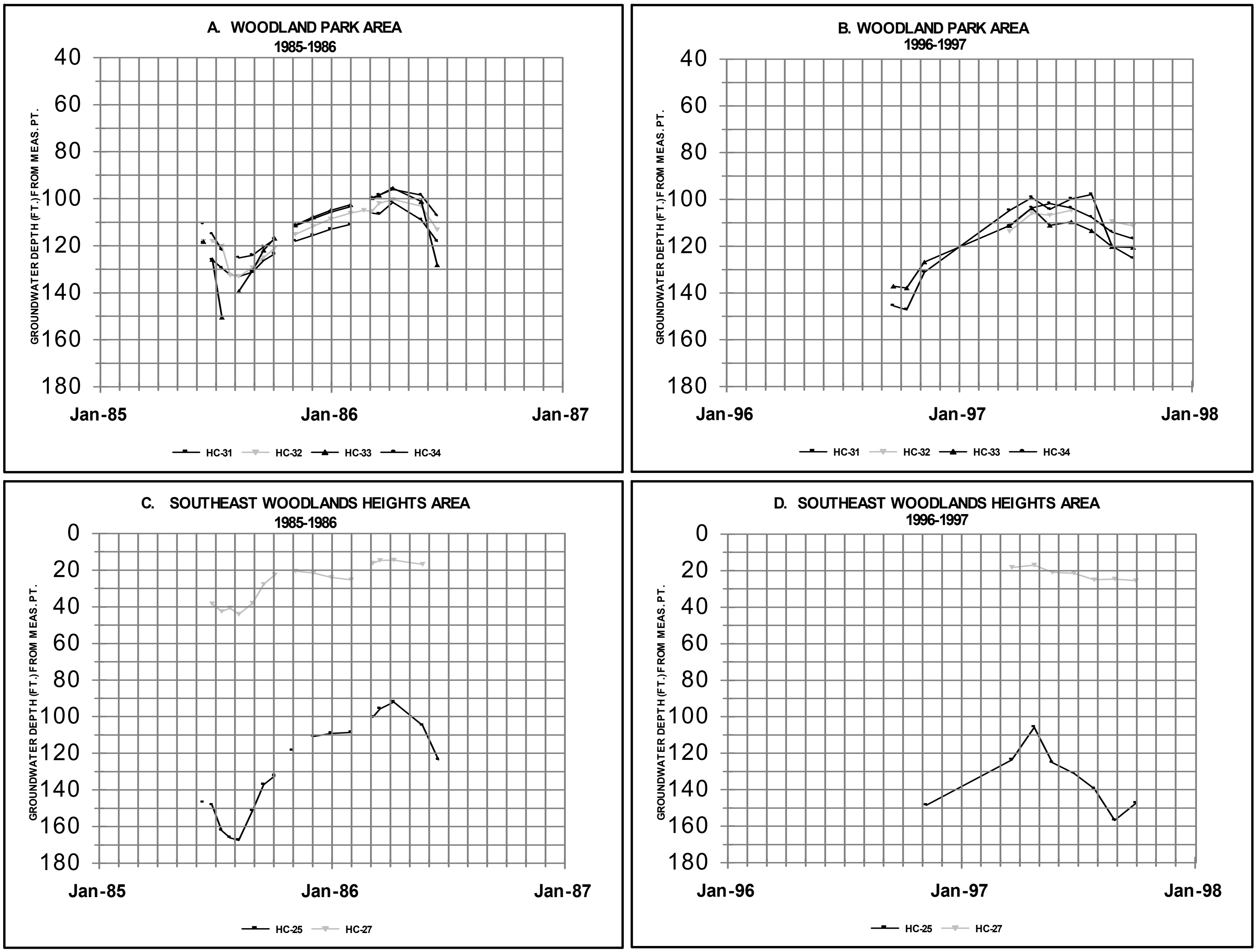


Figure 6. Groundwater Levels in the Woodlands Park and Southeast Woodlands Heights Areas

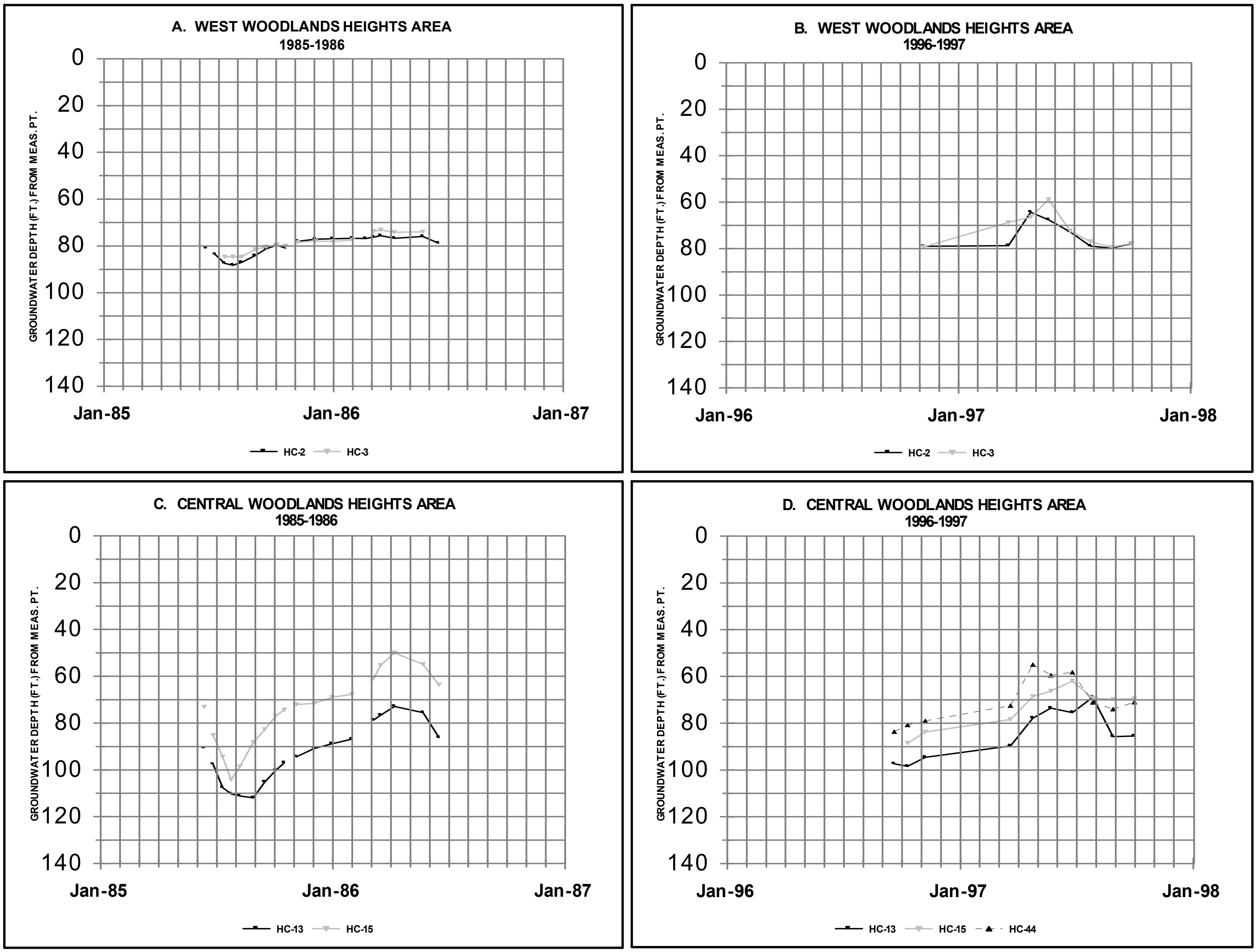


Figure 7. Groundwater Levels in the West and Central Woodlands Heights Areas

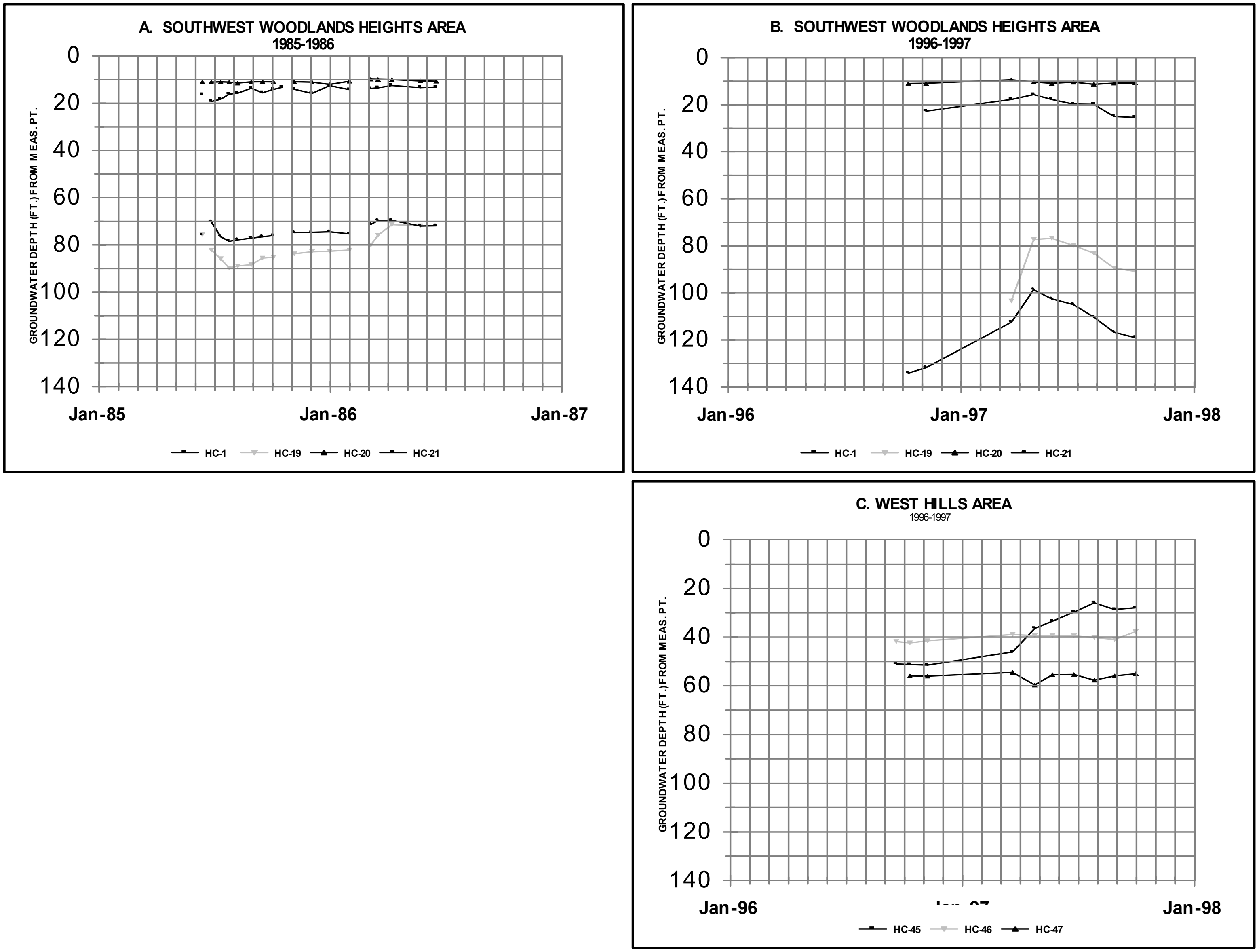


Figure 8. Groundwater Levels in the Southwest Woodlands Heights and West Hills Areas

still have been recovering between March and April in both 1986 and 1997. Part of the water level rise during March and April, however, is likely due to the effects of Spring thaw conditions. Note that the rate of recovery in wells in the Central Woodland Heights area (Figure 7, Graphs C and D) and especially the Southeast Woodland Heights areas (Figure 6, Graphs C and D) slows over the winter, followed by a noticeable water level rise during March and April.

Groundwater levels in the West and Southwest Woodland Heights areas are more stable, with seasonal variations of 15 feet or less in most wells. For some reason, the groundwater level in well HC-21 was markedly lower, and changed more over the seasons, during the recent measurements than in 1985 and 1986. In 1985 and 1986, the groundwater depth ranged from about 70 to 80 feet, whereas groundwater depths ranged from about 100 to 135 feet during 1996 and 1997 (Figure 8, Graphs A and B). This could be a result of an expansion of the impacts of pumping from areas to the north and east where drawdowns are large, or may reflect some change that has occurred in groundwater withdrawal practices at this or other neighboring wells.

Groundwater levels in the three wells in the West Hills area (Figure 8, Graph C) were relatively stable, showing no evidence of a groundwater depletion problem during the summer of 1997.

The distribution of groundwater-level changes induced by pumping for irrigation is mapped in Figure 9. This map compares groundwater levels measured by Bayuk in July 1985 to those measured in April 1986. In July 1985, groundwater levels were depressed due to pumping for irrigation, while in April 1986 groundwater levels were higher after a long period of recovery. The map shows the recovery of groundwater levels in wells monitored. Note that the contours mapped south of the Southeast Woodland Heights area are based on only one well, well HC-36, where a recovery of 89 feet was measured. Because there is only one data point in that part of the map, the confidence level of these contours is much less than for the areas to the north where the contours are based on numerous wells. The 89-foot recovery may be more indicative of conditions locally at the well than in the surrounding aquifer as a whole. Other than well HC-36, the most drastic seasonal changes occur in the Southeast Woodland Heights area. Note the 50 and 60-feet water level change contours in this area. Water level changes between 30 and 70 feet are also mapped for areas within the Central Woodland Heights and Woodlands Park areas. Note that around the west, south, and east margins of the groundwater data, groundwater level changes are quite modest compared with those in the central part of the contoured data.

A similar map comparing groundwater levels measured April 1997 and September 1997 is shown in Figure 10. During 1997, groundwater levels were lowest in most wells in September rather than July. This map depicts falling groundwater levels, rather than recovery, so negative values are mapped in the subdivisions where water levels drop during summer months. Note that the pattern of drawdown is similar to the recovery mapped for 1985 and 1986. Overall, there was less drawdown in the area from pumping in the summer of 1997 compared with the summer of 1985. The greatest water-level change occurred in the Southeast Woodlands Heights area, where groundwater levels were drawn down 42 feet in well HC-25. For comparison, the measured recovery in this well after the summer of 1985 was 74 feet.

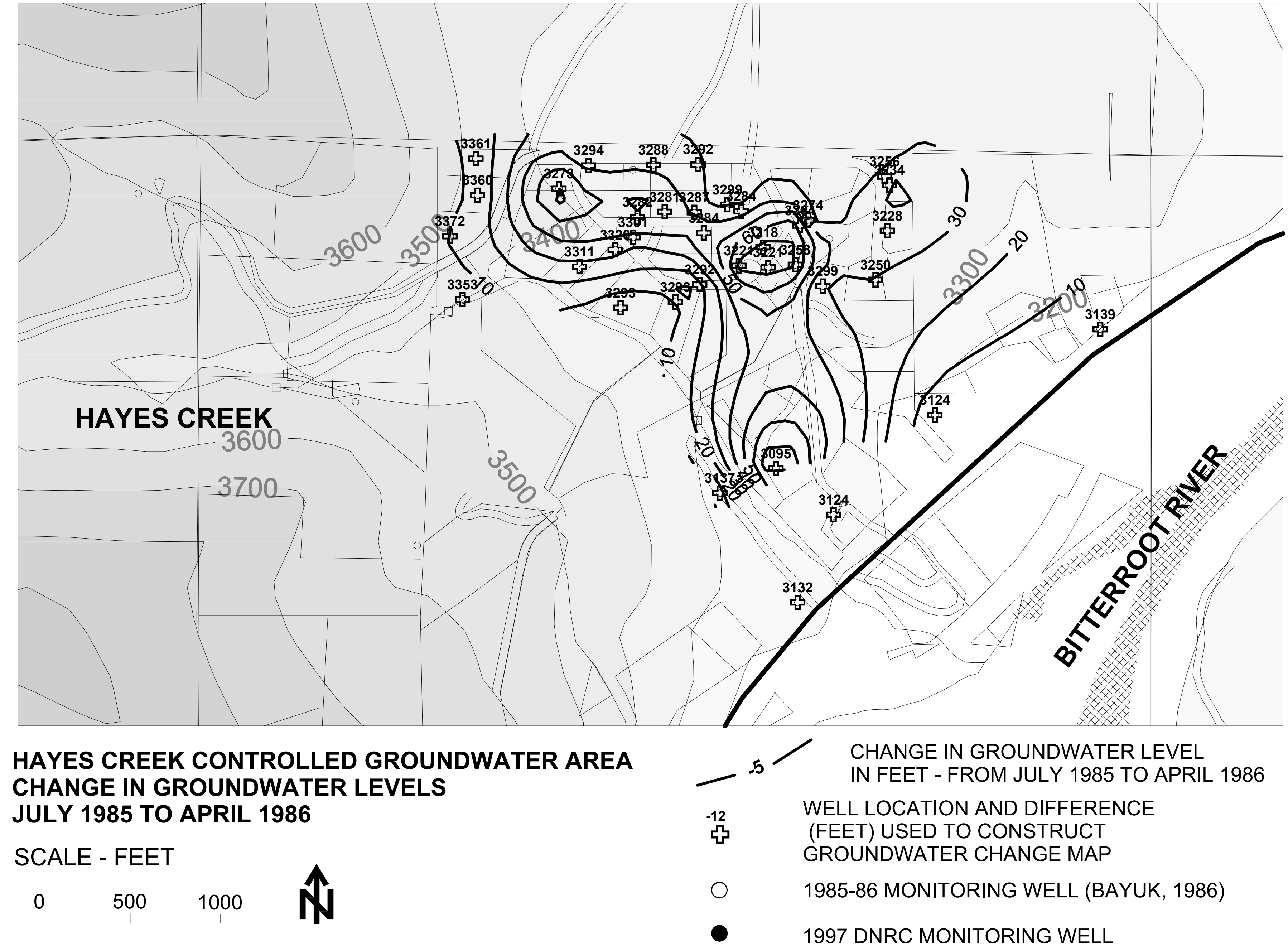


Figure 9. Change in Groundwater Levels July 1985 to April 1986 (data from Bayuk, 1989)

HAYES CREEK CONTROLLED GROUNDWATER AREA
CHANGE IN GROUNDWATER LEVELS
APRIL 1997 TO SEPTEMBER 1997

SCALE - FEET

0 500 1000

-5 CHANGE IN GROUNDWATER LEVEL IN FEET - FROM APRIL 1997 TO JULY 1997

-12 WELL LOCATION AND DIFFERENCE (FEET) USED TO CONSTRUCT GROUNDWATER CHANGE MAP

○ 1985-86 MONITORING WELL (BAYUK, 1986)

● 1997 DNRC MONITORING WELL

Figure 10. Change in Groundwater Levels April 1997 to September 1997

Figure 11 shows surface plots of the seasonal high and low groundwater levels for the 1985-1986 period and for the 1996-1997 period. The smoother appearance of the 1996-1997 data is caused by the fact that there are less groundwater elevation points used to construct the plot, due to fewer monitoring wells.

Water Budget

Bayuk (1989) generated useful data and estimates that provide a framework to analyze the water budget for the bedrock aquifer underlying the Woodland Heights and Woodlands Park subdivisions. However, there are some flaws in Bayuk's interpretation of the water budget. A revised view is presented here, along with explanations of how this view is developed.

Groundwater Movement

The groundwater contour maps in Figures 3 and 4 show groundwater head distribution in the bedrock aquifer. Groundwater head is measured as the water-level elevation at a given point in the aquifer, and may consist of elevation head (unconfined aquifer) or a combination of elevation and pressure head (confined aquifer). Groundwater movement is driven by head differences, so groundwater movement is generally downgradient, or perpendicular to the groundwater surface contours shown in Figures 3 and 4. Arrows in Figure 4 show the expected groundwater flow direction at a few places. The groundwater head distribution in Figure 4 suggests that groundwater in the bedrock system moves generally down-basin toward the Bitterroot River. The mapped groundwater gradient near Hayes Creek generally parallels the direction of the stream. So groundwater underlying areas near the stream is expected to move largely downhill in the same direction as the stream. In the lower part of the study area between the subdivision and US Highway 93, the groundwater map suggests that groundwater may move toward and discharge to Hayes Creek.

Groundwater in Storage

Estimates of water stored in and moving through the aquifer can be made using the aquifer transmissivities and storage coefficient derived by Bayuk from aquifer tests, the mapped groundwater gradient, and the geometry of the aquifer. Consider the area for which the groundwater contours are mapped in Figure 3. The area is about 97 acres, or 4,225,000 ft^2. The only storage coefficient available for the study area is from Bayuk's (1989) aquifer test #5. This test analysis yielded a storage coefficient of 0.004. For the upper 300 feet of saturated aquifer, the water in storage based on these numbers is:

$$4{,}225{,}000\ ft^2 \times 0.004 \times 300\ ft = 5{,}070{,}000\ ft^3 \text{ or } 116 \text{ acre-feet}$$

COMPARISON OF THE GROUNDWATER SURFACE MAPPED IN 1985-86 TO THAT MAPPED IN 1997

THE SURFACE PLOTS SHOW GROUNDWATER LEVELS
IN THE AREA WHERE GROUNDWATER CONTOURS ARE
MAPPED IN FIGURE 3.

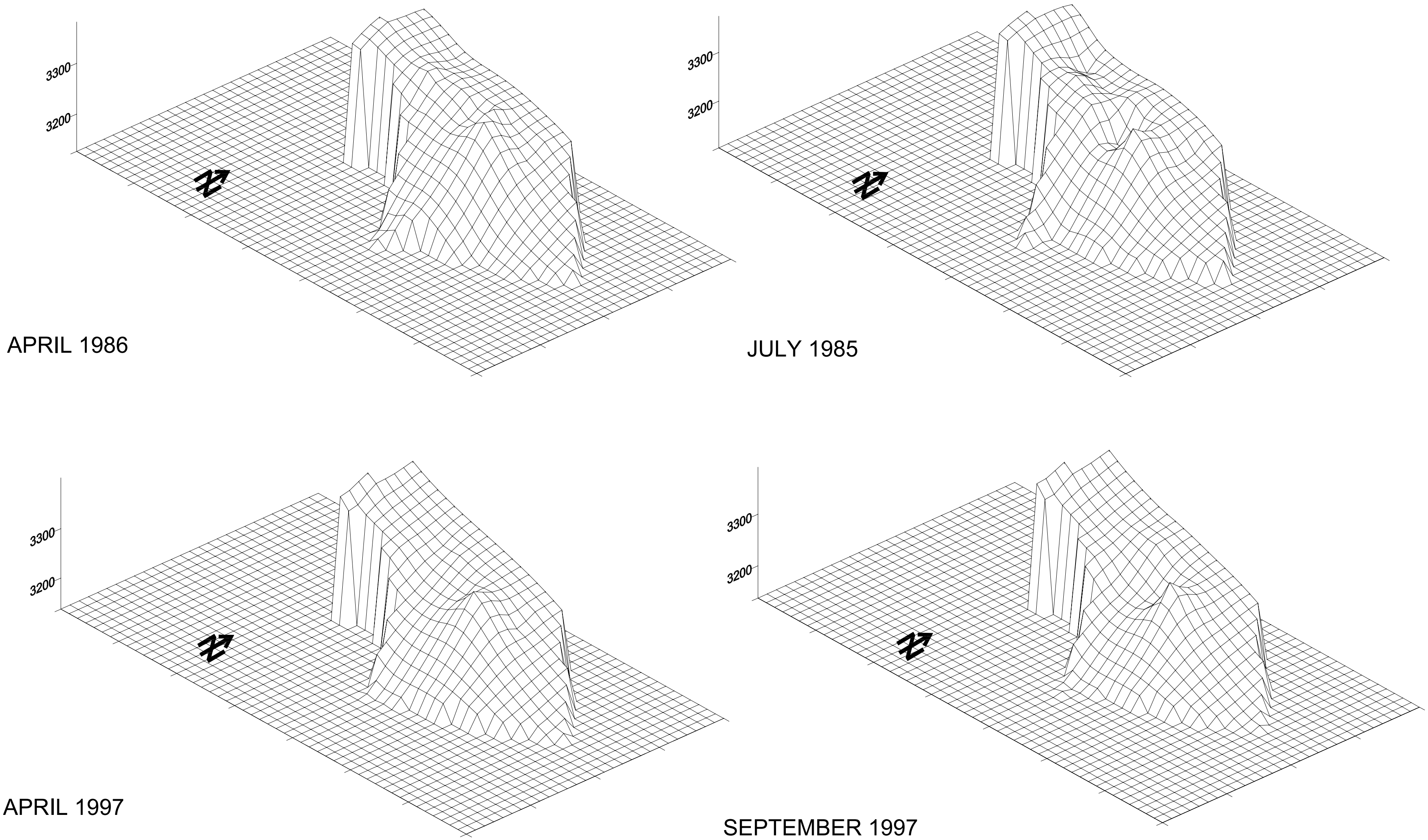


Figure 11. Comparison of the Groundwater Surface Mapped in 1985-1986 to that mapped in 1996-1997

Groundwater Flow Rate Through the Bedrock Aquifer

The amount of groundwater moving into the area is estimated by evaluating the groundwater gradient, the transmissivity of the aquifer, and the width of the aquifer. Bayuk's aquifer test data yielded aquifer transmissivities ranging from 170 to 3700 gpd/ft (23 to 495 ft^2/day, respectively). The groundwater gradient (slope of the groundwater surface) at the west edge of the area can be estimated from Figure 4. The gradient as mapped is about 110 feet per 1000 feet, or 0.11. Using the geometric mean transmissivity calculated by Bayuk (80 ft^2/day), and considering an aquifer width of 1000 feet, the rate of groundwater movement from the west is estimated as:

$$(80\ ft^2/day \times 0.11 \times 1000\ ft) = 8{,}800\ ft^3/day \text{ or } 0.10 \text{ cubic feet per second (cfs)}$$

Similar calculations by Bayuk (1989) using a different method yielded estimates of average monthly groundwater inflow of 211,000 ft^3, equivalent to about 6,900 ft^3/day or 0.08 cfs.

In Bayuk's (1989) water budget analysis, the "mass balance" equation that he developed was reasonable, however, the choice of solving the equation for 'groundwater out' is problematic. The groundwater gradient at the east, downgradient edge of the study area can be assessed using groundwater elevations measured in wells HC-31 and HC-40. In July 1985, when groundwater levels are at seasonal lows due to pumping, the gradient was 0.15, while in April 1986, when groundwater levels are at high levels, the gradient was 0.19. Thus, the gradient increased about 26% from July 1985 to April 1996.

Since other factors that control groundwater flow (transmissivity and width of the aquifer) remain essentially unchanged, the groundwater flow rate out of the aquifer to the east should also increase by roughly 25%. The transmissivity in this part of the aquifer may be lower, as the two lowest transmissivities from Bayuk (1989) were in wells at this end of the subdivision. The steeper groundwater gradient east and southeast of the Woodlands Park subdivision is consistent with this interpretation. The 'groundwater out' for July 1985 can be estimated by the same equation as the 'groundwater in' above. Using the average transmissivity reported for wells HC-25 and HC-31(26 ft^2/day), and the wider aquifer width of about 2000 feet from Hayes Creek to the northeast edge of the area contoured in Figure 3 (this contour approximates a groundwater flow line extending from the north edge of the subdivision), yielding:

$$(26\ ft^2/day \times 0.15 \times 2000ft) = 7800\ ft^3/day \text{ or } 0.09 \text{ cubic feet per second (cfs)}$$

A similar calculation for April 1986, when the gradient is higher, gives a result of 9800 ft^3/day or 0.11 cfs. By solving the "mass balance" equation for 'groundwater out', Bayuk (1989) estimated groundwater outflow to range from 155,000 ft^3/month to 452,000 ft^3/month (0.05 to .17 cfs). If changes of groundwater outflow of this magnitude actually occurred, it would have been manifested as extreme changes in mapped conditions in the aquifer, such as the groundwater gradient or saturated thickness of the aquifer in the outflow area. Neither of these occurs in any data collected. In fact, because of the uncertainties in irrigation withdrawal volumes, recharge from the creek, and precipitation recharge, it would make more sense to solve the water budget equation for one or more of these parameters than for groundwater outflow. Groundwater outflow is expected to be in the same range as groundwater inflow, and should have modest seasonal changes in comparison to other components of the water budget.

Precipitation

Bayuk measured precipitation at the study area, and his estimate of annual precipitation from July 1985 through June 1986 was 18.57 inches (Bayuk, 1989, Appendix E). This may be close to the average annual precipitation at this site, based on a map of annual average precipitation (US Dept. of Agriculture, 1981). The map shows average annual precipitation ranging from 18 inches at the lower end of the basin to 40 inches at the extreme west end. Bayuk used estimates of monthly potential evapotranspiration, precipitation, and water applied for irrigation to derive values of excess water assumed to be recharging the aquifer. In that analysis, some 4 inches of water were deemed available for recharge to the aquifer, with 22% occurring in September 1985 after heavy rains and the other 78% (3.12 inches) occurring in December, January and February the following winter. In actuality, much of the precipitation accumulating in the winter would likely occur as snow on frozen ground, and recharge would occur when it thaws in the spring. Some part of this would be expected to run off as surface water. Because of this, recharge resulting from precipitation in the winter could be much less than 3 inches, and it would usually occur largely in the spring. As noted in the next section, *Groundwater Withdrawals*, the recharge in the spring may result from as little as 0.5 inches of infiltrating water.

Groundwater Withdrawals

Groundwater withdrawals from the bedrock aquifer in the study area are not metered. Bayuk (1989) estimated withdrawals from the subdivisions based on the results of another study by Ver Hay (1987). Domestic water use was estimated to be about 50 gallons per day (gpd) per person. In Bayuk's water budget, this water was considered recycled to the aquifer. Irrigation use was estimated to be 0.051 gpd per square foot of yard area. This is equivalent to about 8 inches of water based on the yard areas estimated by Bayuk, or 14,000 gallons per day from the Woodland Heights and Woodland Park subdivisions. This represents a seasonal volume of 4.3 acre-feet of irrigation water pumped at the subdivisions. For comparison, if there are 100 to 150 persons in these subdivisions, some 5,000 to 7,500 gallons per day would be pumped for domestic use. Over the course of a year, domestic use would be some 5.6 to 8.4 acre-feet.

A water right application (Permit P098110) from a rural subdivision in the Missoula area where groundwater withdrawals are metered provides another source of information to evaluate irrigation withdrawals. The Spring Meadow subdivision consists of about 65 households, with lots about an acre in size. The original water right for the subdivision was for 37 acre-feet. By 1997, it was found that water use was as high as 106 acre-feet per year. This equates to 1.63 acre-feet (530,000 gallons) per household per year. Assuming a household with three people and domestic use of 50 gpd per person, domestic use would account for 55,000 gallons per year. This leaves 475,000 gallons per year per household that can be attributed to irrigation. For a 100-day irrigation season, the daily use of a household in the Spring Meadow subdivision is estimated to be about 4,750 gallons per day. For the entire subdivision (about 65 households), irrigation use could account for as much as 308,000 gallons per day, or 94 acre-feet for the season. These figures show much greater withdrawals than estimated by Bayuk for the Hayes Creek area.

The Spring Meadow subdivision has relatively large lawns. Wes McAlpin, Water Resources Specialist for the Missoula Water Resources Regional Office, estimated that yards in the subdivision might be about 150 by 250 feet, which gives an area of 37,500 ft^2. Using the estimated irrigation use as calculated above, irrigation water applied at this subdivision is as much as 1.75 feet of water per year. This is about 2-½ times the 8 inches of water that Bayuk estimated. Using Bayuk's (1989) tabulation of yard areas, and the value of 1.75 feet of seasonal irrigation application from the Spring Meadow subdivision, the daily use at the Woodland Heights and Woodland Park subdivisions could be about 36,000 gallons per day, or 11 acre-feet per irrigation season. The total of Bayuk's yard areas for the subdivision, however, is 6.4 acres. This seems quite low for a 51-acre subdivision, so even 11 acre-feet may be a considerable underestimate of actual use.

An evaluation of groundwater use for irrigation can be approached in another way. Bayuk (1989) calculated monthly storage changes in the aquifer, but never used these for assessing irrigation withdrawals or recharge, because he solved the groundwater budget equation for 'groundwater out.' Consider the groundwater-level rise in the bedrock aquifer between July 1985 and April 1986, shown in Figure 9. The groundwater-level rise can be separated on the basis of hydrographs to recovery from pumping occurring from about August through January, and response to spring recharge occurring in February, March, and April. The groundwater level rise can be used to estimate changes in the volume of groundwater in storage. The change in the volume of groundwater in storage is estimated by finding the difference between the groundwater surfaces, and multiplying this difference by the storage coefficient. The volume difference for the entire period is 151 million cubic feet. The only available storage coefficient is 0.004 (Bayuk 1989). The total increase in the volume of groundwater in storage is therefore estimated by:

$$151{,}000{,}000 \text{ ft}^3 \times 0.004 = 604{,}000 \text{ ft}^3 \quad (13.9 \text{ acre-feet})$$

70% (420,000 ft^3 or 9.6 acre-feet) of this difference occurred during the period August through January, and 30% (184,000 ft^3 or 4.2 acre-feet) from February through April. Interestingly, only about 0.5 inches of recharge is required to cause the observed groundwater level rise in the aquifer in the spring if a storage coefficient of 0.004 is assumed. A similar calculation using the volume difference calculated from groundwater level declines from April 1997 to September 1997 yields a groundwater volume change of 290,000 ft^3 or 6.7 acre-feet.

Based on this information, groundwater storage change estimates are 6.7 acre feet in 1997 and

9.6 acre-feet in 1985. Because storage coefficients can vary considerably, these results are only best guesses based on the one storage coefficient available. Also, since groundwater storage may not be the only source of water contributing to groundwater withdrawals, these should be considered minimum values for seasonal pumping.

In summary, Bayuk's estimate of about 4.3 acre-feet for summer withdrawals of groundwater for irrigation is probably too low. Considering that only one storage coefficient is available, that the total yard size area may exceed 6.4 acres, and that groundwater storage calculations should reflect minimum withdrawals, it is estimated that actual usage could range anywhere from about 7 to 30 acre-feet per year. If groundwater withdrawals in the area were metered, this information combined with groundwater level data collected simultaneously, could be used to determine a more accurate bulk storage coefficient.

Hayes Creek - Relation to the Bedrock Aquifer

Bayuk (1989) estimated the flow of Hayes Creek using a culvert at one site, SW-1, and measured the flow with weirs at three sites, SW-2, SW-3, and SW-4. The locations of these sites are shown in Figure 2. From this data Bayuk concluded that the average flow through weir SW-2 is 38.7% less than that through culvert SW-1, and that streamflow is nearly constant through weirs SW-2, SW-3, and SW-4. The average loss of 38.7% of streamflow between SW-1 and SW-2 was interpreted by Bayuk to be due to leakage of surface water to the groundwater system. Figure 12 shows the results of Bayuk's measurements at SW-1 and SW-2, and the difference between the measurements that Bayuk thought was lost to the bedrock aquifer.

There are several problems with the interpretation that 38.7% of the flow in Hayes Creek is lost to the groundwater system in the reach between culvert SW-1 and weir SW-2. First, it would be somewhat remarkable for this much water to be lost within a reach 1100-feet long just upgradient from the Woodland Heights and Woodland Park subdivisions. Such losses might be expected if the bedrock consisted of cavernous limestone or if thick sand and gravel aquifers were present, but seem unlikely in the situation of thin alluvial debris and fractured argillite bedrock.

Second, the groundwater gradient in the area slopes generally parallel to or toward the creek, rather than away from it. According to Bayuk, the largest streamflow loss occurred during April 1985. During that month, the streamflow loss calculated from the culvert SW-1 estimates and measurements at weir SW-2, averages about 1.6 cfs. This loss would amount to some 4,100,000 ft^3 for the month of April. This result agrees with Bayuk's figures, although in his report he refers to half the calculated recharge, because he reasoned that only half should apply to the area north of Hayes Creek. Considering that the natural groundwater flow through bedrock is estimated to be about 0.1 cfs, it seems unreasonable that the aquifer could move the average calculated streamflow loss of 1.6 cfs during April without drastic changes in gradient. There is no evidence of the extreme changes in gradient that would have to result from the introduction of this amount of water.

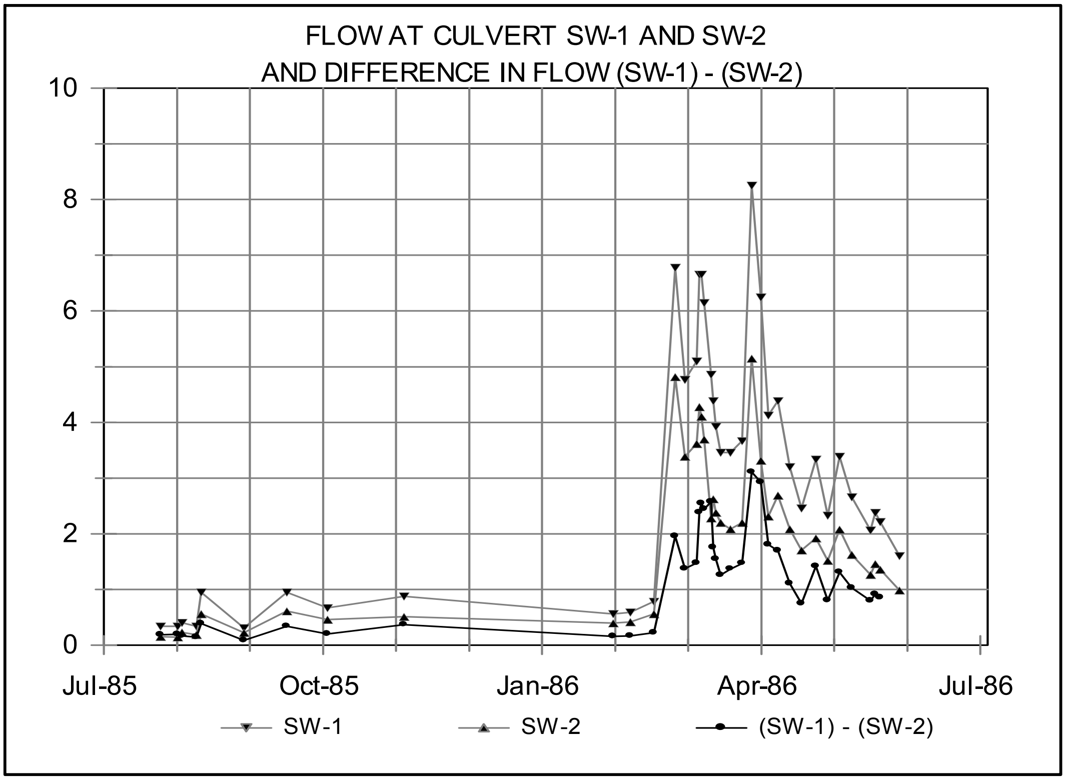


Figure 12. Flow estimated at culvert SW-1, weir SW-2, and difference in flow between SW-1 and SW-2 Data from Bayuk (1989)

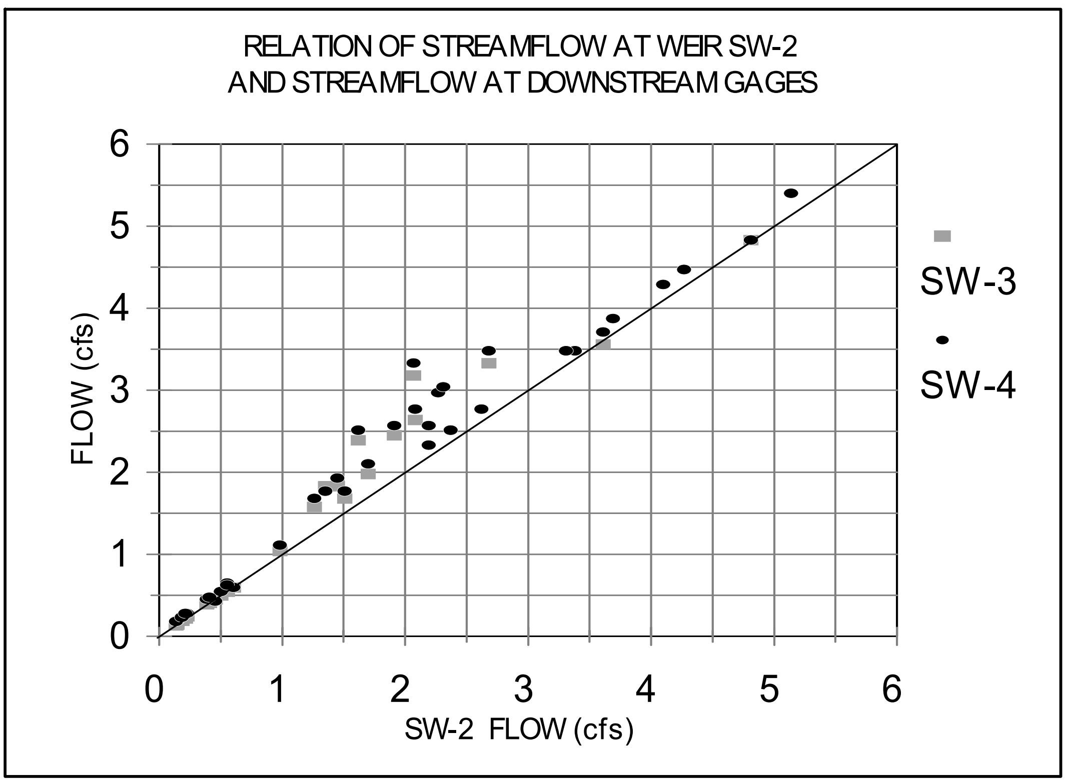


Figure 13. Relation of Streamflow at Weir SW-2 and Streamflow at Downstream Gages SW-3 and SW-4. Data from Bayuk (1989)

Third, the volume of water estimated to enter the groundwater system from Hayes Creek in April alone is equivalent to about 80% of the estimated total groundwater in storage in the upper 300 feet of the aquifer (5,070,000 ft^3) as calculated above in the *Groundwater in Storage* section. Therefore, groundwater levels could be expected to rise some 240 feet near the losing reach in response to the surface water losses. No such water level changes occurred anywhere in the study area. Based on these observations, it seems unlikely that Hayes Creek recharges the bedrock aquifer between culvert SW-1 and weir SW-2 as previously thought.

Figure 13 shows the measurements at weirs SW-3 and SW-4 plotted against the flows measured at SW-2 (data from Bayuk, 1989). There is no significant difference in the flows, as measurement error could account for the scattering of points mainly above the line of equal flow. However, Hayes Creek flow measurements at weirs SW-3 and SW-4 were often slightly higher than those at SW-2.

Groundwater Flow to the North

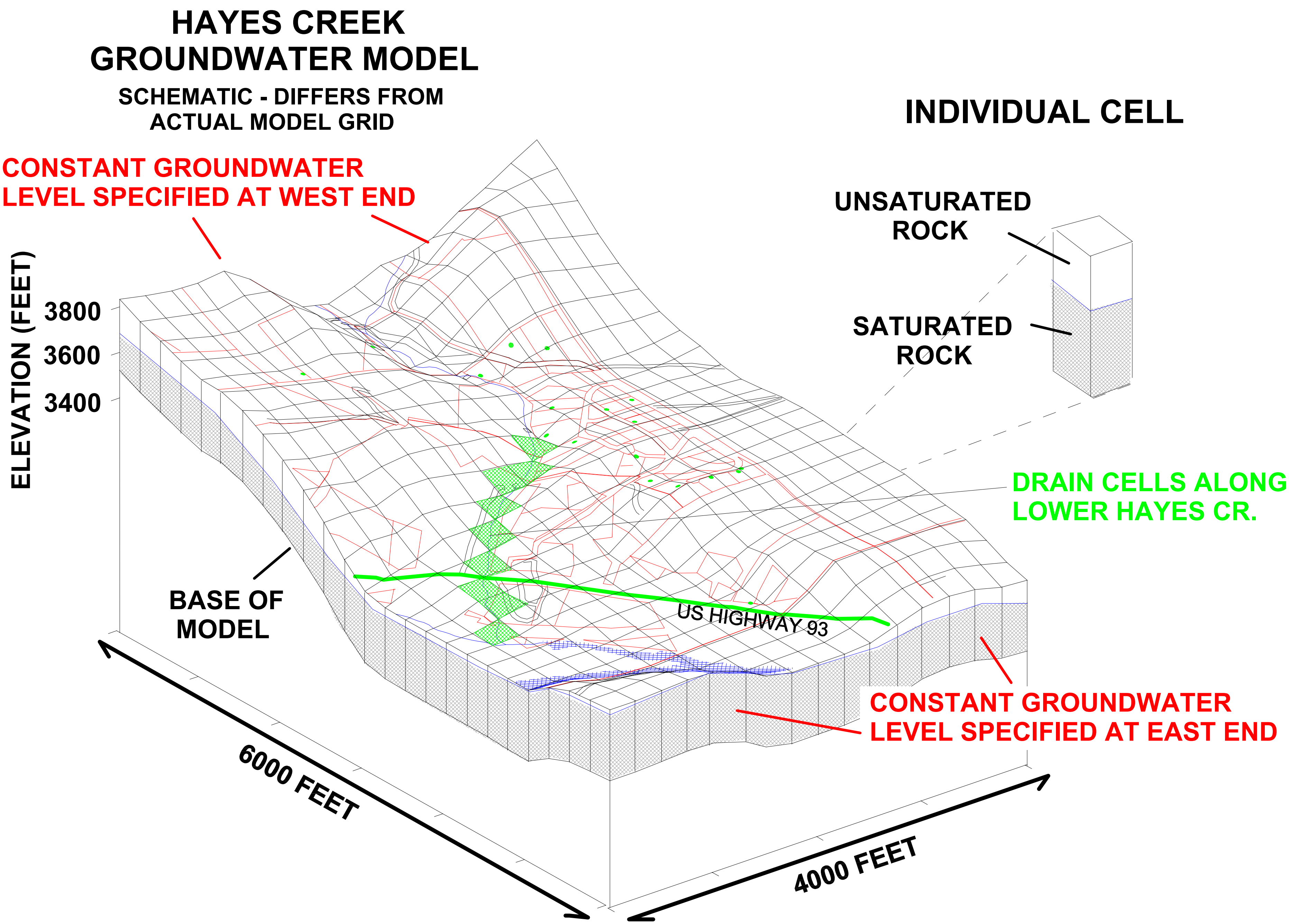
Bayuk (1989) surmised that because all of the water in the budget he developed could not be accounted for, that a significant amount of water must be diverted north out of the study area. If this were true, then the groundwater gradient would slope in that direction. Since the groundwater gradient slopes to the east or southeast along the north edge of the subdivisions (see Figure 4), there is no reason to suspect any significant amount of groundwater is diverted north out of the study area by faults.

Groundwater Model

General Description

A groundwater model was developed for the study area to examine how a fractured bedrock aquifer might respond to seasonal pumping for irrigation, and to test the water budget as developed above. The model was built using MODFLOW (McDonald and Harbaugh, 1984), a three-dimensional, finite-difference groundwater flow model in common use. The groundwater model is used as a tool to test questions about the Hayes Creek water budget -- it is not intended for use as a calibrated and verified model. The model was developed using a relatively simple framework and limited data, and as a result, there is considerable uncertainty associated with these results.

Figure 14 schematically illustrates the general setup of the model. The area modeled is about 6000 feet long in an east-west direction and about 4000 feet wide north to south. The model grid was constructed by dividing the study area into cells 200 feet in length and width, and 350 feet thick vertically. The top elevation of each cell was set to the approximate elevation of the land surface near the cell. Constant groundwater levels were specified at the western, upgradient end of the model and at the eastern, downgradient end of the model. The vertical thickness of 350 feet was used because, as discussed above, fracture permeability is expected to decrease



NOTE: THIS ILLUSTRATION SHOWS EACH CELL BEING 25O FEET WIDE - THE ACTUAL MODEL USED HAS CELLS 200 FEET WIDE

Figure 14. Schematic Diagram - Hayes Creek Groundwater Model

dramatically beyond depths of about a few hundred feet.

Boundaries and Aquifer Properties

The arrangement of boundaries used in the model is shown in Figure 15. The constant head cell boundaries the west and east ends of the model are based on the groundwater contours presented in Figure 4. The boundaries at the north and south limits of the active cell areas are no-flow boundaries. These are arranged to follow a flowpath perpendicular to the groundwater contours. Recharge is applied in the model at a constant rate of 0.9 inches per year.

The groundwater contours in Figure 4 suggest that the groundwater gradient is directed toward Hayes Creek in its lower reach near the east edge of the study area. In the groundwater model, drain cells are placed along the lower part of Hayes Creek to simulate groundwater discharging to the creek.

Hydraulic conductivities from Bayuk's (1989) five aquifer tests ranged from 0.11 to 1.5 ft/d. The two lowest values were obtained from tests at wells HC-31 (0.11 ft/d) and HC-25 (0.13 ft/d) which are in the Woodlands Park and Southeast Woodlands Heights areas as shown in Figure 2. The other reported values were 0.22 ft/d at well HC-10, 0.72 ft/d at well HC-16, and 1.5 ft/d at well HC-2 at the west end of the Woodlands Heights subdivision.

Hydraulic conductivity was initially set to 0.1 ft/d throughout the model. Adjustments were made to the model in various areas, shown in Figure 16, until the calculated groundwater surface was similar to the observed data. A value of 0.75 ft/d was assigned to cells in the central part of the Woodlands Heights subdivision to reflect the higher hydraulic conductivities reported in that area, which in turn forced the calculated groundwater contours to be more widely spaced as mapped in that vicinity. Hydraulic conductivities east and south of the Woodland Park area were decreased to 0.05 ft/d to generate the steep gradient observed in there. Hydraulic conductivities in cells near Hayes Creek were increased to 0.33 ft/d to help the drain cells assigned to lower Hayes Creek draw water out of the aquifer.

As noted earlier, only one storage coefficient is available for the study area, which Bayuk (1989) derived from an aquifer test. The impact of pumping groundwater for irrigation during summer months as tested by this model is highly influenced by the value of the storage coefficient. The value provided by Bayuk is 0.004, and this value was used in the model to produce the following results. At this time, without accurate pumping volumes, there are nearly infinite combinations of storage coefficients and pumping volumes that would produce similar drawdown calculations using the model. Consequently, the model is most useful to analyze the general nature of the system and expected impacts of the location and timing of drawdown and recovery, but is less reliable for estimating drawdowns. This could be improved if groundwater withdrawals are ever measured.

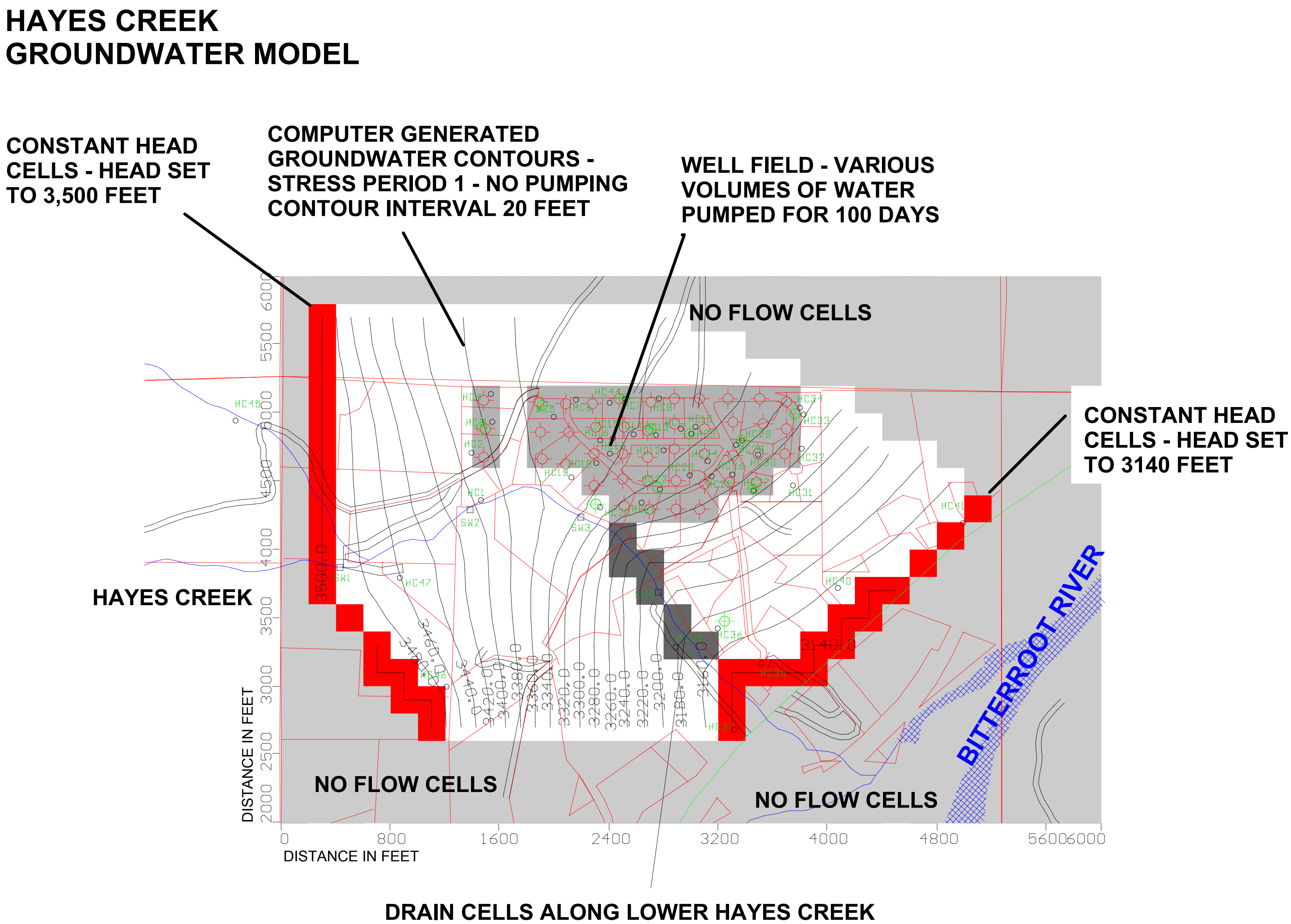


Figure 15. Boundaries and General Setup - Hayes Creek Groundwater Model

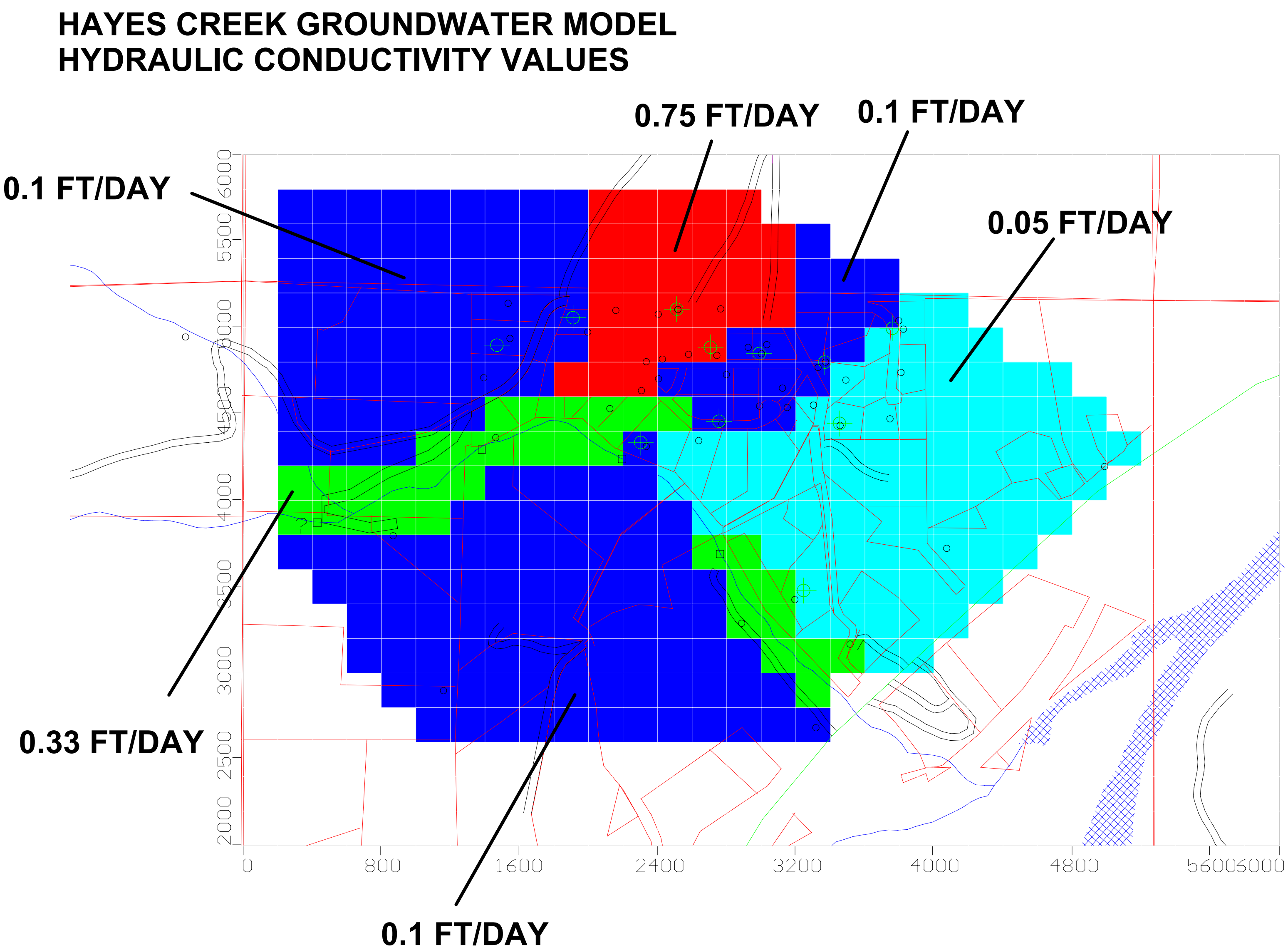


Figure 16. Hydraulic Conductivities Used in the Hayes Creek Groundwater Model

Time

The model presented here evaluates a period of one year, divided into three stress periods. In stress period number 1, the first 150 days modeled, there is no stress applied by pumping, nor is there any recovery occurring. This first period might best be viewed as a steady state condition where nothing is changing over time. During stress period 2, groundwater is pumped at a constant rate continuously for 100 days from wells. In stress period 3, the wells are shut off, and the aquifer recovers from the pumping stress. The model, or program, was run in such manner several times, trying different pumping volumes, well distributions, and other changes. The results of several of these "model runs" are presented here.

Results

The calculated groundwater contours shown in Figure 15 are similar to those observed in the study area (Figure 4). Figure 17 is a graph of observed and calculated groundwater levels at 11 wells in the study area. The greatest differences were for wells HC-27 and HC-20, both labeled on the graph. Well HC-27 has an anomalously high water level, possibly because this well is not quite as deep as several neighboring wells. Well HC-27 is 180 feet deep, while neighboring wells HC-25, HC-30, and HC-31 are reported to be 320, 380, and 250 feet deep, respectively. Well HC-20 is near Hayes Creek, and is only 23 feet deep. Overall, the calculated groundwater surface is similar to that observed using a fairly simple distribution of boundaries and aquifer properties.

Figure 18 shows the results of a model run in which continuous pumping is simulated from 44 wells distributed about the Woodlands Heights and Woodland Park subdivisions, with a total extraction of 11.3 acre-feet over a period of 100 days. 11.3 acre-feet was selected to represent the low end of the estimated range of seasonal pumping for irrigation (7 to 30 acre-feet, as discussed above.) Each simulated well pumps at a constant rate of about 840 gpd or 0.6 gpm. The greater drawdowns predicted at the east end of the well field in this and other model runs are caused primarily by the lower hydraulic conductivity assigned to the aquifer in that area (Figure 16), and to a lesser extent by the proximity of the wells to the discharge end of the system.

As shown in the graph in the lower part of Figure 18, the pattern of drawdown and recovery over time predicted by the model is similar to that observed. Comparison of the calculated and observed drawdown suggests that with the aquifer parameters assigned, the simulated pumping of 11.3 acre-feet does not generate as much drawdown as observed. The calculated recovery is incomplete at the end of the recovery stress period, even though the recovery period is longer than the pumping period, which agrees with observed conditions.

Figure 19 presents the results of a model run in which the pumping rate is doubled, so that a total of 22.6 acre-feet is pumped from the same group of 44 wells. The pattern of drawdown and recovery over time predicted by the model is again similar to that observed, and is also of a similar magnitude. This result suggests that the amount of groundwater pumped during an

GROUNDWATER MODEL OUTPUT COMPARED TO ACTUAL GROUNDWATER LEVELS MEASURED

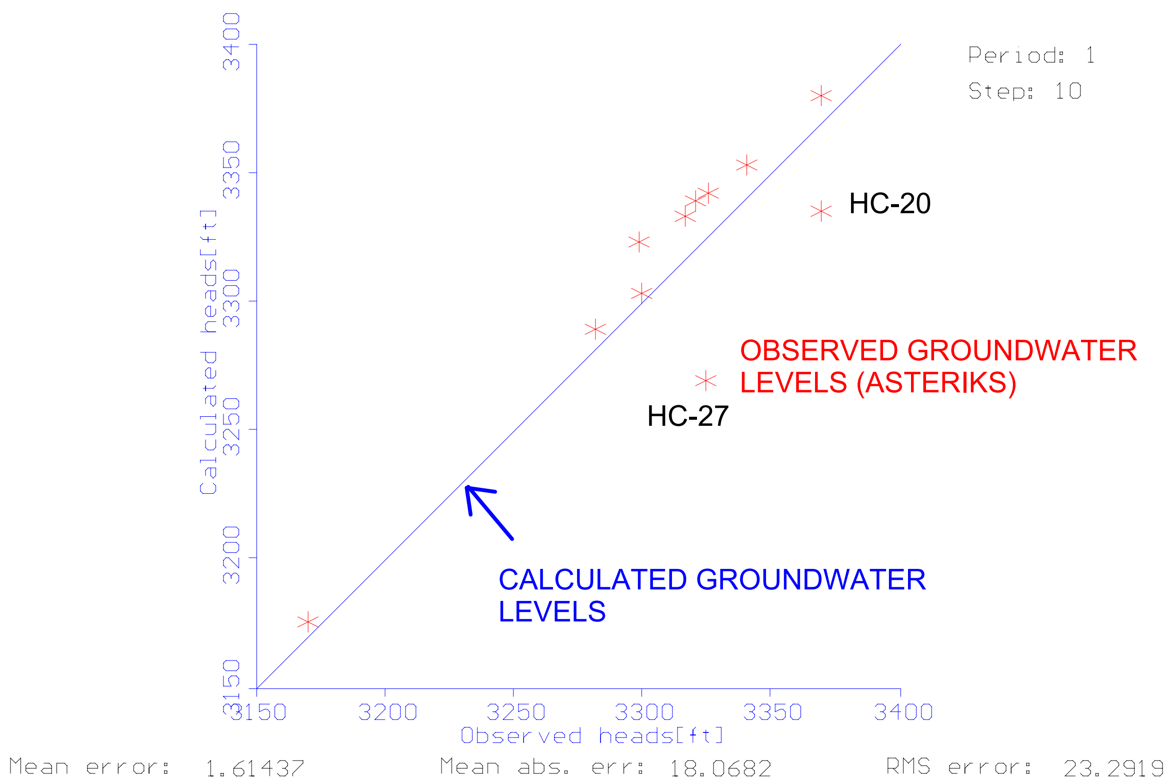
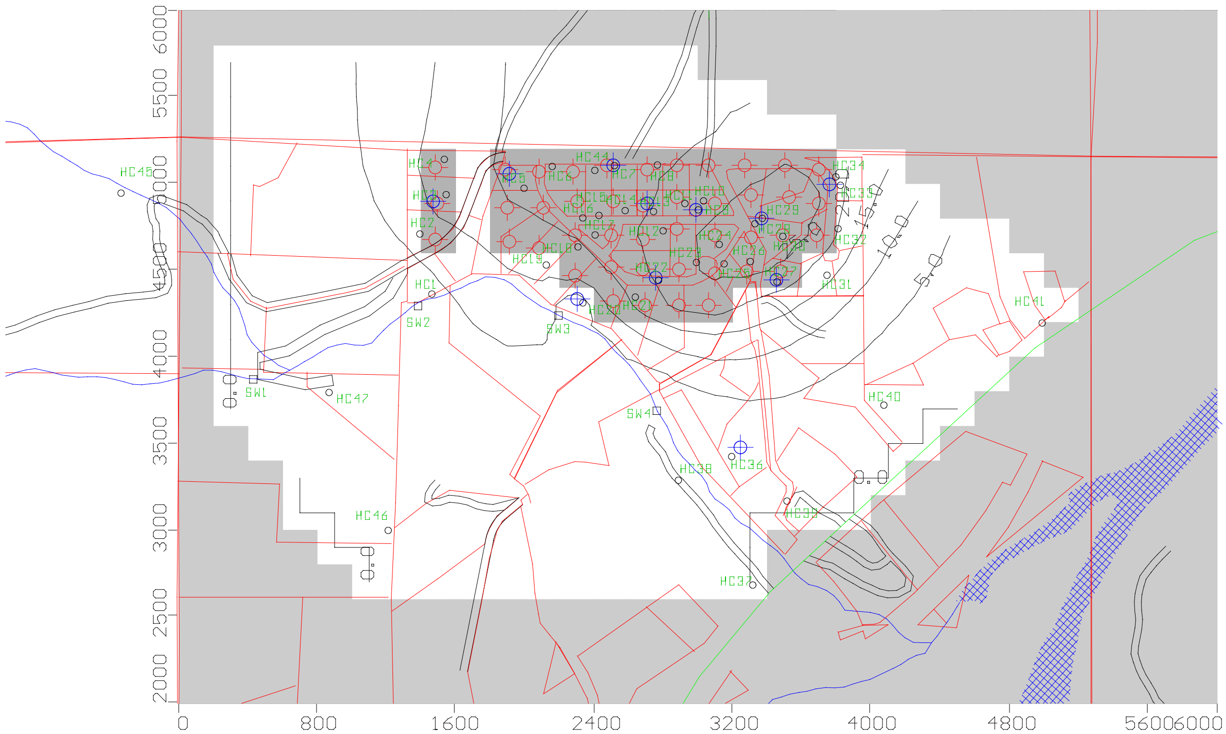


Figure 17. Groundwater Model Output Compared to Actual Groundwater Levels Measured

CALCULATED DRAWDOWN FOR STRESS PERIOD 2 -
PUMPING 11.3 ACRE-FEET IN 100 DAYS
contour interval 5 feet



GROUNDWATER MODEL RESULTS -
OBSERVED VERSUS CALCULATED DRAWDOWN AND RECOVERY

PUMPING 11.3 ACRE-FEET IN 100 DAYS

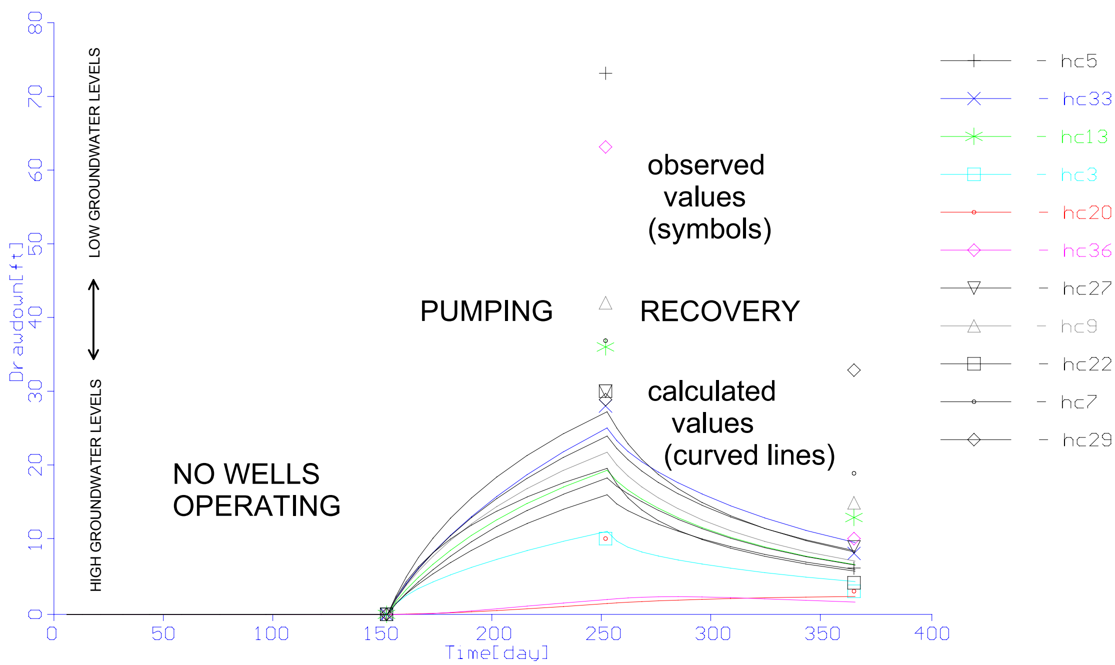
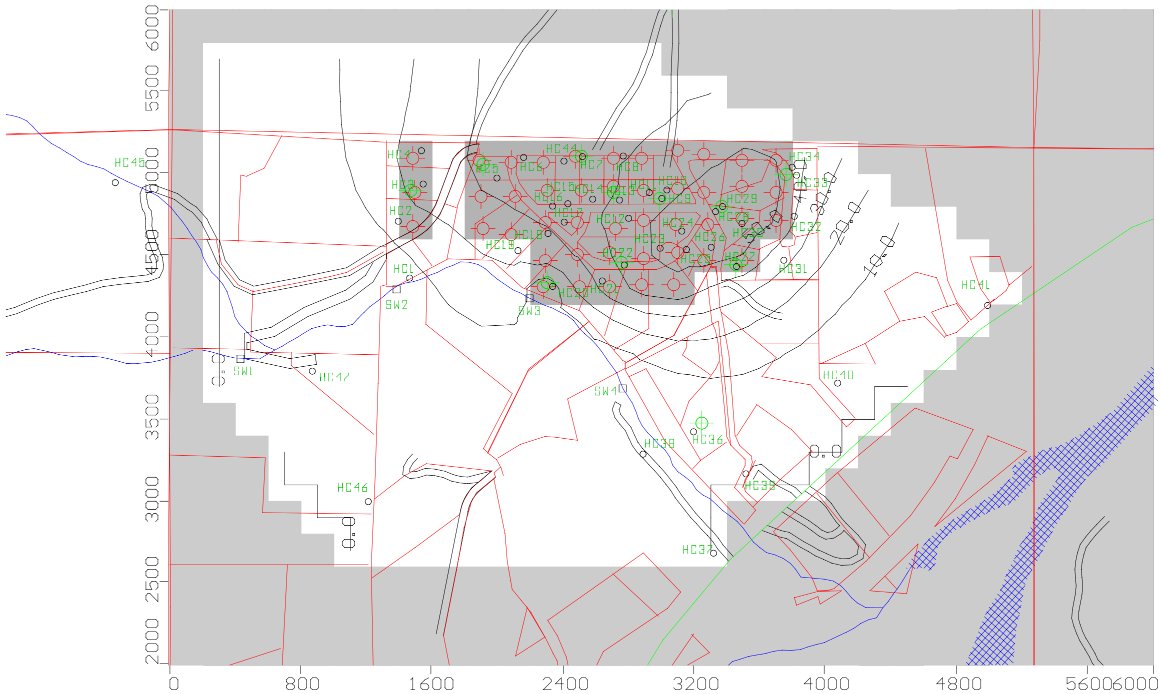


Figure 18. Groundwater Model Results: Calculated Impacts of Pumping 11.3 Acre-Feet for 100 Days

CALCULATED DRAWDOWN FOR STRESS PERIOD 2 -
PUMPING 22.6 ACRE-FEET IN 100 DAYS
contour interval 10 feet



GROUNDWATER MODEL RESULTS
OBSERVED VERSUS CALCULATED DRAWDOWN AND RECOVERY
PUMPING 22.6 ACRE-FEET IN 100 DAYS

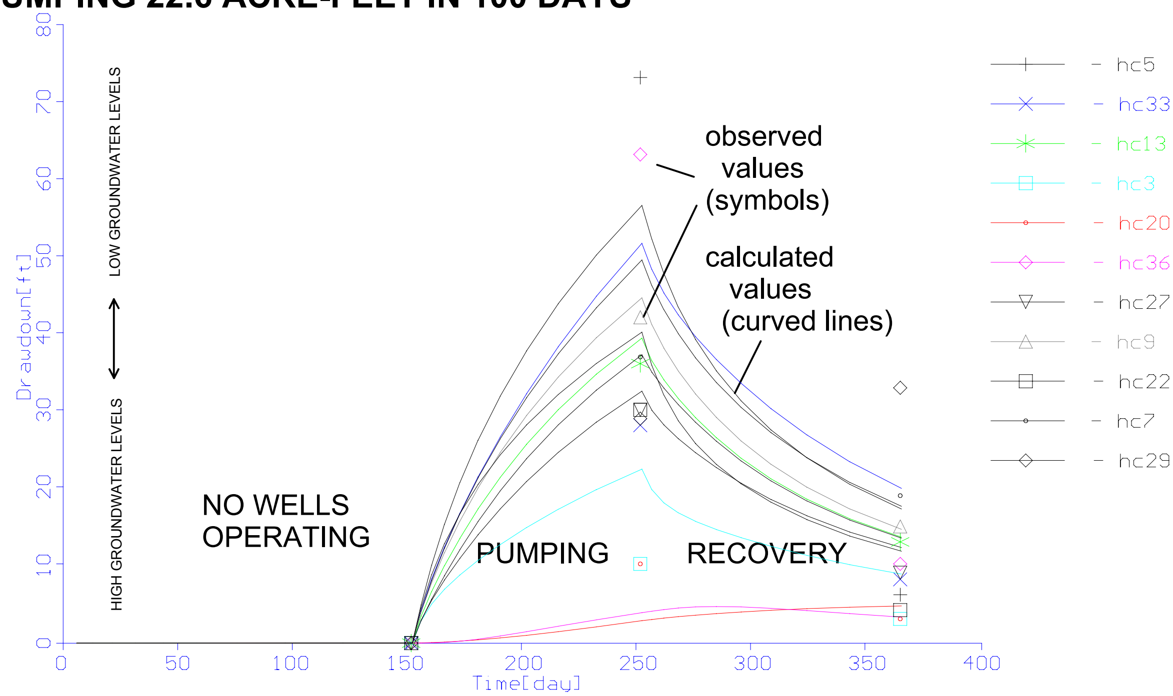


Figure 19. Groundwater Model Results: Calculated Impacts of Pumping 22.6 Acre-Feet for 100 Days

irrigation season might be closer to 20 acre-feet than 10, but this is inconclusive because of the high uncertainty of the storage coefficient used in the model. More important, the model shows that overall, the observed conditions at the site are consistent with a relatively simple simulation of a low-transmissivity, fractured bedrock aquifer some 300 to 400 feet thick.

Figure 20 shows the drawdown expected for a sparse well scenario, where each simulated well pumps at the same rate as in the run shown in Figure 19, but with only 10 wells instead of 44. This simulation was run to get some idea of the magnitude of drawdown that might be expected if groundwater development had been limited to one well per 5-acre plot, but with yard sizes similar to those in the area now. The drawdown has the same general distribution, but is much lower in magnitude compared with the previous simulation.

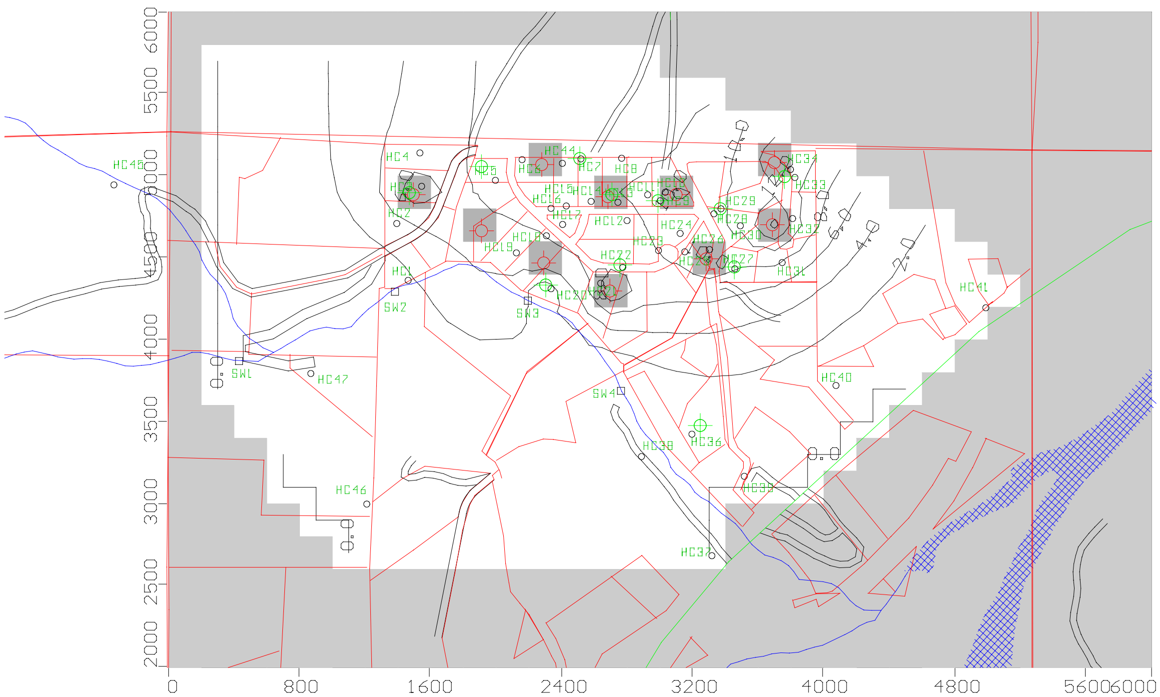
Groundwater Model Water Budget

A summary of the calculated groundwater budget from the model shown in Figure 19 is provided in Table 2. Most of the budget figures are straightforward, however the way the model treats storage demands a brief explanation. 'Storage in' refers to water that is made available from any one cell to flow to other cells, therefore entering the numerical calculations that comprise the model. For example, if the groundwater level falls in a particular cell, storage is released from the aquifer based on the assigned storage coefficient and the amount of groundwater level decline. It is important to realize that 'storage in' actually refers to water *released* from the aquifer, rather than groundwater being put *into storage*.

The calculated budget shows that in the model, 90% of the groundwater pumped during the irrigation season comes out of storage in the aquifer. As a result, a cone of depression is formed in the vicinity of the wells. This creates changes in the groundwater gradient both above and below the subdivision area. The changes in the groundwater gradient cause the groundwater inflow rate from bedrock to the west to increase a small amount, and the groundwater outflow rate to Hayes Creek and the Bitterroot Valley to decrease significantly. This is shown by the increase in the 'constant head in' and decreases in the 'constant head out' and 'drains out' rates for stress period 2 when the wells are pumping, and to a lesser extent stress period 3 when the wells are off. The groundwater outflow rates to drains and constant head cells change by 10 to 15%, while the groundwater inflow rates only inflow about 1.5% After the irrigation season, the cone of depression is slowly filled with water as the aquifer returns to its natural level. The change in the groundwater inflow and outflow rates persist after irrigation withdrawals stop. As the cone of depression fills, the groundwater inflow and outflow rates approach their original rate.

The groundwater model budget suggests that in general, the source of water for the many wells in the subdivisions is largely groundwater in storage, which is ultimately replaced mostly by capturing some of the natural groundwater flow that moves from upgradient areas to the Bitterroot Valley. The natural outflow is estimated to be perhaps 0.09 cfs, a virtually insignificant amount of water compared with streamflow of the Bitterroot River or even Hayes

CALCULATED DRAWDOWN WITH A SPARSE DISTRIBUTION OF WELLS PUMPING 4.9 ACRE-FEET IN 100 DAYS
contour interval 2 feet



GROUNDWATER MODEL RESULTS
CALCULATED DRAWDOWN FOR SPARSE WELL SCENERIO

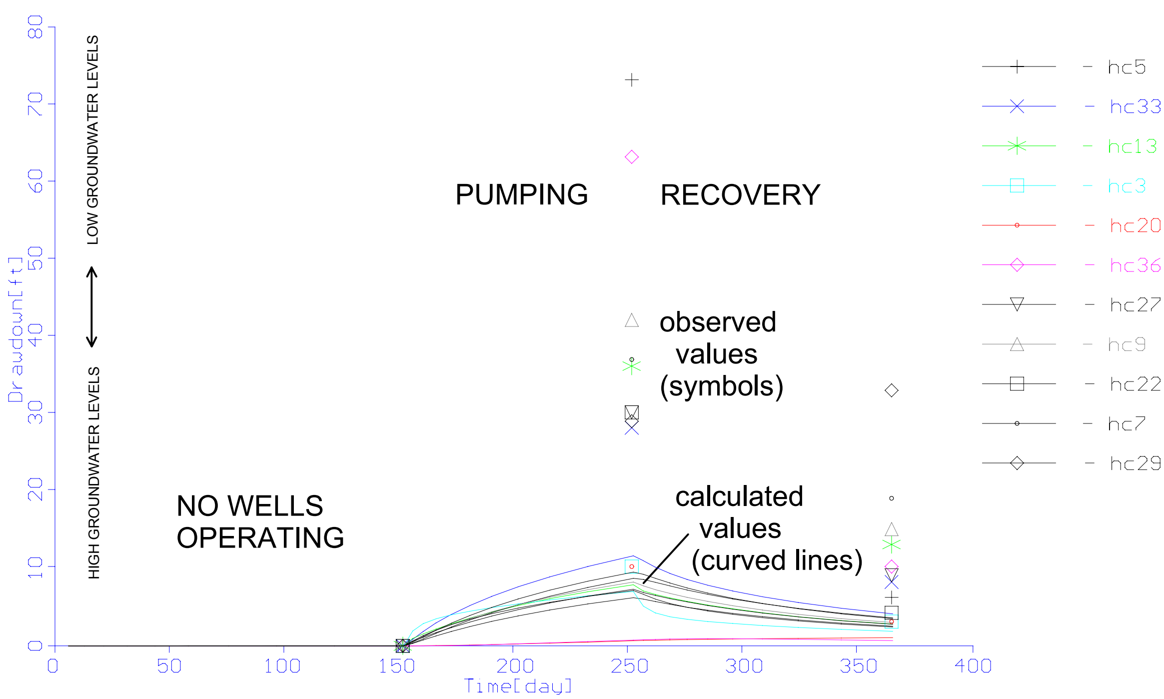


Figure 20. Groundwater Model Results: Calculated Impacts of Pumping 4.9 Acre-Feet for 100 Days

Creek. However, this seemingly small flow rate generates about 7,800 ft^3/day, or some 65 acre-feet per year. The groundwater model budget calculates outflow to the Bitterroot Valley as flow out drains and constant head cells to be between about 10,200 and 11,500 ft^3/day, or 0.11 to 0.13 cfs. But in the model, part of this calculated outflow comes from the area modeled south of Hayes Creek. The portion of the calculated gains in Hayes Creek and to the Bitterroot Valley from the subdivisions area is about 0.04 cfs.

Table 2. Groundwater Model Budget

For the model shown in Figure 19 in which 22.6 acre-feet is withdrawn from wells in stress period 2.

Cumulative Volumes (acre-feet)

	Stress Period 1 No Wells Pumping		Stress Period 2 Wells Extract 22.6 Acre-Feet		Stress Period 3 No Wells Pumping	
	IN	OUT	IN	OUT	IN	OUT
Storage	0	0	21.1	0	26.0	8.5
Constant Head	36.2	20.3	60.1	33.1	87.3	46.3
Wells	0	0	0	22.6	0	22.6
Drains	0	19.8	0	31.9	0	45.2
Recharge	3.9	0	6.4	0	9.3	0

Rates (ft^3/day)

	Stress Period 1 No Wells Pumping		Stress Period 2 Wells Extract 22.6 Acre-Feet		Stress Period 3 No Wells Pumping	
	IN	OUT	IN	OUT	IN	OUT
Storage	4	0	8525	0	864	2069
Constant Head	10363	5814	10472	5269	10514	5140
Wells	0	0	0	9856	0	0
Drains	0	5665	0	4983	0	5273
Recharge	1108	0	1108	0	1108	0

Figure 21 is a summary of the estimated groundwater budget for the Woodlands Heights and Woodland Park subdivision area. The shaded area in Figure 21 is about 100 acres. Also shown

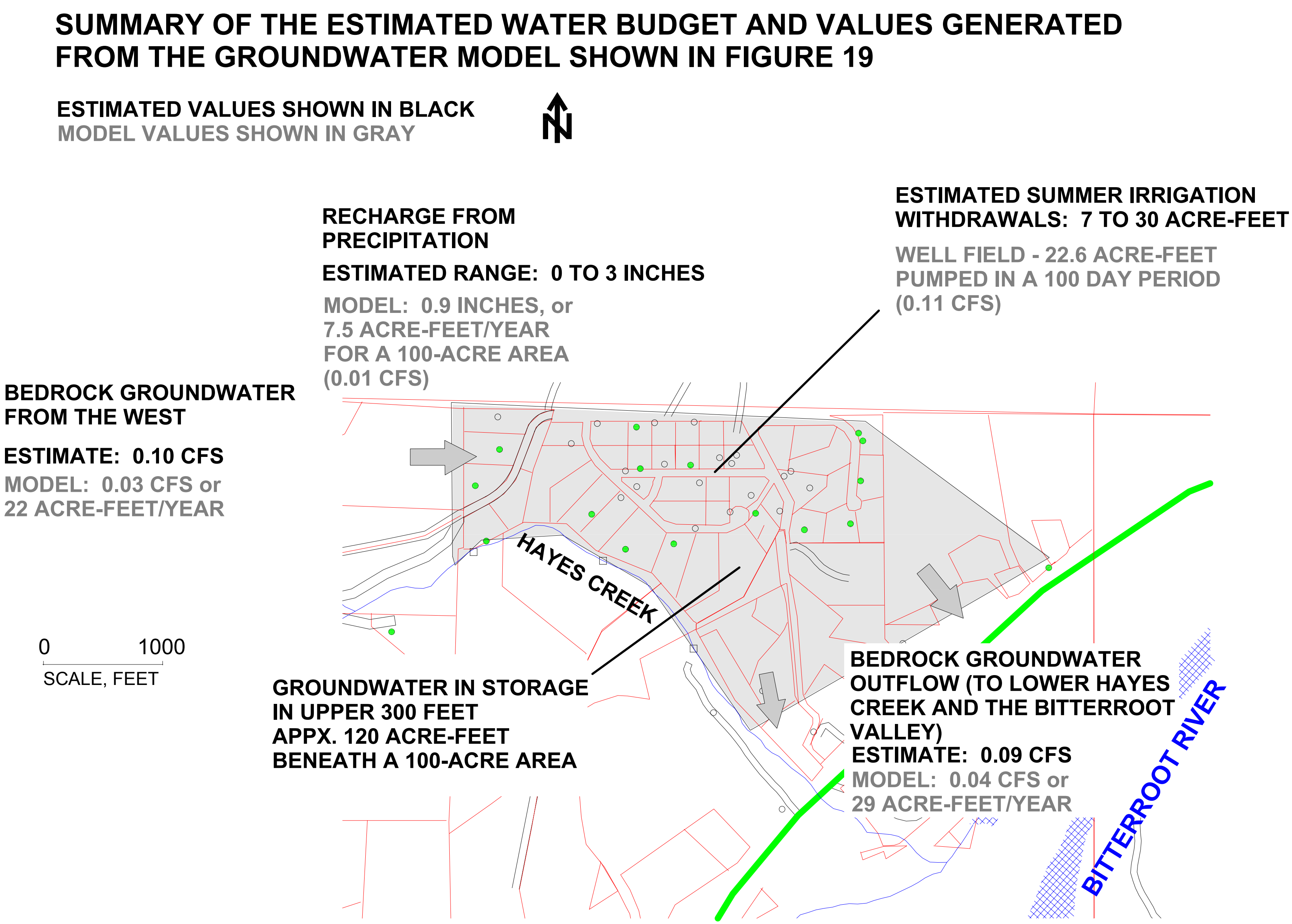


Figure 21. Summary of the Estimated Water Budget and Values from the Groundwater Model Shown in Figure 19.

are values derived from the groundwater model simulation shown in Figure 19, in which 22.6 acre-feet is pumped in a 100-day period.

The comparison of estimated flow and what the groundwater model calculates is useful in evaluating the accuracy of the model. While the values do not match, they are in the same order of magnitude. Because of the uncertainty of most of the estimates, further refinement of the model is not warranted until more definitive data are collected. Nor is the difference surprising, given the many assumptions and simplifications required to develop the model. The order of magnitude agreement, however, suggests that the model is at least a fair representation of the situation.

Discussion

Both the reevaluation of the water budget using available data and the groundwater model suggest that the observed impact of pumping for irrigation at the existing subdivisions is consistent with a low-transmissivity, fractured bedrock aquifer. Although fracture permeability is small, the estimated volume of groundwater in storage in the upper 300 feet of the aquifer is about 116 acre-feet. This represents a substantial volume of stored water that is available for pumping, and is the immediate source of water withdrawn for irrigation. Ultimately, this source is replenished by both a capture of part of the natural groundwater flow from areas to the west toward the Bitterroot Valley and by whatever recharge is available from precipitation, excess irrigation water, and the septic drain field.

From this analysis, we believe that recharge from Hayes Creek is not an important factor in the groundwater budget, and that groundwater may actually contribute a small amount of water, perhaps some 0.05 cfs (25 gpm), to the lower reaches of Hayes Creek, downstream from the location of weir SW-2. Minor losses may occur along some reaches of the stream when groundwater levels are depressed in the late summer and fall, but the amount of water moving from the creek to the aquifer would likely be small compared to stream flow, as the magnitude would be similar to other groundwater flow rates, measured in hundredths of cfs. This magnitude of streamflow depletion would be smaller than the measurement error associated with most streamflow gaging methods.

Development of wells for the Woodland Heights and Woodland Park subdivisions has created a severe, but temporary aquifer drawdown problem that leads to water shortages in some wells during dry, hot summers. These problems are most pronounced at the groundwater discharge end of the system, at the southeast end. This may be due largely to low hydraulic conductivity suspected to predominate in that area, but may also reflect the capture of groundwater flowing out of the area as the ultimate source of groundwater for pumping.

Many aspects of the groundwater system are poorly defined, leaving a high uncertainty concerning true water budget rates and volumes. Recharge to the aquifer from snowmelt, rain, and excess irrigation water is probably the most elusive number to attempt to determine.

Pumping withdrawals are also a matter of sophisticated guesswork, but these could be measured. This information would provide an important piece of the water budget puzzle and, if available, a reassessment of the system would be warranted. Because of the significant role that pumping withdrawals have in the groundwater budget, further work in determining aquifer parameters by aquifer tests is of limited use.

Upgradient development is a reasonable concern, because groundwater flowing from upgradient areas is believed to be the principal source of groundwater to the subdivisions area. Available data suggests that the current level of development has not affected groundwater inflow to any detectable degree. The 'sparse wells' model run depicted in Figure 20 suggests that if development is modest, with one well serving perhaps a 5-acre lot, *and* that withdrawals are in about the same range as existing wells in the subdivisions, the impact would not be severe. Extensive yards or other water demands would likely lead to the same types of well interference problems seen in the subdivisions. This could make matters worse for the subdivisions, depending on how downgradient wells are affected. The exact location of additional wells, and the new information gained from additional wells would have to be evaluated to determine what threat specific developments would have. Some new wells might have almost no impact to the subdivisions, while others may be in more threatening positions.

Conclusions

The Woodlands Heights and Woodland Park subdivisions area is underlain by a fractured bedrock aquifer. The observed response of groundwater levels in the aquifer to seasonal pumping for lawn irrigation is an expected condition for this rock type and geographic setting.

The water budget at the subdivisions area remains uncertain, although the approximate range of many components can be estimated. Since pumping withdrawals for lawn irrigation are a major component of the water budget, and have bearing on estimating recharge from the surface, the measurement of these withdrawals would provide an important constraint in the water budget that would improve our understanding of the system. Recharge from Hayes Creek is probably not a major component of the water budget as previously thought.

The recurrent groundwater problems are a result of pumping groundwater from a concentrated area in the Woodlands Heights and Woodland Park subdivisions during dry summers. Because of the low transmissivity of the bedrock, the immediate source of water is largely groundwater in storage in the aquifer. This water is slowly replaced over the seasons by natural groundwater flow through the aquifer and whatever recharge is available from precipitation, excess irrigation water, and drain fields at the surface.

The principal source of water at the subdivisions area is believed to be groundwater moving into the area from the west. Available data suggests that the current level of development has not affected groundwater inflow to the subdivisions area to any detectable degree. Groundwater development in areas west of the subdivision at modest levels with one well serving perhaps a 5-acre lot, *and* with withdrawals in about the same range as existing wells in the subdivisions would not be expected to significantly affect the subdivisions. The location of additional wells, and the new information gained from additional wells would have to be evaluated to determine what threat specific developments would have. Some new wells might have minimul impact to the subdivisions, while others may be in more threatening positions. Because of the limited amount of private land where further development can be expected that is upgradient of the subdivisions area, the threat to substantial changes in groundwater flow from the west is limited.

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Appendix A - Static Water Levels

MP = Measuring Point.   !985 - 1986 Data from Bayuk (1989). Locations and elevations are shown in Table 1.

WELL HC-1
MP: TOP OF CASING
MP FROM LAND SURFACE (ft.): 1.3

06/13/85	16.37
06/27/85	19.39
07/12/85	18.44
07/25/85	16.24
08/08/85	15.81
08/29/85	13.73
09/16/85	15.65
10/03/85	14.18
10/17/85	13.29
11/05/85	14.12
12/03/85	15.89
12/31/85	12.60
01/31/86	14.34
03/06/86	13.88
03/17/86	13.50
04/08/86	12.57
05/23/86	13.44
06/17/86	13.24
11/07/96	22.72
03/21/97	17.75
04/25/97	15.75
05/23/97	17.79
06/26/97	19.75
07/28/97	19.90
08/29/97	25.00
10/01/97	25.40

WELL HC-2
MP: TOP OF CASING
MP FROM LAND SURFACE (ft.): 0.7

06/13/85	81.08
06/27/85	83.76
07/12/85	87.50
07/25/85	88.28
08/08/85	87.10
08/29/85	84.19
09/16/85	81.28
10/03/85	79.75
10/17/85	80.91
11/05/85	78.05
12/03/85	77.20
12/31/85	76.98
01/31/86	76.77
02/21/86	76.94
03/06/86	76.32
03/17/86	75.69
04/08/86	76.84
05/23/86	75.97
06/17/86	78.91
11/07/96	79.05
03/21/97	78.75
04/25/97	64.42
05/23/97	67.67
06/26/97	72.83
07/28/97	79.00
08/29/97	79.85
10/01/97	78.00

WELL HC-3
MP: TOP OF CASING
MP FROM LAND SURFACE (ft.): 2.6

07/12/85	84.76
07/25/85	84.68
08/08/85	84.74
08/29/85	81.58
09/16/85	80.49
10/03/85	79.56
10/17/85	80.08
11/05/85	78.50
12/03/85	77.94
12/31/85	78.09
01/31/86	77.52
03/06/86	73.82
03/17/86	73.24
04/08/86	74.18
05/23/86	74.01
11/07/96	79.35
03/21/97	68.75
04/25/97	66.58
05/23/97	58.92
06/26/97	72.50
07/28/97	77.00
08/29/97	79.50
10/01/97	77.80

WELL HC-13
MP: TOP OF CASING
MP FROM LAND SURFACE (ft.): 1.0

06/13/85	90.88
06/27/85	97.73
07/11/85	107.63
07/25/85	110.28
08/08/85	111.19
08/29/85	112.01
09/16/85	105.22
10/03/85	100.31
10/17/85	97.02
11/05/85	94.46
12/03/85	90.91
12/31/85	88.89
01/31/86	86.87
03/06/86	78.77
03/17/86	76.68
04/08/86	72.95
05/23/86	75.61
06/17/86	86.17
09/19/96	97.45
10/10/96	98.50
11/07/96	94.64
03/21/97	89.75
04/25/97	77.92
05/23/97	73.58
06/26/97	75.50
07/28/97	69.00
08/29/97	85.85
10/01/97	85.50

WELL HC-15
MP: TOP OF CASING
MP FROM LAND SURFACE (ft.): 0.0

06/13/85	73.24
06/27/85	85.27
07/11/85	94.54
07/25/85	104.15
08/08/85	98.70
08/29/85	88.30
09/16/85	82.86
10/03/85	77.05
10/17/85	74.37
11/05/85	72.12
12/03/85	71.64
12/31/85	69.09
01/31/86	67.74
03/06/86	61.12
03/17/86	55.35
04/08/86	50.02
05/23/86	54.96
06/17/86	63.72
10/10/96	88.56
11/07/96	83.82
03/21/97	78.50
04/25/97	68.67
05/23/97	66.33
06/26/97	62.00
07/28/97	69.32
08/29/97	69.85
10/01/97	69.58

WELL HC-19
MP: TOP OF CASING
MP FROM LAND SURFACE (ft.): 1.0

06/13/85	75.72
06/27/85	82.23
07/11/85	85.95
07/25/85	89.75
08/08/85	88.94
08/29/85	88.35
09/16/85	85.59
10/03/85	85.19
11/05/85	83.80
12/03/85	82.89
12/31/85	82.70
01/31/86	82.22
03/06/86	80.05
03/17/86	75.99
04/08/86	71.42
05/23/86	71.89
03/21/97	103.42
04/25/97	77.33
05/23/97	76.75
06/26/97	79.83
07/28/97	83.10
08/29/97	89.50
10/01/97	90.90

Appendix A - Static Water Levels (cont.)

WELL HC-20
MP: TOP OF CASING
MP FROM LAND SURFACE (ft.): 0.6

06/13/85	11.03
06/27/85	11.20
07/11/85	11.04
07/25/85	11.20
08/08/85	11.56
08/29/85	11.07
09/16/85	10.96
10/03/85	11.06
11/05/85	10.93
12/03/85	11.16
12/31/85	12.13
01/31/86	10.74
03/06/86	9.85
03/17/86	9.94
04/08/86	10.09
05/23/86	10.64
06/17/86	10.71
10/10/96	11.01
11/07/96	10.99
03/21/97	9.50
04/25/97	10.33
05/23/97	10.92
06/26/97	10.50
07/28/97	11.34
08/29/97	10.90
10/01/97	10.80

WELL HC-21
MP: TOP OF CASING
MP FROM LAND SURFACE (ft.): 0.0

06/13/85	75.98
06/27/85	70.22
07/11/85	76.64
07/25/85	78.50
08/08/85	77.89
08/29/85	77.18
09/16/85	76.63
10/03/85	76.14
11/05/85	74.76
12/03/85	74.67
12/31/85	74.54
01/31/86	75.38
03/06/86	71.29
03/17/86	69.80
04/08/86	69.69
05/23/86	72.06
06/17/86	71.91
10/10/96	134.10
11/07/96	131.82
03/21/97	112.50
04/25/97	98.67
05/23/97	102.58
06/26/97	105.00
07/28/97	110.27
08/29/97	116.70
10/01/97	119.00

WELL HC-25
MP: TOP OF CASING
MP FROM LAND SURFACE (ft.): 1.4

06/13/85	147.11
06/27/85	148.41
07/11/85	162.24
07/25/85	166.21
08/08/85	167.52
08/29/85	151.46
09/16/85	137.29
10/03/85	132.33
10/31/85	118.66
12/03/85	110.79
12/31/85	109.15
01/31/86	108.72
03/06/86	100.45
03/17/86	95.75
04/08/86	92.13
05/23/86	104.85
06/17/86	123.57
11/07/96	148.61
03/21/97	123.75
04/25/97	105.83
05/23/97	125.25
06/26/97	131.08
07/28/97	139.49
08/29/97	156.85
10/01/97	147.44

WELL HC-27
MP: TOP OF CASING
MP FROM LAND SURFACE (ft.): 0.5

06/27/85	38.48
07/11/85	42.65
07/25/85	40.67
08/08/85	44.16
08/29/85	38.21
09/16/85	27.89
10/03/85	22.69
11/05/85	20.65
12/03/85	21.60
12/31/85	24.05
01/31/86	25.32
03/06/86	16.20
03/17/86	14.71
04/08/86	14.56
05/23/86	16.92
03/21/97	18.25
04/25/97	17.00
05/23/97	21.00
06/26/97	21.50
07/28/97	25.10
08/29/97	24.70
10/01/97	25.56

WELL HC-31
MP: TOP OF CASING
MP FROM LAND SURFACE (ft.): 2.0

06/13/85	118.88
06/27/85	126.10
07/11/85	129.61
07/25/85	132.33
08/08/85	133.14
08/29/85	131.24
09/16/85	126.28
10/03/85	123.50
11/05/85	118.10
12/03/85	115.56
12/31/85	113.00
01/31/86	110.93
03/06/86	106.11
03/17/86	106.58
04/08/86	101.58
05/23/86	109.02
06/17/86	118.19
09/19/96	145.53
10/10/96	147.19
11/07/96	131.13
03/21/97	104.75
04/25/97	99.25
05/23/97	104.33
06/26/97	99.83
07/28/97	98.00
08/29/97	120.00
10/01/97	125.25

WELL HC-32
MP: TOP OF CASING
MP FROM LAND SURFACE (ft.): 2.0

06/13/85	118.04
06/27/85	118.04
07/11/85	120.13
07/25/85	132.57
08/08/85	133.05
08/29/85	129.36
09/16/85	125.09
10/03/85	121.05
11/05/85	115.18
12/03/85	111.84
12/31/85	108.70
01/31/86	106.21
02/21/86	104.98
03/06/86	105.43
03/17/86	102.04
04/08/86	100.32
05/23/86	103.25
06/17/86	113.25
03/21/97	113.75
04/25/97	106.00
05/23/97	106.75
06/26/97	104.67
08/29/97	109.50
10/01/97	111.30

Appendix A - Static Water Levels (cont.)

WELL HC-33
MP: TOP OF CASING
MP FROM LAND SURFACE (ft.): 1.5

06/13/85	118.31
06/27/85	125.95
07/11/85	150.46
08/08/85	139.35
08/29/85	130.63
09/16/85	121.93
10/03/85	116.94
11/05/85	111.25
12/03/85	107.91
12/31/85	104.95
01/31/86	102.58
03/06/86	99.63
03/17/86	98.58
04/08/86	95.58
05/23/86	101.22
06/17/86	128.18
09/19/96	137.10
10/10/96	137.90
11/07/96	126.78
03/21/97	111.25
04/25/97	103.67
05/23/97	111.17
06/26/97	109.67
07/28/97	113.40
08/29/97	120.30
10/01/97	120.60

WELL HC-34
MP: TOP OF CASING
MP FROM LAND SURFACE (ft.): 1.5

06/13/85	110.99
06/27/85	115.16
07/11/85	121.95
08/08/85	125.17
08/29/85	124.15
09/16/85	120.56
10/03/85	117.24
11/05/85	111.56
12/03/85	108.59
12/31/85	105.81
01/31/86	103.36
03/06/86	100.10
03/17/86	98.58
04/08/86	96.03
05/23/86	98.56
06/17/86	107.30
03/21/97	111.50
04/25/97	103.75
05/23/97	101.83
06/26/97	103.67
07/28/97	107.64
08/29/97	114.00
10/01/97	116.85

WELL HC-41
MP: TOP OF CASING
MP FROM LAND SURFACE (ft.): 0.0

06/21/85	21.21
07/11/85	23.52
07/26/85	25.56
08/29/85	23.39
09/16/85	22.07
10/03/85	22.77
11/05/85	22.37
12/03/85	23.32
01/31/86	23.25
03/06/86	19.31
03/17/86	22.04
04/08/86	21.29
05/23/86	18.94
05/23/97	16.00
06/26/97	19.17
07/28/97	22.10
08/29/97	23.90
10/01/97	23.00

WELL HC-44
MP: TOP OF CASING
MP FROM LAND SURFACE (ft.): 1.2

1996/09/19	00:00 83.65
1996/10/10	00:00 80.73
1996/11/07	00:00 79.1
1997/03/21	00:00 72.5
1997/04/25	00:00 55
1997/05/23	00:00 59.5
1997/06/26	00:00 58.25
1997/07/28	00:00 71.1
1997/08/29	00:00 74
1997/10/01	00:00 71.05

WELL HC-45
MP: TOP OF CASING
MP FROM LAND SURFACE (ft.): 2.0

12/18/91	60.00
11/14/92	53.21
10/07/94	55.86
06/25/95	56.75
02/27/96	54.10
09/19/96	51.02
10/10/96	51.29
11/07/96	51.54
03/21/97	46.17
04/25/97	36.50
05/23/97	33.50
06/26/97	29.75
07/28/97	26.00
08/29/97	28.75
10/01/97	28.00

WELL HC-46
MP: TOP OF CASING
MP FROM LAND SURFACE (ft.): 2.2

09/19/96	41.80
10/10/96	42.40
11/07/96	41.52
03/21/97	39.00
04/25/97	39.42
05/23/97	39.42
06/26/97	39.50
07/28/97	40.20
08/29/97	41.00
10/01/97	37.80

WELL HC-47
MP: TOP OF CASING
MP FROM LAND SURFACE (ft.): 2.9

10/10/96	56.00
11/07/96	56.07
03/21/97	54.58
04/25/97	59.75
05/23/97	55.50
06/26/97	55.42
07/28/97	57.75
08/29/97	56.00
10/01/97	55.10