FINAL

CORRECTIVE MEASURES STUDY/FEASIBILITY STUDY GROUNDWATER FLOW MODELING REPORT FOR OPERABLE UNIT 2 (OU2)

U.S. DEPARTMENT OF ENERGY
Rocky Flats Environmental Technology Site
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1.0
INTRODUCTION

This report presents the details and results of groundwater flow modeling conducted in support of the Rocky Flats Environmental Technology Site (RFETS) Operable Unit No. 2 (OU2) Resource Conservation and Recovery Act (RCRA) Corrective Measures Study/Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) Feasibility Study (CMS/FS). This report is based on site-specific information contained primarily in the Phase II RCRA Facility Investigation/Remedial Investigation (RFI/RI) Report, 903 Pad, Mound, and East Trenches Area, Operable Unit No. 2 (DOE 1995a), hereafter referred to as the Phase II RFI/RI Report. The reader is encouraged to review this CMS/FS modeling report in conjunction with the Phase II RFI/RI Report.

1.1 MODELING PURPOSE AND OBJECTIVES

A groundwater flow model was applied to the upper hydrostratigraphic unit (UHSU) saturated groundwater system at OU2 in support of the OU2 CMS/FS. This groundwater model will be used to support screening assessments of various remedial action alternatives being considered in the CMS/FS to remediate UHSU groundwater contamination in OU2.

The purpose of the flow modeling was to develop a detailed numerical representation of the complex geologic and hydrogeologic UHSU saturated groundwater system within OU2 to reasonably simulate groundwater flow system behavior under current conditions and in response to the imposition of stresses from various proposed remedial action alternatives. For the purposes of selecting the modeling objectives, four example remedial alternative types were specified: (1) no action, (2) groundwater extraction to dewater the UHSU, (3) installation of an upgradient barrier (e.g., a slurry wall) in the No. 1 Sandstone to reduce inflow from the west, and (4) reduction of infiltration through installation of a surface cover (e.g., asphalt pavement) or enhancement of evapotranspiration. In addition, the groundwater flow model is designed to provide results that will serve as input to the contaminant fate and transport model also developed to support the CMS/FS.

The objectives of the groundwater flow modeling were as follows:

- Integrate hydrogeologic and hydraulic components of the Rocky Flats Alluvium and No. 1 Sandstone groundwater system into a representative hydrodynamic flow model with calibrated hydraulic parameters. These parameters characterize the physical system to simulate the groundwater flow system at a level of detail sufficient for screening of remedial alternatives.

- Simulate hydraulic effects in the Rocky Flats Alluvium and No. 1 Sandstone in response to stresses from various CMS/FS remedial alternatives.

- Provide groundwater flow fields for the Rocky Flats Alluvium and No. 1 Sandstone to serve as input for the numerical fate and transport model to be developed and applied for the CMS/FS.

This report documents flow model development and testing to verify its satisfactory performance for simulation of typical remedial action scenarios during the CMS/FS. Use of the model for remedial action screening and development and application of the numerical fate and transport model are not documented in this report.

1.2 DATA SOURCES

To serve as a framework for application of the groundwater flow numerical model, a conceptual model (Section 3.0) of the groundwater flow conditions in the UHSU was developed. The primary data source for site-specific hydrogeologic information used to develop this conceptual model is Section 3.0 (Physical Characteristics of OU2) of the Phase II RFI/RI Report (DOE 1995a). Other sources of information used in the modeling study include the OU-2 Phase II RFI/RI Aquifer Test Report (DOE 1992), and Technical Memorandum No. 4, Site Model for Hydrogeologic/Contamination Distribution for Trench T-3; IHSS 110; OU-2 Subsurface IM/IRA, Soil Vapor Extraction Test, Site No. 1 (DOE 1995b).

1.3 MODELING TEAM

Biographical sketches of the groundwater flow modeling team members and a brief summary of their qualifications are presented below:

Mr. Wayne Belcher is the lead technical representative for the modeling study. Mr. Belcher has over seven years of professional experience in groundwater modeling studies, and has provided technical oversight and direction for modeling studies conducted in OU2 and other RFETS OUs for two years.

Dr. Chuan-Mian Zhang is the lead groundwater modeler for this project. Dr. Zhang is a senior engineer with over seven years of professional experience in performing and overseeing detailed numerical modeling studies for groundwater and surface water. Dr. Zhang was primarily responsible for all technical work conducted under this study.

Mr. Richard Newill provided senior technical oversight and review for the project. Mr. Newill is a senior engineer and hydrogeologist with over ten years of experience in performing and overseeing hydrogeologic and modeling studies involving contamination assessment and remediation. Mr. Newill has been a senior hydrogeologist for studies in OU2 for nearly three years.

Dr. James Warner provided senior peer review during the modeling study. Dr. Warner is an Associate Professor in the Civil Engineering Department at Colorado State University, Ground Water/Environmental Hydrogeology Program, and has over 25 years of experience, including groundwater engineering and groundwater modeling studies.

Dr. Yongqiang (Frank) Lan provided modeling support to Dr. Zhang. Dr. Lan is a civil engineer with specialties in hydraulic/hydrologic flow and contaminant transport modeling.

Mr. Michael Schreiber also provided modeling support to Dr. Zhang. Mr. Schreiber is a hydrogeologist with several years of experience at OU2, including performing groundwater modeling and aquifer testing.

1.4 QUALITY ASSURANCE AND PEER REVIEW PROCESS

The groundwater flow modeling work conducted for this project was performed in accordance with strict quality assurance and peer review procedures. As discussed in Section 4.0, the flow modeling code used for this study was the United States Geological Survey (USGS) MODFLOW code. This code has been extensively documented and tested, and has been successfully applied to numerous groundwater flow problems. As discussed in Section 4.0, minor modifications of the code were necessary to overcome limitations related to dewatering of layers during simulations. The code modifications were made by Dr. Zhang, a highly qualified computer programmer, and were reviewed by Dr. Lan. The model results were thoroughly reviewed to ensure that the modified code produced results that were numerically reasonable.

The limitations of the groundwater flow model are discussed in the following sections where they apply and in general in Section 8.0.

2.0
GENERAL SITE CONDITIONS

This section provides a brief description of the OU2 site conditions, including discussions of site location (Section 2.1), Climate (Section 2.2), Soils (Section 2.3), Geology (Section 2.4), and Hydrogeology (Section 2.5). A more detailed discussion of site conditions is found in the Phase II RFI/RI Report (DOE 1995a).

2.1 SITE LOCATION

RFETS, formerly known as the Rocky Flats Plant (RFP) is located on federally owned land in northern Jefferson County, Colorado, approximately 16 miles northwest of Denver (Figure 2.1-1). Surrounding cities include Boulder, Broomfield, Superior, Westminster, and Arvada, all located within ten miles of the site. Within RFETS is an industrial area (IA), including a high security Protected Area (PA), where virtually all plant production facilities are located. Surrounding the IA is a buffer zone of relatively undeveloped property.

OU2 is located in the eastern portion of the buffer zone, immediately east of the IA (Figure 2.1-2). OU2 contains the 903 Pad, Mound, Northeast Trenches, and Southeast Trenches areas. Each of these areas contains several Individual Hazardous Substance Sites (IHSSs), which are sites of past waste handling, storage, or disposal. The IHSSs of OU2 are located on a relatively flat pediment between Woman Creek to the south and South Walnut Creek to the north (Figure 2.1-3). OU2 ranges in elevation from approximately 5,700 feet above mean sea level (msl) at the eastern facility boundary, along Indiana Street, to 5,980 feet along the top of the pediment on the west side of the site. Surface water flow in both Woman Creek and South Walnut Creek is generally eastward toward Indiana Street.

2.2 CLIMATE

The RFETS area has a semi arid climate that is characteristic of much of the central Rocky Mountain region. The average annual precipitation at RFETS is approximately 15 inches, of which approximately 35 percent falls during the spring season, much of it as snow. Temperatures are moderate, with extremely warm or cold weather rare and for short durations.

The air flow around RFETS is strongly influenced by the close proximity of the Rocky Mountains and High Plains, which produce a diurnal cycle of wind patterns (upslope and downslope) when there are no strong storm systems or large-scale patterns within the region. Northwest winds are predominant at RFETS. Chinook windstorms may occur during the spring as winds moving from west to east over the Continental Divide plunge down the east side of the mountain slopes.

2.3 SOILS

The surface soils at OU2 are predominantly deep, well-drained loams, clay loams, and very cobbly sandy loams. The soils along the flood plains and low terraces of Woman and South Walnut Creeks consist of stratified loamy alluvium. The soils at the top of the OU2 pediment, where gravel and cobbles of the Rocky Flats Alluvium are common, consist of gravelly and sandy loam.

2.4 GEOLOGY

Surficial geologic units within the OU2 area consist of alluvial, hillslope, and man-made deposits. Alluvial deposits include the Rocky Flats Alluvium, high terrace alluviums, and valley fill alluviums. Hillslope deposits within OU2 consist of colluvium, debris fans, and slumps. Shallow bedrock geologic units with OU2 consist of Cretaceous-aged claystones, siltstones, and sandstones of the Arapahoe Formation and the upper portion of the Laramie Formation. The No. 1 Sandstone of the Arapahoe Formation is a distinct bedrock unit separate in geologic characteristics from the underlying Laramie Formation sandstones. Detailed discussions of each of these units are provided in the Phase II RFI/RI Report (DOE 1995a). The following paragraphs focus on the Rocky Flats Alluvium and Arapahoe Formation No. 1 Sandstone, the two units of primary concern for the modeling study.

Rocky Flats Alluvium. The Rocky Flats Alluvium is the topographically highest and the oldest alluvial deposit beneath RFETS. The Rocky Flats Alluvium was deposited as large coalescing alluvial fans along the base of the adjacent mountain front. The Rocky Flats Alluvium within the OU2 area caps the relatively flat pediment between South Walnut and Woman Creeks, and is completely truncated to the north, east, and south by those drainages.

Rocky Flats Alluvium does not extend from the OU2 pediment to the eastern facility boundary at Indiana Street.

Relief on the top of the Rocky Flats Alluvium is relatively flat within the OU2 area. The unconformity between the Rocky Flats Alluvium and the underlying bedrock units, however, is highly irregular due to the erosional nature of the top of bedrock surface. Therefore, the thickness and geometry of the Rocky Flats Alluvium is variable and is controlled by certain top of bedrock features.

The erosional relief on the top of bedrock surface is the result of channeling by paleostreams. Those streams either predate deposition of the Rocky Flats Alluvium, or represent the incipient drainage system that brought the Rocky Flats Alluvium into the area.

OU2 Phase II field investigations have confirmed the presence of two paleoridges, a medial paleoscour, and a bedrock step as top of bedrock surface features. The contoured top of bedrock surface is shown on Figure 2.4-1. The top of bedrock surface features are illustrated in Figure 2.4-2. Profiles of the top of bedrock illustrating the main bedrock surface features are shown in Figure 2.4-3.

The medial paleoscour, which lies between the north and south paleoridges, extends east-northeastward from beneath the 903 Pad to just east of the Northeast Trenches Area, where it bends to the north, and then resumes an east-northeast trend (Figures 2.4-1 and 2.4-2). Further to the east, the feature is interpreted to take a northward bend and is truncated along the South Walnut Creek hillside. Where this paleoscour intersects the hillside, a well-developed surface drainage gully is present. Groundwater is observed to seep from the Rocky Flats Alluvium along the head of this gully during much of the year. The importance of the medial paleoscour to alluvial groundwater flow is discussed in the next section.

The two paleoridges parallel the medial paleoscour and confine alluvial groundwater flow to the medial palescour over most of their length. This is discussed further in the next section.

The origin of the bedrock step feature (Figures 2.4-1 through 2.4-3), located just east of the Southeast Trenches Area, is unclear. It has alternately been interpreted to be a fault-related feature, a syndepositional slump or slip feature, or an erosional feature. For the purposes of this modeling study, the exact origin of this feature does not appear to be of substantial importance because hydrogeologic data do not indicate that this feature substantially influences groundwater flow (See Sections 3.6 and 5.3 in the Phase II RFI/RI Report [DOE 1995a]).

As mentioned previously, the thickness of the Rocky Flats Alluvium is controlled primarily by the underlying top of bedrock features. Figure 2.4-4 illustrates representative cross-sections of alluvial thickness along the same lines as the top of bedrock profiles in Figure 2.4-3. The materials that make up the Rocky Flats Alluvium consist predominantly of beds and lenses of poorly to moderately sorted clayey and silty gravels and sands. A few lenses or beds of clay and silt also occur. These deposits have been grouped into three lithofacies based on the percent of fines within the material and probable similarity in depositional process. Although the distribution of the lithofacies probably influences the hydraulic conductivity distribution within the alluvium to some extent, available data do not suggest that lithofacies distribution is a primary controlling factor in alluvial groundwater flow. Rather, alluvial groundwater flow appears to be most influenced by the top of bedrock features discussed earlier.

Arapahoe Formation No. 1 Sandstone. The Arapahoe Formation No. 1 Sandstone is the most significant shallow bedrock unit influencing UHSU groundwater flow. The No. 1 Sandstone is interpreted to be a paleostream channel deposit composed of channel, point bar, and overbank deposits. The geometry of the No. 1 Sandstone channel is shown on Figure 2.4-5. Just east of the Inner East Gate, beneath Central Avenue, the channel is about 800 feet wide and trends north. Beneath the Northeast Trenches Area, the channel appears to bend and trends northeast. To the north and south, the No. 1 Sandstone subcrops beneath the colluvium along the South Walnut and Woman Creek hillsides. A secondary, smaller channel is located just west of the 903 Pad. It trends north-northeast and may or may not join with the main channel in the vicinity of the Mound Area. Lithologically, the No. 1 Sandstone consists predominantly of an interbedded sequence of sandstone, silty to clayey sandstone, and sandy claystone (commonly fining upward). Less frequently occurring lithologies consist of clayey to sandy siltstone and silty claystone.

Texturally, the No. 1 Sandstone is poorly to well sorted. Grain roundness ranges from sub-angular to rounded. Sand size is predominantly very fine- to fine-grained, but medium- to coarse-grained sizes occur in cleaner (less fines) sandstone intervals. The cleaner sandstone intervals tend to be very friable, moderately sorted, and apparently are more permeable than other intervals of the lithologic unit. These intervals have been identified in the Northeast Trenches area around IHSS 110 (Trench T-3)(DOE 1995b). The more permeable interval in the Trench T-3 area is found in the upper third of the No. 1 Sandstone thickness. The presence of the more permeable portion of the sandstone is suggested by pumping test results (Section 2.5) and is reflected in the distribution of hydraulic conductivity discussed in Section 6.0.

The No. 1 Sandstone is the stratigraphically highest sandstone encountered within the OU2 area. The sandstone directly underlies (i.e., subcrops beneath) the Rocky Flats Alluvium along much of the medial paleoscour (Figure 2.4-6). This subcrop area beneath the Rocky Flats Alluvium is apparently an important feature in allowing vertical groundwater flow to the No. 1 Sandstone from the overlying alluvium. Where the sandstone does not directly underlie the alluvium, a claystone/siltstone layer overlies it. The claystone/siltstone layer overlying the sandstone is present along the adjoining paleoridges (Figure 2.4-6).

The No. 1 Sandstone is erosionally truncated to the north and south by the South Walnut and Woman Creek drainages (Figure 2.4-6). The top of the No. 1 Sandstone is shown in Figure 2.4-7. Like the alluvium, the No. 1 Sandstone does not extend from the OU2 pediment to the eastern facility boundary. Although the erosional expression of the sandstone is typically masked on the hillsides by the presence of overlying colluvium, it is exposed at several locations along man-made ditches or cuts. Its presence is also indicated by evidence of seeps beneath the colluvial cover.

Upper Laramie Formation. The Upper Laramie Formation deposits are representative of a lower delta plain depositional environment. Lithologies, in the order of apparent abundance, consist of claystone and silty claystones, sandy or clayey siltstones, or clayey sandstones. The Upper Laramie Formation sandstone and siltstone intervals are approximately 15 feet thick or less, except where lenses are stacked, and are laterally discontinuous and isolated vertically by relatively thick intervals of claystones (DOE 1995a). The Upper Laramie Formation is not considered part of the UHSU and was not addressed in the OU2 UHSU groundwater flow system model.

2.5 HYDROGEOLOGY

Hydrogeologic conditions in the shallow units of OU2 are strongly influenced by local geologic conditions, and local areal recharge. Groundwater flow is controlled to a great degree by the shape of the top of bedrock surface and by the geometry and lithology of the geologic units. Groundwater recharge occurs primarily as a result of local infiltration of snowmelt, rainfall, and surface water within the OU2 area. The majority of OU2 groundwater discharges to surface seeps within the boundaries of OU2 because the major shallow water-bearing units are completely truncated on the north, east, and south by South Walnut and Woman Creeks. Groundwater also flows laterally from the major shallow water-bearing units through the hillslope colluvium to the surface water systems.

The hydrogeologic system at OU2 is comprised of two distinct water-bearing zones; the UHSU and the Lower Hydrostratigraphic Unit (LHSU). The CMS/FS groundwater flow modeling was limited to the UHSU because the greatest impact from site activities have occurred in the UHSU, and there is limited hydraulic communication between the UHSU and LHSU. Therefore, remediation of groundwater in OU2 is expected to be limited to the UHSU.

The UHSU within OU2 consists of the saturated portions of the unconsolidated surficial deposits (Rocky Flats Alluvium, high terrace deposits, colluvium, and disturbed ground), the No. 1 Sandstone, and weathered and/or fractured claystones of the Arapahoe and/or Laramie Formations. The majority of groundwater flow in the UHSU occurs in the saturated Rocky Flats Alluvium and the No. 1 Sandstone and, thus, those units are the focus of the modeling study.

Rocky Flats Alluvium. Groundwater flow in the Rocky Flats Alluvium is strongly influenced by the top of bedrock features and by the geometry and lithology of alluvial geologic units. Saturated alluvial conditions occur predominantly within lows and scours in the top of the bedrock materials. The largest of the scours, the medial paleoscour (Figures 2.4-1 and 2.4-2) contains and transmits most of the alluvial groundwater in OU2. Bedrock paleoridges, capped by claystone, to the north and south of the paleoscour and a claystone high west of the paleoscour appear to bound the lateral extent of saturated alluvium across much of OU2 west of the East Spray Fields. It is believed that alluvial groundwater inflow to OU2 from the west is restricted by the claystone high west of the 903 Pad. Much of the alluvial groundwater flowing within the paleoscour discharges at the head of a well-developed surface drainage gully on the hillside, probably as a result of truncation of the paleoscour at this location. The remainder either discharges from other alluvial seeps to hillslope colluvium, or migrates downward into the No. 1 Sandstone, where it is ultimately discharged from sandstone seeps to hillslope colluvium. Seepage then can travel laterally through the hillslope colluvium to surface water drainages. Thus, virtually all alluvial groundwater in OU2 originates from local precipitation within OU2, and is discharged to the surface water drainages and the saturated valley fill within OU2.

The areal extent and thickness of the saturated alluvium within the medial paleoscour varies considerably with the season. Figures 2.5-1 and 2.5-2 illustrate the areal extent and thickness of the saturated alluvium in the first and second quarters of 1992, respectively. First quarter conditions (March 1992) represent typical low groundwater level conditions. During this period, the areal extent of saturated alluvium is confined mostly to the central portion of the medial paleoscour, and the maximum saturated thickness is about 8 feet. Second quarter conditions (May 1992) represent typical high groundwater level conditions. The areal extent of the saturated alluvium is, in general, still bounded within the paleoscour, but is much wider, with a maximum thickness of about 17 feet. In addition, during second quarter, alluvial water levels rise high enough to overtop the south paleoridge, southeast of the 903 Pad, resulting in southward alluvial seepage and groundwater flow toward Woman Creek.

Recharge to the alluvium occurs primarily due to local direct infiltration of precipitation. The rate of recharge to the alluvium is greatest during the spring when precipitation is high and evapotranspiration is low. Although precipitation can also be high during thunderstorms in the summer months, the effects of increased temperature and evapotranspiration tend to minimize the recharge rate during summer. Recharge during fall and winter is low due to the low precipitation during those months.

Water level fluctuations in response to precipitation events tend to be greater in the medial paleoscour than near the paleoridges. This phenomenon is believed to be related to collection of recharging groundwater within the scour, which acts as an underground groundwater collection basin in much the same way that a surface watershed acts as a collection mechanism for surface flow (Figure 2.5-1 and 2.5-2).

The flow direction of alluvial groundwater in the medial paleoscour is generally to the northeast along the paleoscour. Figures 2.5-3, 2.5-4, and 2.5-5 show the water table elevations for the saturated alluvium in first quarter, second quarter, and third quarter 1992, respectively. As described earlier, first and second quarter 1992 represent the low and high groundwater level conditions for that year, respectively. Third quarter 1992 represents an intermediate groundwater level condition.

Based on aquifer testing conducted in the alluvium, hydraulic conductivity ranges from 1 x 10^{-4} cm/s (0.3 ft/day) to 4 x 10^{-3} cm/s (11 ft/day), with a geometric mean of about 8 x 10^{-4}cm/s (2.3 ft/day). The estimated average hydraulic gradient for the alluvium from 1992 water level measurements is 0.020 feet/ft. Assuming an effective porosity of 10 percent, the average potential groundwater flow seepage velocity (average linear velocity) is estimated to be about 160 feet/year.

The Rocky Flats Alluvium is completely truncated to the north, east, and south within the OU2 area. A portion of alluvial groundwater is discharged to alluvial seeps along the slopes of the drainages, and some alluvial groundwater migrates vertically downward into the underlying No. 1 Sandstone. Two alluvial seep areas have been identified within the OU2 area as being large relative to other seeps in OU2. One of these seeps occurs along and surrounding the head of a surface drainage gully located south-southwest of Pond B-5. As discussed earlier, alluvial groundwater flowing along the medial paleoscour is believed to discharge at seeps along the head of this gully. Separate measurements of flow from this seep area indicated flow rates of 0.2 to 1 gallons per minute (gpm), May and April, 1993, respectively.

The second relatively large alluvial seep in OU2 is located southeast of the 903 Pad. Groundwater flow within this seep is heavily influenced by seasonal variations in alluvial groundwater elevations. During high groundwater level periods, groundwater within the alluvium overtops a large portion of the south paleoridge, and flows southward and discharges from the alluvium to hillslope colluvium at a seep line where the alluvium is truncated by the Woman Creek drainage. During lower groundwater level periods, the south paleoridge prevents southward flow from the paleoscour, and this seep area tends to shrink and dry out.

No. 1 Sandstone. The saturated No. 1 Sandstone is bounded in areal and vertical extent by the surrounding bedrock deposits, which are predominantly claystone, and by the South Walnut and Woman Creek drainages, where the sandstone is eroded away. The No. 1 Sandstone subcrops beneath the Rocky Flats Alluvium in some locations and is separated from the alluvium by claystone in others (Figure 2.4-6). The sandstone occurs under unconfined conditions in most of the OU2 area. Where it is separated from the alluvium by claystone, it may occur under either semi-confined or unconfined conditions. Semi-confined conditions may also occur intermittently, during high groundwater level periods when recharge for the alluvium is at a maximum. In addition, in parts of the subcrop area, claystone layers interbedded within the upper part of the sandstone may act to retard vertical flow between alluvium and the lower part of the sandstone, causing the sandstone to behave locally as a confined unit.

Recharge to the No. 1 Sandstone probably occurs as a result of infiltration of precipitation and surface water through overlying unsaturated deposits, vertical flow from overlying saturated alluvium, and inflow to the area from upgradient portions of the sandstone west of OU2. The No. 1 Sandstone is the uppermost water bearing zone in some areas of OU2 outside the saturated alluvium zone.

The No. 1 Sandstone is believed to receive vertical leakage from overlying saturated alluvium in areas where the alluvium and sandstone are in direct contact, or where they are separated by only a few feet of weathered and/or fractured claystone. Downward vertical flow between the units is indicated by downward vertical gradients between the units, as discussed in Section 3.6 of the Phase II RFI/RI Report (DOE 1995a). In addition, OU2 groundwater geochemistry data indicate that the two units have similar groundwater geochemistry (i.e., both are calcium-bicarbonate type waters with low total dissolved solids). This supports the conclusion that the No. 1 Sandstone receives recharge from the overlying alluvium (DOE 1995a).

Well hydrographs indicate that the No. 1 Sandstone groundwater elevations increase in response to direct groundwater recharge and vertical recharge from alluvium. The rise of the groundwater level is rapid and occurs primarily during spring recharge periods. In areas where the units are in less hydraulic connection, the response of water levels in the sandstone is less and there is a longer delay between the initial precipitation event and the response of the sandstone water level (DOE 1995a).

Groundwater flow direction within the No. 1 Sandstone (Figures 2.5-6 through 2.5-8) is controlled by the geometry of the sandstone unit and its interaction with the overlying alluvium and South Walnut and Woman Creek drainages. Groundwater in the sandstone primarily flows to the north-northeast, with some flow to the southeast. The hydraulic gradient in the No. 1 Sandstone varies from approximately 0.028 feet/foot to as much as 0.1 feet/foot.

The potentiometric surface of the No. 1 Sandstone appears to be mounded in the contact area between Rocky Flats Alluvium and the sandstone along the medial paleoscour east of the 903 Pad (Figures 2.4-6 and 2.5-6 through 2.5-8), apparently causing flow in the sandstone to diverge, with most flow moving to the north and northeast and some flow moving to the southeast. Groundwater flowing north and northeast discharges to subsurface sandstone seeps where the sandstone subcrops beneath colluvium along the southern slope of the South Walnut Creek drainage. The component of flow to the southeast is discharged from subsurface seeps on the northern slope of the Woman Creek drainage.

Aquifer testing results for three areas of the No. 1 Sandstone were evaluated for this modeling study. Hydraulic conductivity values from a pumping test conducted in 1992 at Site 1 (Figures 2.5-6 through 2.5-8) ranged from 3.7×10^{-4} cm/s (1 ft/day) to 6.2×10^{-4} cm/s (1.8 ft/day) (DOE 1992). The estimated result from a slug test performed at Site 2 in 1992 was 5×10^{-6} cm/s (0.01 ft/day) (DOE 1992). Results for hydraulic conductivity from a pumping test conducted at IHSS 110 as part of the OU2 Subsurface IM/IRA range from 1×10^{-3} cm/s (2.8 ft/day) to 4×10^{-3} cm/s (11 ft/day) (DOE 1995b).

Intervals of the No. 1 Sandstone that were subjected to pumping stresses at the Site 1 and IHSS 110 aquifer test locations appear to be the highly friable and coarser-grained intervals described in Section 2.4. Boring logs for Well 3687 (an observation well in the Site 1 pumping test) and Wells 12191, 24993, 25093 (observation wells in the IHSS 110 pumping test), and 24193 (pumping well in the IHSS 110 pumping test) indicate the presence of highly friable and relatively coarse-grained sandstone in the tested intervals. Based on these observations, the hydraulic conductivity results from these pumping tests are believed to be in the upper range of values for the No. 1 Sandstone.

CONCEPTUAL FLOW MODEL

The conceptual flow model for OU2 is a conceptual representation of the actual UHSU groundwater flow system based on the site conditions briefly described in Section 2.0 and in more detail in the Phase II RFI/RI Report (DOE 1995a). The purpose of the conceptual flow model is to provide a framework for development of the mathematical flow model described in Section 5.0. Although OU2 has been investigated and characterized to a high degree relative to most investigation sites, it is recognized that the actual groundwater flow regime at the site is more complicated than that described by this conceptual interpretation due to the stratigraphic and hydrogeologic complexity of the area. However, it is believed that sufficient site-specific data have been incorporated in this conceptual interpretation to reasonably represent the significant components of the UHSU flow system in OU2, and therefore this conceptual model is adequate and appropriate to serve as a framework for development of the mathematical model.

3.1 HYDROSTRATIGRAPHY

The hydrostratigraphy of OU2 is complex (Figure 3.1-1). Groundwater modeling to support the CMS/FS was limited to the UHSU because groundwater contamination at OU2 exists primarily in the UHSU, and no remediation of the LHSU appears warranted. As described in Section 2.5 and the Phase II RFI/RI Report (DOE 1995a), the principal units of the UHSU at OU2 are the saturated Rocky Flats Alluvium and the No. 1 Sandstone. The saturated alluvium is unconfined and generally, the sandstone is unconfined, although the unit may be confined or semi-confined in some areas.

Potentiometric maps of the Rocky Flats Alluvium/colluvium and No. 1 Sandstone are presented in Section 2.5 as they were originally presented in the Phase II RFI/RI Report (DOE 1995a). The May 1992 Rocky Flats Alluvium/colluvium potentiometric map was revised for the conceptual model to limit the saturated alluvium area in the area just east and south of the 903 Pad (Figure 3.1-2). The saturated extent of the alluvium in that area approximately follows the south paleoridge. The No. 1 Sandstone May 1992 potentiometric map was also revised (Figure 3.1-3) to reflect a change in the interpretation of the water surface in the Northeast Trenches Area.

The interaction between these units is complex and varies both spatially and with time. The saturated Rocky Flats Alluvium and the No. 1 Sandstone appear to be in hydraulic communication in much of OU2 where the sandstone and alluvium are in contact or in close vertical proximity. Groundwater elevation observations indicate that, in general, the units are in less hydraulic communication in areas where they are separated by claystone. In addition, the Rocky Flats Alluvium and the No. 1 Sandstone may be in less hydraulic communication in some areas where the units are in contact but interbedded claystones within the No. 1 Sandstone act to retard vertical flow between the units. In the area west of the 903 Pad, flow may occur from the sandstone to the alluvium. This is evidenced by the similar water levels and an apparent eastward component of hydraulic gradient observed in this location in May 1992 in both the alluvium and No. 1 Sandstone (Figures 2.5-4 and 2.5-7).

The conceptual model consists of three layers, the top layer being saturated Rocky Flats Alluvium, and the bottom layer representing the No. 1 Sandstone, with a discontinuous claystone/siltstone layer between them. Vertical hydrogeologic cross-sections illustrating the conceptual hydrogeologic model are shown in Figures 3.1-5 through 3.1-7. The locations of the cross-sections are shown on Figure 3.1-4. Cross-section A-A' (Figure 3.1-5) illustrates the condition where the potentiometric surfaces of the alluvium and No. 1 Sandstone are not equal despite the fact that the units are in contact. Section B-B' (Figure 3.1-6) illustrates an area where those units are generally in hydraulic communication. C-C' is a longitudinal cross-section (Figure 3.1-7), illustrating areas where both of those conditions exist. Water levels depicted on these cross-sections are based on interpolated actual water levels.

3.2 AREAL RECHARGE

Groundwater recharge from infiltration of precipitation is believed to be the major source of water to the OU2 Rocky Flats Alluvium and No. 1 Sandstone groundwater flow system. This is based on observations of water level fluctuations within the Rocky Flats Alluvium that closely correlate with precipitation events, as well as the presence of a bedrock high and apparent absence of saturated alluvium at the western boundary of OU2, which indicates no source of inflow of alluvial water to OU2 from offsite locations.

Therefore, the groundwater recharge is a key component for development of the groundwater flow model. Based on analysis of alluvial hydrographs, groundwater recharge was directly estimated using observed aquifer responses to specific storm events. The recharge estimation was performed independently as discussed in the Phase II RFI/RI Report (DOE 1995a). The recharge estimation approach consisted of assessing the change in aquifer storage that occurred between March and May 1992, the main recharge season for the site during 1992, and estimating the recharge area and specific yield of the alluvium. This estimate was evaluated further by hydrologic analysis of (1) specific storm events and the resulting groundwater level responses in the alluvium to identify when recharge may have occurred, and (2) assessment of the potential runoff during those events to estimate the remaining quantity of water available for recharge.

The results of these analyses indicate that the net annual groundwater recharge to the alluvium ranges from about 1.0 to 1.3 inches per year based on an estimated specific yield range of 3 to 4 percent. The average value of specific yield, S_y, of the Rocky Flats Alluvium was estimated based on the results of the Phase II aquifer tests (DOE 1992). The details of the analysis can be found in Appendix E Groundwater Modeling of the Phase II RFI/RI Report (DOE 1995a).

The historic precipitation records (Figure 3.2-1) and well hydrographs (Appendix B4 in the RFI/RI Report) indicate that the annual seasonal precipitation and water level patterns are similar from year to year and that conditions in 1992 do not substantially differ from typical conditions. Thus, the estimated net groundwater recharge in 1992 is assumed to represent the typical annual net groundwater recharge for OU2 during past history and in the future.

3.3 BOUNDARY CONDITIONS

The conceptual lateral boundary conditions for the Rocky Flats Alluvium and No. 1 Sandstone at OU2 are no-flow boundaries (i.e., where claystone bedrock laterally bounds the units) and seep boundaries (i.e., where erosion by the South Walnut Creek or Woman Creek drainages laterally bound the units). Vertically, the conceptual boundary condition for the Rocky Flats Alluvium and the No. 1 Sandstone where they overlie claystone is a no-flow boundary based on the low hydraulic communication with the underlying LHSU (Sections 3.5, 3.6, 4.5, and 5.3 of the Phase II RFI/RI Report [DOE 1995a]).

The lateral boundaries of the saturated alluvium within the medial paleoscour change in elevation in response to the substantial seasonal fluctuations of water levels. Note that while the boundary of saturated alluvium changes with time in the real hydrogeologic system, the boundary in the numerical model will be fixed (Section 5.0). Figures 2.5-1 and 2.5-2 show the interpreted lateral extent of the saturated alluvium in the low-water level (March 1992) and high-water level (May 1992) seasons, respectively. In both cases, it is believed that little or no inflow of water occurs in alluvium across the western boundary of OU2 because it appears that saturated alluvium does not extend across that boundary. The outflow from the alluvium occurs laterally at seepage boundaries where the alluvium subcrops along the hillsides of South Walnut Creek and Woman Creek drainages, and vertically downward across a flow boundary to the underlying No. 1 Sandstone where it subcrops beneath the alluvium.

The boundary conditions for the No. 1 Sandstone are similar to the alluvium except that there appears to be inflow of water to OU2 within the sandstone where it crosses the western boundary of OU2. No data are available to estimate the flow rate across this boundary, but an eastward hydraulic gradient in the sandstone near the western boundary indicates that it is occurring. Discharge from the No. 1 Sandstone occurs almost entirely as subsurface discharge to colluvium along the hillsides of the South Walnut Creek and Woman Creek drainages. In some cases, these discharge areas are visible at the ground surface (Plate 3.6-1 of the Phase II RFI/RI Report [DOE 1995a]); in others they are obscured by the presence of colluvium or terrace deposits. Downward vertical flow from the No. 1 Sandstone to the underlying LHSU Laramie Formation sandstones, siltstones, and claystones is limited due to the limited hydraulic communication between the UHSU and LHSU (Sections 3.5, 3.6, 4.5, and 5.3 of the Phase II RFI/RI Report [DOE 1995a]).

3.4 SEASONAL VARIATIONS

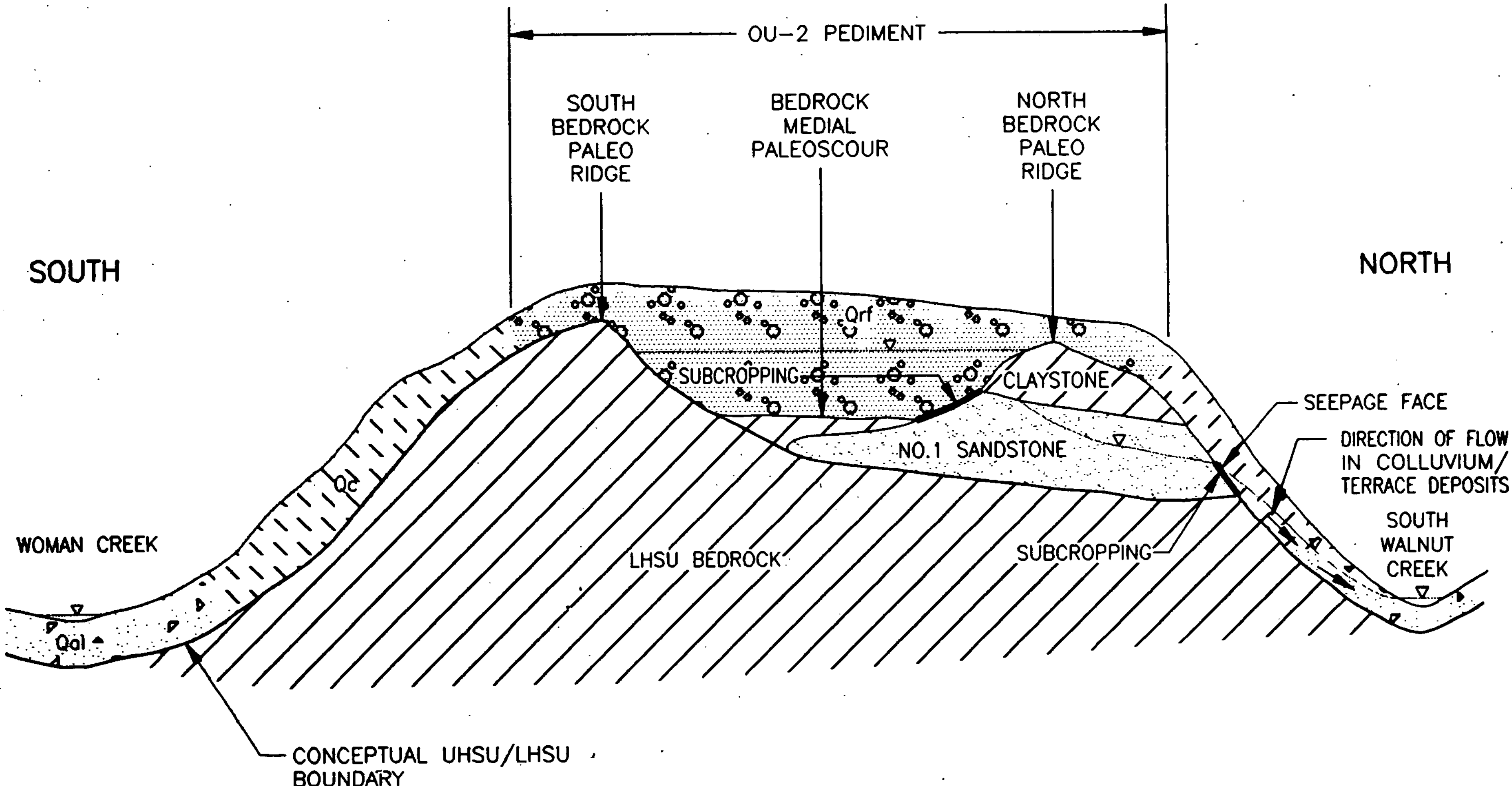
As described previously, changes in groundwater recharge, due to the seasonal distributions of precipitation and evapotranspiration, cause temporal variations in the groundwater system. In general, the extent and thickness of saturated alluvium, and the saturated thickness of the No. 1 Sandstone, increase in response to springtime recharge and decrease throughout the remainder of the year as water levels fall. Hydrographs for alluvial wells 1587 and 1787 (Figures 3.4-1 and 3.4-2) demonstrate the rise and fall of groundwater elevations associated with recharge and subsequent drying periods.

In general, alluvial and sandstone seepage rates increase in response to springtime recharge and decrease as water levels fall during the remainder of the year.

The seasonal behavior of recharge and seepage flow observed in data from 1992 is believed to be typical of conditions at the site. The conceptual model of water level conditions is based in part on the simplifying assumption that these conditions repeat on an annual cycle. The hydrographs for Wells 1587 and 1787 demonstrate that variability in the response to recharge occurs at different locations. The peaks in the hydrographs (Figures 3.4-1 and 3.4-2) occur at different times; the peak in the well 1587 hydrography occurred in spring 1989 while the well 1787 hydrograph peak occurred in spring 1992. Thus, while the annual cycle of rising and falling of water levels is evident at both wells, the magnitudes of these changes may differ in response to various events.

3.5 CONTAMINANT DISTRIBUTIONS

Distributions of total volatile organic compounds (VOCs) for the alluvial/colluvial (Figure 3.5-1) and No. 1 Sandstone (Figure 3.5-2) components of the OU2 groundwater system are presented to illustrate contaminated areas of interest in OU2. Total VOCs in alluvial/colluvial groundwater are present at high concentrations in the 903 Pad Area and south of the Pad in the Trench T-2 area. High concentrations of total VOCs in the No. 1 Sandstone are apparent in the Northeast Trenches Area, east of the 903 Pad, and in the Mound Area. Detailed descriptions of contaminant distributions in the alluvial/colluvial and No. 1 Sandstone units are presented in the Phase II RFI/RI Report (DOE 1995a). Contaminant transport is not simulated in this part of the CMS/FS modeling work. Contaminant distributions information was qualitatively used in the development of the flow model.



EXPLANATION

Qrf	Rocky Flats Alluvium
Qc	Colluvium/Terrace Deposits
Qal	Valley Fill Alluvium
∇	Water Level

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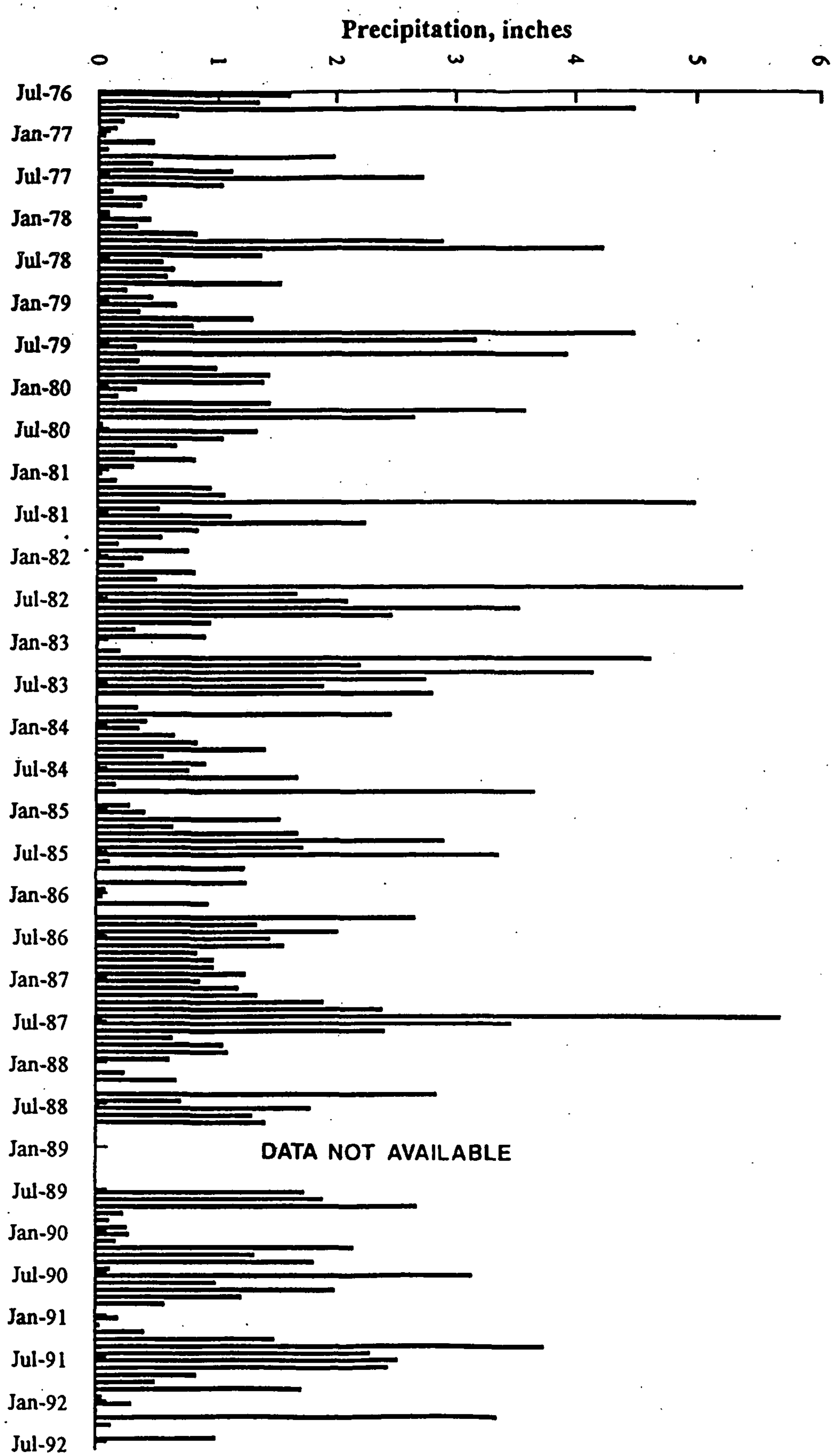
SCHEMATIC CROSS-SECTION
OF UHSU HYDROSTRATIGRAPHY

FIGURE 3.1-1 JUNE 1995

OU2FS030 1=1



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HISTORIC MONTHLY PRECIPITATION
AT ROCKY FLATS
(1976-1992)

FIGURE 3.2-1

JUNE 1995

OU2F3031

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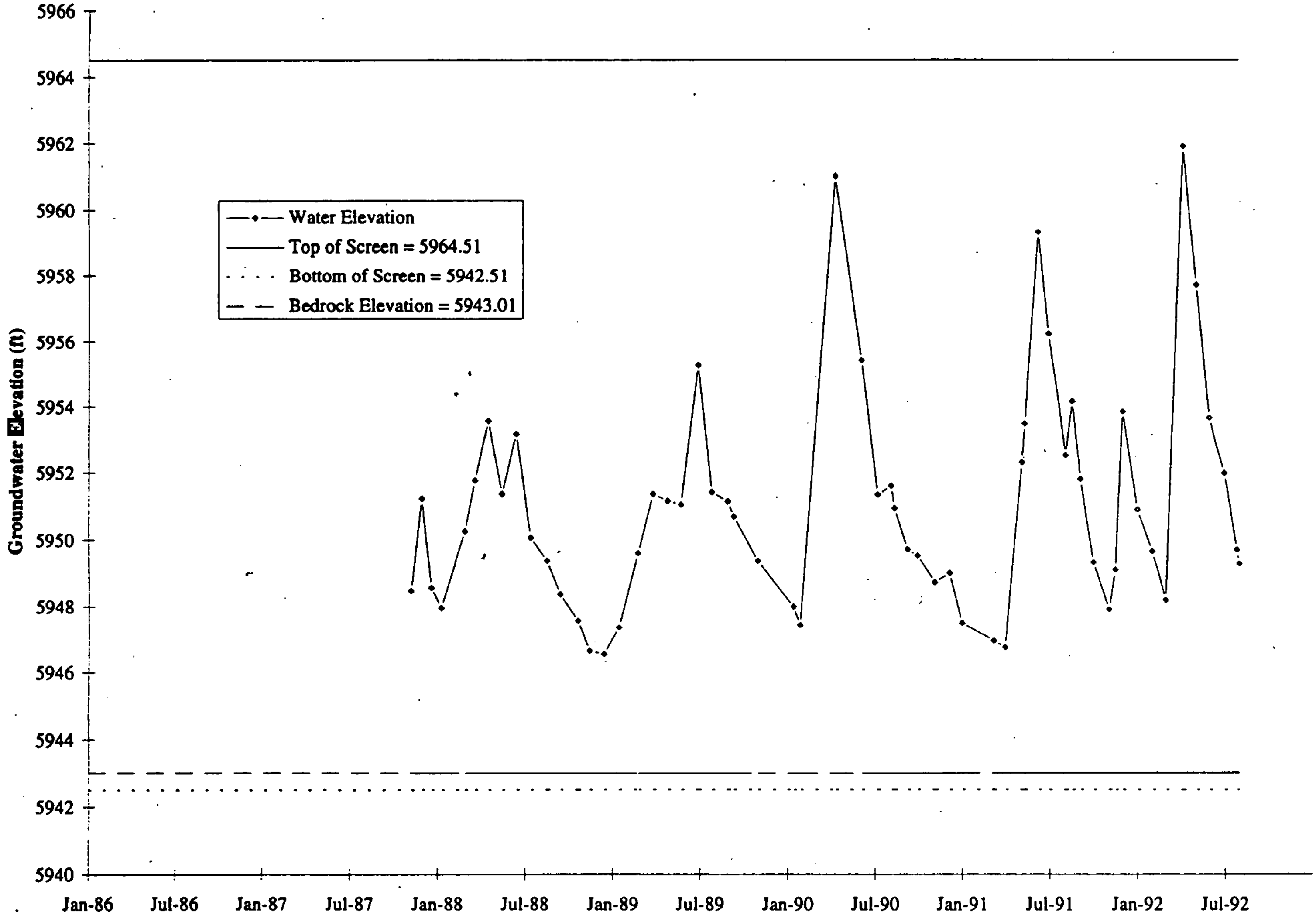

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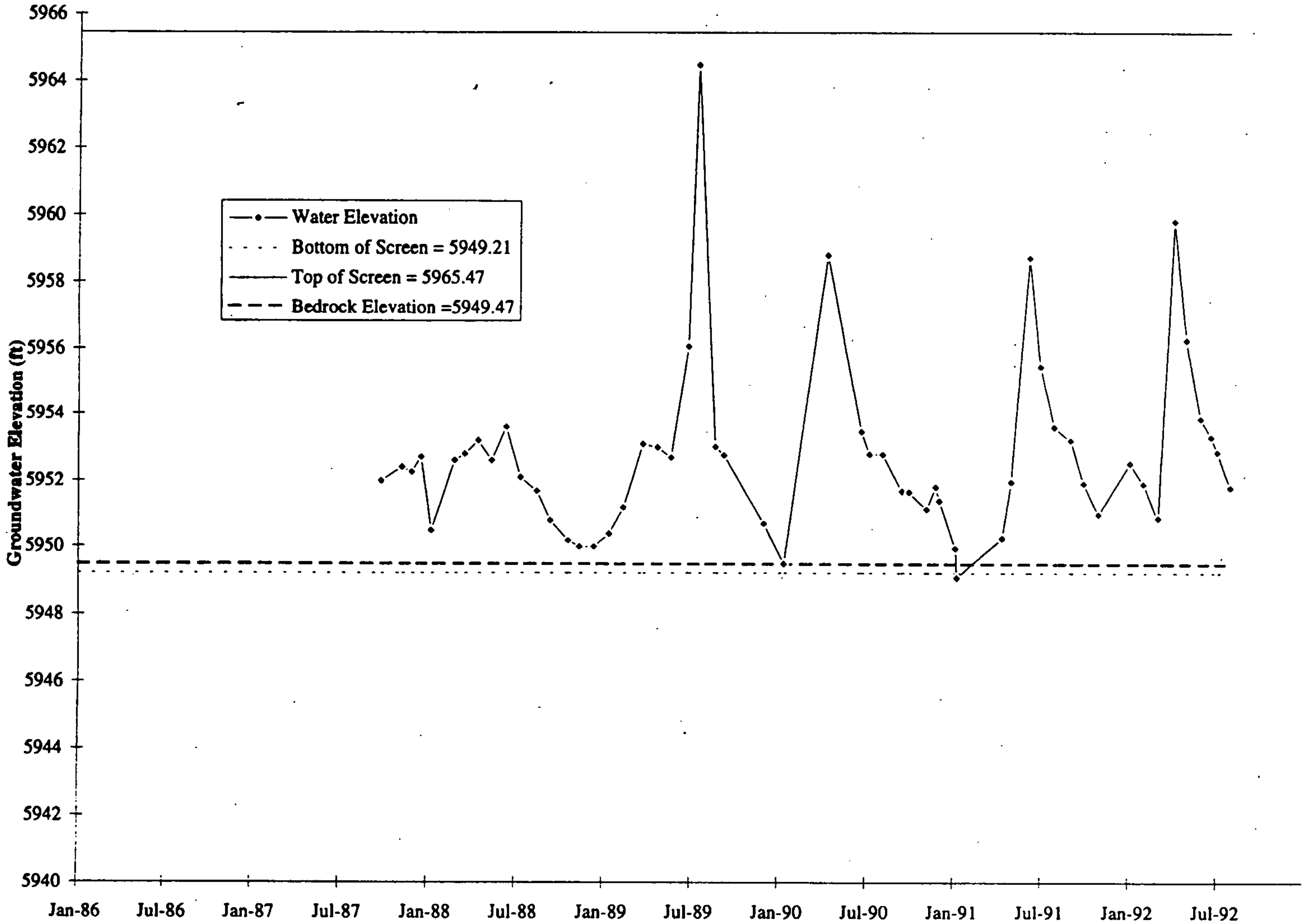
WELL 1787 HYDROGRAPH
(ROCKY FLATS ALLUVIUM)

FIGURE 3.4-2

JUNE 1995

OU2FS032 1=1



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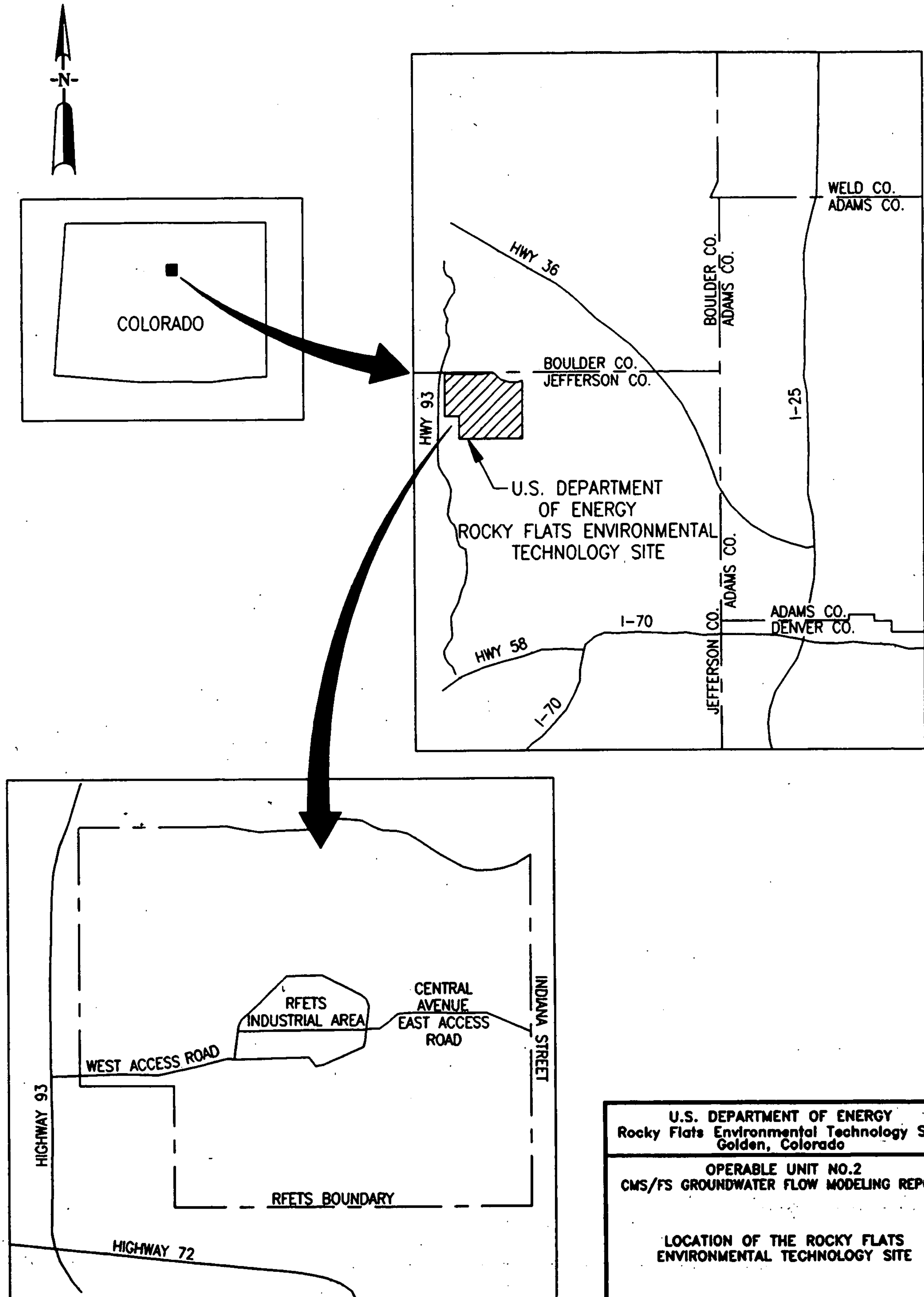
WELL 1587 HYDROGRAPH
(ROCKY FLATS ALLUVIUM)

FIGURE 3.4-1 JUNE 1995

OU2FS033 1=1



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LOCATION OF THE ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE

FIGURE 2.1-1 **JUNE 1995**

OU2FS31 1=1

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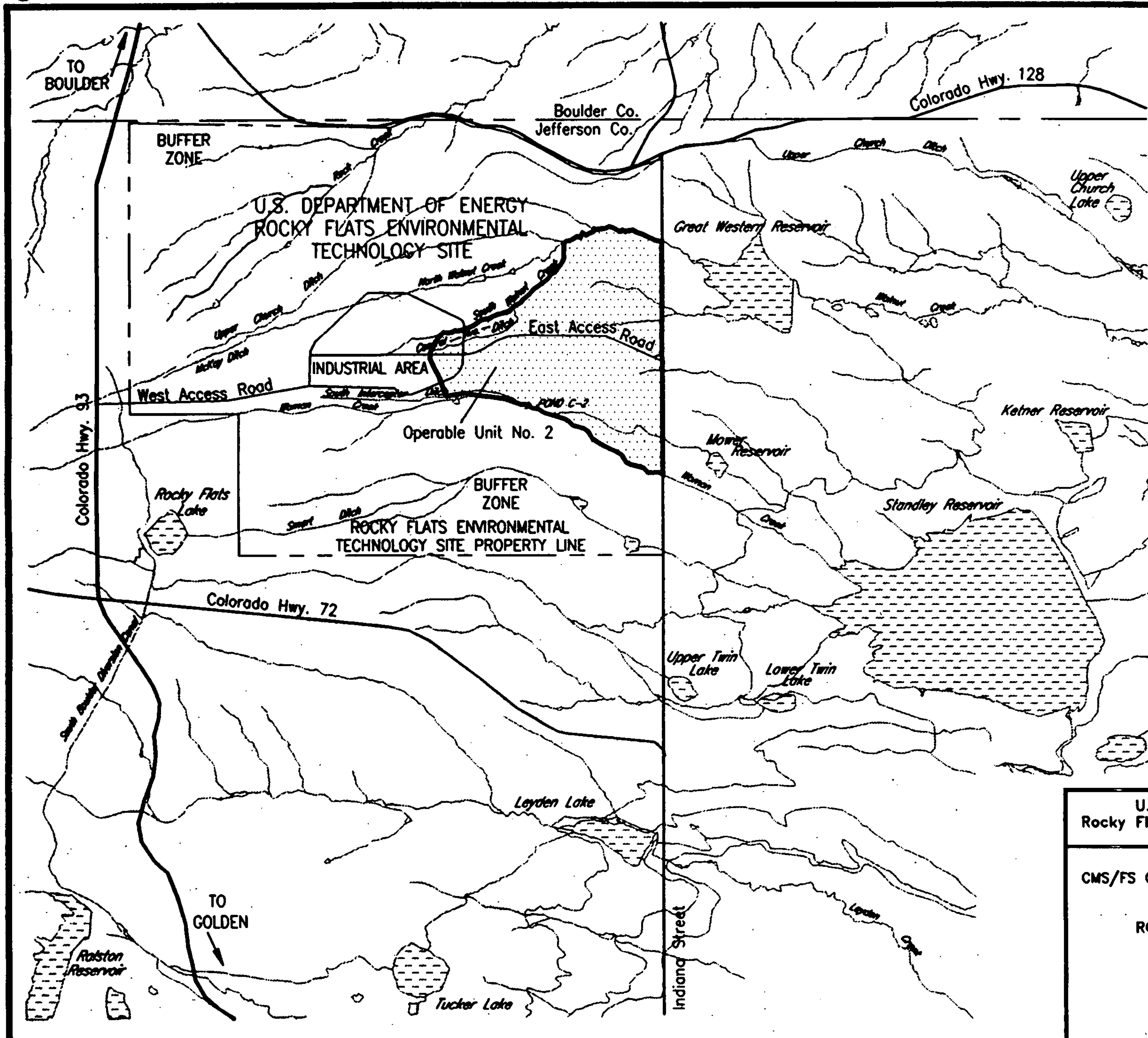

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ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE OPERABLE UNIT NO. 2

FIGURE 2.1-2 JUNE 1995

OU2FS30 1=1

4.0
MODEL SELECTION

A quasi-three-dimensional numerical model was used to simulate the groundwater flow system of the saturated Rocky Flats Alluvium and the No. 1 Sandstone to support hydraulic assessment of remedial action alternatives and to provide a flow field for contaminant transport simulations.

The computer code selected for the flow model was the USGS finite difference groundwater flow model MODFLOW (McDonald & Harbaugh 1988). MODFLOW is a public domain code designed to simulate groundwater flow in saturated porous media. MODFLOW was selected for use in this study because of its wide use and acceptance, and its flexibility in simulating highly variable site conditions.

4.1 MODFLOW CODE MODIFICATION

The transient simulations performed for this study involved substantial seasonal and stress-induced hydraulic head fluctuations resulting in "drying" and "re-wetting" of model cells. In its original version, MODFLOW converts any active cells into inactive cells if they go "dry" during the simulation (i.e., if the hydraulic head in the cells drops to or below the layer bottom elevation). To address "drying" and "re-wetting" problems, the authors of MODFLOW developed the Block Centered Flow 2 (BCF2) package, which allows "re-wetting" of dry cells under certain conditions. However, use of the BCF2 package can result in model convergence problems if a substantial number of cells experience "drying" and "re-wetting." Early simulations during this modeling study indicated that use of the unmodified BCF2 module would result in model convergence problems during simulations involving "re-wetting" processes. Therefore, an alternative approach to the "drying" and "re-wetting" problem was necessary for transient calibration.

To address this problem, the MODFLOW code was modified slightly. The code modification for the BCF2 package involved two parts: (1) assignment of a minimum saturated thickness in "dry" cells to prevent the cells from becoming inactive; and (2) correction of the vertical flux calculation to prevent unrealistic upward fluxes in those "dry" cells.

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4.1.1 Assignment of Minimum Saturated Thickness

The first part of the code modification involved specification of a minimum saturated thickness (0.1 feet) for model cells in which simulated hydraulic heads were equal to or less than the bottom elevations of the layer (i.e., "dry" cells). The code modification was based on recommendations by Dr. John Doherty of the Queensland Department of Primary Industries, Land Use and Fisheries, in Australia (personal communication 1993). The modification involved changing a statement in the SBCF2H subroutine of the BCF2.FOR module, as shown below:

```
C6-----CHECK TO SEE IF SATURATED THICKNESS IS GREATER THAN ZERO.
       IF(THCK.LE.0) GOTO 100
```

was changed to

```
C6-----CHECK TO SEE IF SATURATED THICKNESS IS GREATER THAN ZERO.
       IF(THCK.LE.0) THCK=0.1
```

With this change, the simulated hydraulic head in a cell is allowed to drop to an elevation below the bottom of the model layer (usually causing the cell to become inactive), but the saturated thickness cannot be less than 0.1 feet. This prevents MODFLOW from converting the cell to an inactive cell, thus allowing "re-wetting" to occur without numerical convergence problems. The "dry" cells can be identified by comparing the simulated hydraulic head with the layer bottom elevation using a post-processor.

4.1.2 Correction of Vertical Flux Calculation

The second part of the code modification was made to prevent simulation of unrealistic upward fluxes between model layers in locations where cells are simulated to go "dry." This problem, which is an artifact of the first modification discussed above, can occur where hydraulic heads in the "dry cells" in the upper layer are simulated to drop below the elevation of the bottom of the upper layer, and the hydraulic head in the lower layer drops below the top of the lower layer. Under this condition, the vertical flux between layers is computed based on the elevation difference between the hydraulic head in the upper layer and the

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bottom elevation of the upper layer (McDonald and Harbaugh 1988). When the head is below the bottom of the upper layer, a negative elevation difference is calculated, resulting in an artificial negative, or upward, gradient. This does not normally occur in MODFLOW because the upper cell is designated as inactive when the head drops below the cell bottom, and therefore, no vertical flux can occur. However, because the first modification prevents MODFLOW from designating the "dry" cells as inactive, MODFLOW calculates an artificial upward flux at a rate proportional to the elevation difference and the specified vertical conductance factor.

To eliminate this problem, an additional code modification was made to change the vertical conductance value to zero in locations where the upper layer cell is "dry" (i.e., where the hydraulic head in the upper layer cell drops to or below the upper layer bottom elevation) (see Appendix A for the modified model code). This was accomplished by adding a second vertical conductance array in the BCF2.FOR module. At the beginning of each iteration, the code checks the saturated thickness value in the upper layer cell. During the "drying' period (i.e., the period when hydraulic heads are falling), if the saturated thickness in the upper layer cell is greater than 0.1 feet, the model uses the specified vertical conductance value between the layers to simulate the flux between the upper layer and the lower layer. If the saturated thickness in the upper layer cell decreases to 0.1 feet, the model specifies a value of zero for vertical conductance, thereby shutting off vertical flow between the cells. During the "re-wetting" period (i.e., the period when hydraulic heads are increasing), the model resumes using the original vertical conductance value when the saturated thickness of the upper layer cell increases to greater than 1.0 foot, thereby turning flow back on between the layers. The threshold value of 1.0 foot in saturated thickness used during "re-wetting" was selected to avoid numerical oscillations that can occur with smaller values.

4.1.3 Evaluation of Code Modification

The modified BCF2 code was used only during transient flow simulations. Steady state calibration was performed using the unmodified code. The potential impact on model results using the modified BCF2 module was evaluated. A comparison was made between model results using the unmodified BCF2 module and the modified BCF2 modules for an 11-month drying period and no significant differences were observed (Appendix A). The solutions produced using the modified code are more stable and acceptable for the model objectives.

MODEL DESIGN

This section discusses the translation of the conceptual model to a quasi-three-dimensional numerical model.

5.1 MODEL GRID

The numerical model domain is shown on Figure 5.1-1. The rectangular model domains consists of a uniform grid with 76 rows and 223 columns, each cell with uniform dimensions of 20 feet by 20 feet. The total model domain is 1,520 feet by 4,460 feet in area and is oriented in the long dimension from southwest to northeast along the direction of the OU2 pediment. The primary reasons for using this fine and uniform model grid are: (1) the flow directions in the two permeable model layers are approximately perpendicular to each other in some areas; and, (2) fine and uniform grids can reduce potential numerical problems, or at the least, facilitate identification of the potential problems.

5.2 VERTICAL DISCRETIZATION

Vertically, the model consists of two layers, saturated Rocky Flats Alluvium and the Arapahoe Formation No. 1 Sandstone. Layer 1, representing the saturated alluvium, is simulated as an unconfined aquifer. Layer 2, representing the sandstone, is simulated as an unconfined/confined aquifer (type 3 MODFLOW condition), because the hydraulic head in the No. 1 Sandstone is believed to generally exist under unconfined conditions but may be confined or become confined at times (a semiconfined condition) in some locations.

Between the alluvium and the No.1 sandstone, discontinuous claystone layers or lenses are present and act as a confining layer between the two units. In some parts of the subcropping area (shaded area in Figure 2.4-6), where borehole data suggest that no claystone separates the saturated layers, substantial differences (5 to 10 feet) in hydraulic heads in the alluvium and underlying No. 1 Sandstone exist; this may indicate that some kind of vertical barrier exists. It is speculated that this may be attributed to the presence of interbedded claystone with relatively low permeability near the top of the No. 1 Sandstone layer.

The claystone between the saturated geologic layers was not simulated as a separate model layer based on the following rationale:

- Horizontal flow in claystone layers or lenses is not expected to be significant due to the low hydraulic conductivity of the claystones (on the order of 1×10^{-7} cm/s);

- Claystone lenses are discontinuous and the dimensions of the lenses are not well defined.

- Hydraulic heads specific to the claystone layer are not available.

Therefore, this model was designed as a quasi three-dimensional model of two layers. Interaction between those layers (e.g., vertical flow) and the effect of claystone between the layers (where it occurs) is represented by a vertical conductance factor that regulates flows between the layers. The retarding effect of claystone layers between the alluvium and No. 1 Sandstone and other unspecified vertical barriers was represented using low values of vertical conductance that limited vertical leakage between the model layers. In the areas where the intervening claystone layers are not present, higher values of vertical conductance are used to simulate a greater amount of vertical leakage. Values of vertical conductance were calibrated during model calibration.

5.3 IMPLEMENTATION OF NUMERICAL MODEL SETUP

The contoured surfaces that define the groundwater flow system at OU2, including the top of bedrock surface (Figure 2.4-1), the top of the No. 1 Sandstone (Figure 2.4-7), and the May, 1992 potentiometric surfaces for the Rocky Flats Alluvium and the No. 1 Sandstone (Figures 2.5-4 and 2.5-7), were digitized and converted to X (easting), Y (northing), and Z (elevation) coordinates. Each of the digitized surfaces were presented in the Phase II RFI/RI Report (DOE 1995a) with the exception of the base of the No. 1 Sandstone surface. The base of the No. 1 Sandstone map and the digitized version of it were created for the numerical model. The coordinates were then input to the Contour Plotting System (CPS/PC) (Radian 1990) graphics software package, regridded, and then converted to digital values at each model grid in ASCII format electronic files.

The ASCII files, which are comprised of X, Y, and Z values for each model grid, were then checked to verify that the relationships between the surfaces were reasonable. If discrepancies were identified, the files were modified using a pre-processor. Once satisfactory ASCII files were developed, the files were used to create MODFLOW input files for the various model layers. The digital top of bedrock surface (Figure 5.3-1) is the bottom of model layer 1, and the top and base of the No. 1 Sandstone (Figures 5.3-2 and 5.3-3) are the top and bottom of layer 2, respectively. The regridded version of the subcropping area between alluvium and the No. 1 Sandstone is shown on Figure 5.3-4.

The final regridded versions of the various model surfaces and potentiometric surfaces are, in general, very similar to the original interpretations of the surfaces. They do not match exactly due to the smoothing of contours that occurred in the computer contouring process in CPS/PC. In addition, the contours may not reflect all heterogeneities in the physical system.

Vertical cross-sections of the flow system were also created in CPS/PC from the regridded surfaces to check the relationships between surfaces for consistency and reasonableness. The cross-sections (Figures 5.3-5 through 5.3-9) demonstrate the complexity and major features of the flow system and depict the close match between the digital model layers and the site conceptual model layers. These cross-sections were used in the model calibration to visualize the flow system. Note that the model cross-sections in these figures only show features of the flow system considered to be of primary interest for the modeling.

5.4 MODEL ACTIVE DOMAIN

The active model domain for layer 1 follows the extent of saturated alluvium for a representative high flow period (May, 1992). The active model domain for layer 2 follows the extent of the No. 1 Sandstone channel. The active areas of the two layers have different irregular shapes and partially overlap (Figures 5.4-1 and 5.4-2). Layer 1 consists of 6,960 active cells, and layer 2 consists of 7,684 active cells.

5.5 MODEL BOUNDARY CONDITIONS

The model boundary conditions represent the hydrologic interaction between the model area and the outside area. To simulate the physical lateral boundaries of the groundwater flow system, a variety of boundary conditions were assigned to the model boundary as follows (Figures 5.4-1 and 5.4-2):

Seep boundary. All the seeps, including the southwest alluvial seeps, the alluvial surface drainage gully seep at the northeast corner of the model domain, and the north and part of the south boundaries of the No. 1 sandstone are simulated as seep boundary cells using the drain package in MODFLOW.

Variable flow boundary. The east boundaries of both layers are simulated as variable flow boundaries using the drain package to reflect the phenomena that flow out of the model domain is dominated by the variation of hydraulic head inside of model domain.

Specified flux boundary. The west boundary of layer 2 is simulated as a specified flux boundary using the well package in MODFLOW to reflect the seasonal variable flux into the model domain.

No-flow boundary. The remaining portions of the boundaries for both layers are simulated as no-flow boundaries.

Special features of the model boundary conditions in this model are:

- **Due to the limited extent of the flow system, the model boundaries cannot be set a substantial distance away from the area of interest (as is common groundwater modeling practice); rather, the model boundaries are an important part of the system.**

- **Except for the no-flow boundary, boundary condition parameters needed to be calibrated.**

- All the variable boundary conditions, including drain cells and specified flux, were set as prescribed head boundary conditions during steady state calibration. The head values were assumed to be the same as the potentiometric surface values for May, 1992 for the respective locations and layers.

- When steady state calibration was satisfied, steady state boundary conditions (i.e., prescribed head boundary conditions) were transferred to time-variable boundary conditions (i.e., drain cells and specified flux boundaries).

5.6 NET GROUNDWATER RECHARGE

The net groundwater recharge, one of the key model input parameters, was estimated independently using the hydrologic analysis discussed in Section 3.2. The estimated annual typical recharge at OU2 is estimated to range from 1.0 to 1.3 inches/year. Model calibration was performed using this basic estimation. The temporal and spatial distribution of recharge was estimated and adjusted during model calibration.

The spatial distribution of recharge was estimated based on ground surface and subsurface conditions in the model area. The assumptions for the distribution of recharge in the model are (1) the alluvium receives direct recharge from infiltrating precipitation; (2) the alluvium within the medial paleoscour receives more recharge because of the effect of the subsurface groundwater collection basin as described in Section 2.5; (3) where the alluvium is absent, the sandstone channel receives less direct recharge because it is overlain by claystone; (4) minimal recharge occurs in relatively impervious areas; (5) more recharge occurs in areas where trenches or ditches are located; (6) caliche layers in alluvium retard infiltration of precipitation and recharge; and, (7) storm runoff is greater on hillsides than in areas where the slope is less, therefore recharge is less on hillsides. Recharge zones (Figure 5.6-1) were classified as follows:

Zone 1	Baseline recharge area
Zone 2	Impervious area, such as the 903 Pad, and other paved areas
Zone 3	Concentrated recharge area, which is the central area of alluvium within the medial paleoscour

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Zone 4	Hillside area
Zone 5	The area where a caliche layer in the shallow alluvium delays recharge
Zone 6	The area where the No. 1 Sandstone underlies claystone and unsaturated alluvium
Zone 7	Trenches and ditches

The baseline recharge area is considered to be typical of recharge conditions for the site, with pervious surface conditions, low topographic slope, and no natural or man-made features that would significantly affect recharge rates. Ratios between the baseline recharge rate and the rates of the other zones were estimated and adjusted during steady state calibration. The temporal distribution of recharge was estimated and calibrated in the transient calibration.

5.7 HYDRAULIC PARAMETERS

Hydraulic parameters of interest in this model include distributed hydraulic conductivity, specific yield and storativity, and vertical conductance. Hydraulic conductivity was calibrated within the range discussed in Section 2.5. The estimated values of specific yield from two alluvial pumping tests range from 0.004 to 0.09; while the estimated values of specific yield or storativity from two sandstone pumping test results range from 0.005 to 0.03 (DOE 1992). Storage coefficient was calibrated as discussed in Section 6.0. No site-specific data for vertical conductance are available. This parameter was calibrated as discussed in Section 6.0.

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6.1 CALIBRATION STRATEGY

The goal of model calibration was not only to match the spatial hydraulic head and flow distributions in both layers, but also to match the temporal variations of hydraulic heads and flow in both layers. To meet the calibration goal, transient calibration was needed.

Based on the site conditions and model objectives, the following parameters were identified as requiring calibration: (1) hydraulic conductivity; (2) storage coefficient; (3) vertical conductance; (4) groundwater recharge; (5) conductance of drain cells; and, (6) specified boundary fluxes. Because of the complexity of the site conditions, it is extremely difficult to calibrate all the parameters simultaneously. Therefore, decomposition of calibration into steady state calibration and transient calibration was necessary.

An iterative calibration strategy involving steady state and transient calibration was designed, as illustrated in the flow chart in Figure 6.1-1. The strategy is a three-step process: (1) steady state calibration, (2) conversion of steady state boundary conditions to time-variable boundary conditions, and (3) transient calibration.

The steady state calibration involved those parameters that may be separated from transient phenomena, making the transient calibration less complex. Steady state calibration focused on calibration of horizontal hydraulic conductivity, vertical conductance, and spatial distribution of groundwater recharge. Transient calibration focused on adjustment of storage coefficient, seasonal variations of boundary conditions, and vertical conductance under transient conditions.

The actual groundwater system is highly transient, and therefore, no steady state data are available. Steady state calibration was conducted under an assumed steady state (high flow) condition with an assumed groundwater recharge rate (which was based on an estimated recharge rate). In addition, steady state calibration was performed with constraints on horizontal hydraulic conductivity and ratios of horizontal to vertical hydraulic conductivity.

Errors associated with uncertainties in assumptions and assignment of parameter constraints were not seen in the steady state calibration results. Only during transient calibration did the appropriateness of steady state calibration parameters become evident. Therefore, iteration between steady state and transient calibration was necessary and was repeated until satisfactory transient simulation results were obtained.

The rationale for developing the two-phase calibration strategy are:

- The system is too complicated to adjust the hydraulic conductivity distribution, specific yield, storage coefficient, drain conductance, and other parameters simultaneously in time-consuming transient calibrations.

- The hydraulic conductivity distribution is believed to be the key parameter in calibration of such a complex system. Without a detailed and representative hydraulic conductivity distribution, even a steady state simulation cannot result in a converged solution; thus, it was necessary to determine the hydraulic conductivity distribution before attempting calibration of other parameters.

- Using steady state calibration to obtain a reasonable hydraulic conductivity distribution is efficient and cost-effective.

- The parameters associated with time-variable boundary conditions can be easily obtained from the steady state calibration assuming the boundary conditions are under steady state conditions.

- Uncertainties associated with steady state calibration can be identified during transient calibration and reduced by the iterations between the two phases.

6.2 STEADY STATE CALIBRATION

The objectives of steady state calibration were twofold:

- Obtain a detailed hydraulic conductivity distribution reflecting site heterogeneities.

- Prepare an initial hydraulic head distribution for transient calibration.

A recently developed automated calibration procedure (Guo and Zhang 1994) was used for steady state calibration. Use of this procedure resulted in a detailed hydraulic conductivity distribution reflective of the heterogeneous nature of geologic material at the site, and facilitated successful convergence of the numerical model for this highly non-linear groundwater system. In addition, the efficiency of the procedure allowed for repeated steady state calibrations (more than 5,000 runs) associated with various changes in recharge rate, boundary conditions, hydraulic conductivity constraint zonation, the ratio of horizontal to vertical hydraulic conductivity, and the geometry of the No. 1 Sandstone channel.

Steady state calibration was performed using the unmodified MODFLOW code.

6.2.1 Assumptions

Steady state conditions do not exist at the site and therefore, no steady state data are available. In addition to previously stated model assumptions, the following assumptions were necessary specifically for conducting the steady state calibration.

- May 1992 hydraulic head distributions were assumed to be the steady state for both model layers; this provided for the maximum saturated alluvial extent and therefore, the maximum active model area.

- An artificial steady state recharge rate corresponding to a high flow condition was assumed and adjusted during iterative calibration processes; a rate of 3 inches/year (0.83×10^{-2} inches/day) was selected as the final baseline rate for Zone 1 (Section 5.6). Recharge rates for the other zones (Table 6.2-1) are proportional to this rate. This artificial recharge value was necessary to maintain high water levels in the steady state simulation.

6.2.2 Calibration Targets

Hydraulic head distributions for the alluvium and the No. 1 Sandstone in May 1992 (Figures 3.1-2 and 3.1-3) were used as the calibration targets for steady state calibration. As described in Section 5.3, these potentiometric surfaces are regridded versions (from CPS/PC) of the original surface interpretations. Regridded hydraulic head values may differ slightly from actual well data because of smoothing of contours in the regridding process. Heterogeneities in the flow system may be, in part, masked by the smoothing of the surfaces. The potentiometric surfaces are, however, believed to be reasonable representations of the flow system.

6.2.3 Calibration Constraints

Calibration was conducted under the following constraints:

- Hydraulic conductivity constraints based on geologic information (borehole data and lithofacies interpretations) and pumping test results were applied;
- Groundwater recharge zonation was based on site conditions;
- Qualitative understanding of the spatial distribution of seep flow rates.

6.3 STEADY STATE CALIBRATION RESULTS

Under the given boundary conditions, recharge intensity and recharge zonation, and hydraulic conductivity constraint zonation, the automated calibration procedure led to a satisfactory match of hydraulic head distributions for both layers. Evaluation of the calibration results follows.

6.3.1 Simulated Hydraulic Head Distributions

The simulated hydraulic head distributions are presented in Figures 6.3-1 and 6.3-2. The correspondence of the interpreted and simulated heads for layer 1 is very good. Deviation observed in the comparison of heads in layer 2 is related to constraints on hydraulic conductivity imposed for that layer.

6.3.2 Root Mean Squared Error of Simulated and Observed Hydraulic Heads and Residual Distribution

The root mean squared (RMS) error is defined as the squared differences in measured and simulated heads as follows:

$$RMS = \left[1/n \sum (h_o - h_s)^2 \right]^{0.5} \qquad (1)$$

where n is the number of observations, h_o is observed (or interpreted) head, and h_s is simulated head. In this application, RMS was calculated in two ways: one as the differences between interpreted and simulated heads at all model cells where n is the total number of active cells; and the other as the differences in measured and simulated heads at all observation wells.

The first type of RMS error is 0.72 feet and 1.1 feet for layers 1 and 2, respectively. The second type of RMS error is 1.4 and 2.3 feet for layer 1 and 2, respectively. The magnitude of the second type of RMS error may be attributed in part to differences between well observations and interpreted potentiometric surfaces generated in the regridding process (Section 5.3). Comparisons of simulated and observed head values for 36 alluvial wells and 28 sandstone wells are given in Table 6.3-1.

The residuals, defined as the difference between simulated and interpreted hydraulic head, are shown in Figures 6.3-3 and 6.3-4 for layer 1 and layer 2, respectively. For layer 1, most of the residual values are less than or equal to 1.0 foot, except for the southeast bedrock low area where calibrated hydraulic conductivity values are at the upper bound of constraint ranges. For layer 2, residuals with relatively high values (greater than 2.0 feet) are located in three areas within the east channel of the sandstone. They are the result of applying tight hydraulic conductivity constraints (Section 6.3.4) in three areas: (1) in the vicinity of IHSS 110, where relatively high values of hydraulic conductivity were applied as constraints to match the results of aquifer testing at the site; and (2) and (3) on the north and south hillsides of OU2, where hydraulic conductivity value constraints were applied to match the qualitative understanding of seep flow conditions.

Linear regression analyses of observed and interpreted hydraulic heads versus simulated hydraulic heads are presented in Figure 6.3-7 and 6.3-8 for layer 1 and layer 2, respectively. Regression lines for both comparisons on the two figures are nearly 45 degrees. Deviations from the best-fit lines are small, indicating strong correlation in the comparisons. In addition, data points are randomly distributed around best fit lines indicating no spatial bias.

6.3.3 Calibrated Hydraulic Conductivity Distributions

As a result of calibration, detailed hydraulic conductivity distributions for both layers were obtained (Figures 6.3-5 and 6.3-6). The ranges of hydraulic conductivity values for layer 1 and layer 2 are 0.01 ft/day to 22 ft/day, and 0.001 ft/day to 10 feet/day, respectively. The ranges were specified by setting the constraints on hydraulic conductivity when local information was available. Hydraulic conductivity for claystone lenses was assigned as 0.001 ft/day. During repeated steady state calibrations, the calibrated values of hydraulic conductivity were changed due to the changes in recharge rate, boundary conditions, hydraulic conductivity constraint zonation, and other parameters. The relative patterns of the hydraulic conductivity distributions did not significantly change during the repeated calibrations, reflecting the hydraulic head distributions of the layers.

6.3.4 Assessment of Calibrated Hydraulic Conductivity against Pumping Test Results

Of the four hydraulic conductivity values reported based on pumping test results used for this study, three were matched very well by the automated calibration procedure. At the fourth location, which is in the sandstone in the vicinity of the soil vapor extraction site (Trench T-3 in the Northeast Trenches IHSS Area), use of the automated calibration procedure to obtain a good match between simulated and interpreted hydraulic heads resulted in a poor match between simulated and measured hydraulic conductivity (2E-05 cm/s versus 9.9E-04 to 4.0E-03 cm/s). Review of site data on hydraulic head, hydraulic gradient, and hydraulic pumping test results, as well as soil vapor extraction pilot test pumping records (which indicate 30,000 gallons of water were pumped from the sandstone in three weeks [DOE 1995b]), suggests a conflict between the measured hydraulic head data and the measured hydraulic conductivity data in this area. Resolution of this apparent conflict will likely require data not available for this modeling study. Therefore, a choice had to be made between matching the interpreted hydraulic heads in this location, or matching the measured hydraulic conductivity in this area. Because a key objective of this modeling effort was to simulate hydraulic effects from pumping, it was decided that it was more important to accurately represent the measured hydraulic conductivity in this area, at the expense of a good match between simulated and interpreted hydraulic heads. Therefore, tight constraints were specified for the K values (0.6 to 1.5 ft/day) in this area of layer 2, resulting in simulated hydraulic heads below the interpreted heads.

6.3.5 Calibrated Vertical Conductance Under Steady State Conditions

Vertical conductances values (Vcont) between layer 1 and layer 2 were calibrated where both upper and lower cells are active cells. In this model, Vcont is a critical parameter which controls the vertical leakage rate from layer 1 to layer 2. Hydrogeologic data and experience gained during calibration indicate that the amount of vertical leakage from the alluvium to the sandstone is substantial; however, no direct information about the rate is available.

Vertical conductance under steady state conditions was estimated using the following equation provided in the MODFLOW manual (McDonald and Harbaugh, 1988):

$$V_{cont} = \frac{1}{\frac{\Delta Z_u/2}{K_{zu}} + \frac{\Delta Z_c}{K_{zc}} + \frac{\Delta Z_l/2}{K_{zl}}} \quad (1)$$

where

Δz_u is the thickness of the upper aquifer
Δz_c is the thickness of the confining bed
Δz_l is the thickness of the lower aquifer
K_{zu} is the vertical hydraulic conductivity of the upper aquifer
K_{zc} is the vertical hydraulic conductivity of the confining unit
K_{zl} is the vertical hydraulic conductivity of the lower aquifer

The vertical hydraulic conductivity was assumed to be proportional to horizontal hydraulic conductivity. The ratio of horizontal versus vertical hydraulic conductivity was adjusted by trial and error. The reasonableness of the calibrated vertical conductance was evaluated during transient calibration. In the cases when transient simulations indicated too much or too little downward vertical flux, steady state calibration was repeated by adjusting the ratios of horizontal versus vertical hydraulic conductivity. When vertical flux rates were too high, the alluvium became dry in areas where observations indicate it should not be dry. Vertical flux rates that were too low did not allow layer 2 hydraulic heads to recover from low to high flow conditions. Among the parameters involved in calibration, the vertical conductance is believed to have the greatest uncertainty, due to the complexity of the system and lack of direct information. The calibrated vertical conductance ranges from 0.2×10^{-3} to 0.1×10^{-2} day^{-1} for the area where significant vertical hydraulic communication occurs.

6.3.6 Simulated Steady State Flow Rates under High Flow Conditions

The simulated seep flow resulting from steady state calibration was considered representative of the seep flow spatial distribution under high flow conditions. The simulated alluvial seep flow rate at the surface drainage gully is 2.8 gpm, which is considered reasonable compared to the measured rate of 1 gpm on April 17, 1993 that corresponded to a medium flow condition. The simulated seep flow rate at the southwest boundary of the alluvium is 1.2 gpm. At the south boundary of the sandstone it is 0.5 gpm and at the north hillside of the sandstone it is 6.8 gpm. No measurements of seep flow are available for comparison other than the measurement for the alluvium at the surface drainage gully.

At the east boundary of the model domain, the simulated flow rates out of the alluvium and No. 1 Sandstone are about 1.3 gpm and 0.3 gpm respectively. The calibrated flux entering the model domain at the west boundary of the No.1 sandstone is 0.01 gpm.

Under assumed steady state conditions, the vertical leakage rate for the entire model domain from layer 1 to layer 2 is 3 gpm.

6.4 TRANSIENT CALIBRATION

The transient simulation results simulate the typical transient field conditions and can be used directly in assessing remedial alternatives for the CMS/FS. The objectives of transient calibration require that model results not only match the spatial distribution of hydraulic heads and flow rates, but also match the temporal variation of the spatially distributed hydraulic heads and flow rates.

Parameters calibrated under transient conditions include storage coefficient, vertical conductance under transient conditions, temporal variation of drain cell conductance and specified flux, and temporal variation of groundwater recharge. Due to complexity of the system, transient calibration was a very time consuming process.

6.4.1 Calibration Targets

The hydrogeology discussion presented in the Phase II RFI/RI (DOE 1995a) report focused on 1992 groundwater conditions. The most complete data set was available for that year, therefore it was selected as a representative year for calibration. A one year transient simulation was performed from high water level conditions to low water level conditions, and then to high water level conditions again, reflecting water level falling and rising processes. The transient calibration targets are:

- Match hydraulic head distributions for both layers in different seasons, including matching of the saturated areas of alluvium.

- Match hydrographs at each observation well, including the rate of groundwater level rise and fall.

- Qualitatively match variation of seep flow conditions, including seep flow rates and seep areas (some seeps become dry in low flow season).

- The annual total outflow should be equal to the annual total inflow based on the assumption that the transient process is an annual cycle.

The seasonal hydraulic head distributions from the OU2 RFI/RI Report are based on data from groundwater elevation measurements. The quarterly measurements for each potentiometric map were taken during one-month periods. As indicated in Appendix E of the Phase II RFI/RI Report, substantial changes in groundwater elevation can occur over a one-month period at OU2, particularly during recharge periods. Therefore, the observed hydraulic head data for a given season may not be representative of the hydraulic heads in the flow system at a single point in time.

6.4.2 Stress Periods

MODFLOW allows the user to specify stress periods in transient simulation. Within each stress period, flow system stresses are constant. Four stress periods were specified for the transient simulation to represent typical annual seasonal variations in groundwater conditions.

The four stress periods are specified to represent typical annual recharge conditions beginning with the end of the spring recharge period. The first three stress periods are drying periods, and the fourth period is a wetting period. The first period begins under high water conditions due to April recharge and covers May and June. No recharge occurs during this period, except for recharge Zone 5 (Figure 5.6-1) where it is assumed that the alluvial caliche layer delays groundwater recharge of infiltrating precipitation that occurs in April. The second period covers July to October, and the third period covers November to March. The fourth period represents the groundwater recharge month of April.

6.4.3 Time Steps

The time step in MODFLOW is another numerical parameter that has strong influence on numerical results and can possibly cause numerical oscillations. Usually, when an aquifer is under sudden stress, the smaller the time step, the more accurate the solution. After several trial runs it was found that 30 time steps for the first period of two months with a multiplier of 1.1, and 30 time steps for the fourth period of one month with a multiplier of 1.1 were appropriate. For stress periods two and three, a time step of 3 days was acceptable.

6.4.4 Transient Boundary Conditions

Before transient calibration, prescribed head boundary conditions (except for the layer 2 west boundary) for steady state calibration were transformed to drain cells for transient calibration. The conductance (ft^2/day) for each drain cell is calculated by dividing the calibrated flux rate through the prescribed head cell by the saturated thickness in the steady state condition. The

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conductance values obtained in this manner are considered maximum (high flow) values of conductance.

At the west boundary of layer 2, the prescribed head boundary conditions were transferred to specified flux boundary conditions for transient calibration. The calibrated flux rate for each boundary cell under steady state conditions was used as the specified flux rate under transient conditions. Similarly, the flux rate obtained from steady state calibrations is considered the maximum flow rate.

After transforming prescribed head boundary conditions to drain cells and specified flux boundary conditions as described above, an additional steady state simulation was run to obtain the final steady state hydraulic head distribution. This hydraulic head distribution is more suitable for use as the initial condition for transient calibration because the solution was obtained under the same boundary conditions as those used in the transient calibration process. The hydraulic heads obtained in each of these simulations are virtually identical.

Using drain cells, transient seep flow rates were simulated. The seep flow rate is proportional to the hydraulic head difference (difference between the hydraulic head and layer bottom elevation) and drain conductance at each drain cell. When the simulated hydraulic head drops below the layer bottom elevation, the drain flow rate through the cell is zero and the drain is inactive; when the simulated hydraulic head rises above the layer bottom elevation, the drain cell will activate again.

Like transmissivity, which may vary with time in an unconfined system, the conductance of a seep (drain) cell may vary with time when the seepage face cross-sectional area changes in response to changes in water level. In MODFLOW, conductance can be changed during each stress period. A representative average conductance value for each stress period was calibrated. Based on the assumption that the values of conductance for drain cells under steady state conditions are the maximum values, the variation of conductance over the seasons are calculated as a percentage of the maximum values. Calibrated percentages are 80 percent, 20 percent, 10 percent, and 60 percent, for stress periods one to four, respectively.

Seasonal calibrated percentages for the specified flux rate at the west boundary of layer 2 are 80 percent, 30 percent, 15 percent, and 70 percent for the four stress periods, respectively.

6.4.5 Initial Conditions

The initial hydraulic head distributions for transient calibration were obtained from the steady state calibration. As described in Section 4.4, the final steady state hydraulic head distribution was obtained under the boundary conditions to be used in transient calibration.

6.4.6 Temporal Distribution of Net Groundwater Recharge

The temporal distribution of net groundwater recharge was estimated and calibrated in the transient calibration process. Based on the conceptual understanding of site hydrologic conditions (Section 3.4), it was assumed that groundwater recharge occurs during one month of the year in the spring (April), and no recharge occurs during the other eleven months of the year. An area that was an exception to this assumption was recharge Zone 5, the southeast area of the alluvium, where the caliche layer in the alluvium is believed to delay groundwater recharge until June or July, as indicated by hydrographs for wells in the area (e.g., Wells 3287,4186 and 4991, etc.) (DOE 1995a).

The final calibrated transient net recharge rates for each zone are listed in Table 6.2-1. The baseline rate for Zone 1 (Section 5.6, Figure 5.6-1) is 1.2 inches/month (0.4×10^{-2} inches/day). The areal average recharge rate for the whole active model area in the transient calibrations is 1.2 inches/year.

6.4.7 Specific Yield and Storativity

Specific yield (S_y) and storativity (S) are two major distributed parameters calibrated in transient simulation. The usual range of S_y is 0.01 to 0.30 for an unconfined aquifer, and the usual range of S is 0.00005 to 0.005 for a confined aquifer (Freeze and Cherry 1979). The estimated values of specific yield from two alluvial pumping test results range from 0.004 to 0.09; while the estimated values of specific yield or storativity from two sandstone pumping test results range from 0.0005 to 0.03 (DOE 1992).

The initial model input of S_y and S at each cell was estimated numerically based on the head difference calculated between March and May 1992, which ranges from 0.5 to 11 feet. Then the values of S_y and S were further adjusted during calibration processes. The calibrated S_y

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and S distributions are plotted in Figures 6.4-1 and 6.4-2. The calibrated values of S_y for layer 1 range from 0.008 to 0.04, and for layer 2 from 0.005 to 0.03. The values of S range from 0.005 to 0.01.

The calibrated values of S_y for both layers are supported by the pumping test results but are at the lower end or less than literature values. The values may be representative for apparent specific yield, or may be explained by the concept of fillable porosity. Fillable porosity, defined by Bouwer (1978) as the amount of water that unconfined aquifers can store per unit rise in the water table per unit area, is usually less than specific yield because of hysteresis.

6.4.8 Vertical Conductance under Transient Conditions

Vertical conductance under transient conditions changes with time (Anderson and Woessner 1992). Under transient conditions, vertical leakage rates may be increased due to the release of water stored in compressible fine-grained confining layers (Leake et al. 1994). In MODFLOW, the calculation of vertical conductance (Vcont) using equation (1) is applicable only for steady state conditions. Therefore, the variation of Vcont under transient conditions cannot be simulated. A new MODFLOW package for calculating transient vertical leakage, TLK1 (Leake et al. 1994), is available, however, it can only be applied if the dimensions of confining units are known. Since these data are not available, calibration of Vcont was conducted to determine an effective average transient Vcont value representative of transient conditions for an entire year. Note that the Vcont values calibrated under transient conditions are not Vcont as a function of time. Rather, the calibrated distribution of Vcont values is assumed to be representative of the entire one-year transient simulation period under specified conditions. The calibrated vertical conductance under transient conditions ranges from 0.75×10^{-3} to 0.1×10^{-2} day^{-1} for the area where significant vertical hydraulic communication occurs.

6.5 TRANSIENT CALIBRATION RESULTS

Transient calibration was performed using the modified code of MODFLOW (Section 4.2), in order to simulate drying and re-wetting conditions. The calibration results are presented in Sections 6.5.1 through 6.5.4.

The transient calibration results are acceptable given the modeling objectives and the complexity of the transient groundwater flow system. The simulated results of transient calibration were evaluated by comparison with the interpreted seasonal head distributions and observed well hydrographs, qualitative assessment of simulated seasonal flow rates, and annual water budget analysis.

The transient calibration results were evaluated in a less rigorous manner than the steady state calibration results. More rigorous evaluation of transient calibration results was not performed primarily because of the variability of the highly transient flow system. The model was calibrated for typical transient conditions that reflect the most significant aspects of the actual groundwater flow system. Some of the variability within the entire model domain may not have been rigorously accounted for in the transient calibration. Based on this consideration, the model results are satisfactory, as indicated below:

- The calibrated model can simulate the process of decreasing hydraulic head over a typical 11-month drying period to the approximate elevations observed before the recharge season, and then simulate the one-month process of hydraulic head recovery to initial conditions. In this way, the calibrated model simulates the complete typical annual hydrologic cycle of the system.

- The simulated hydraulic head distributions at the end of the one-year simulation match the interpreted hydraulic head distribution in May, 1992 for both layers reasonably well (Section 6.5.1).

- The calibrated model can simulate the magnitude of spatial and temporal variation of hydraulic heads, a major feature of the transient flow system. Observed well hydrographs show that the responses of different areas of the saturated units to a typical month of groundwater recharge are highly variable, ranging from approximately 2 feet to 15 feet. The calibrated model simulates this degree of variation fairly well (Section 6.5.2).

Further, the complexity of infiltration processes in the vadose zone, and the complicated precipitation and snowmelt patterns, which are all highly variable in space and time, complicate the transient system and limit the ability to rigorously evaluate transient calibration results.

6.5.1 Simulated Seasonal Hydraulic Head Distributions

The simulated hydraulic head contours at the ends of July, March and April are plotted, on Figures 6.5-1, 6.5-2, and 6.5-3 for layer 1, and Figures 6.5-4, 6.5-5, and 6.5-6 for layer 2. In Figures 6.5-3 and 6.5-6 (for Rocky Flats Alluvium and No. 1 Sandstone, respectively), simulated (end of April) and interpreted (May 1992) hydraulic head distributions are displayed together to facilitate comparison of calibrated and observed results.

As shown in the figures, simulated hydraulic heads match interpreted heads reasonably well for the transient simulation of the four stress periods of the year-long cycle. In most areas, the differences in hydraulic heads range from 2 to 3 feet.

The interpreted hydraulic head distributions for third quarter and first quarter, 1992 (Figures 2.5-3 and 2.5-5) were not included in the presentation of simulated transient results (Figures 6.5-1 and 6.5-2, alluvium; Figures 6.5-4 and 6.5-5, No. 1 Sandstone). These interpreted potentiometric surfaces were not rigorously developed for use in the conceptual model as were the May 1992 surfaces (Figures 3.1-2 and 3.1-3). In addition, the simulated results for the end of the third stress period (Figures 6.5-2 and 6.5-5) correspond to first quarter, second calendar year water levels. The interpreted first quarter maps (March 1992) do not directly correspond to simulated first quarter results (second year) making direct comparison impractical. Readers are, however, encouraged to roughly compare the figures for general conditions.

6.5.2 Comparison of Simulated and Observed Well Hydrographs

Comparison of simulated and observed well hydrographs for four seasons (approximate) are listed in Tables 6.5-1 and 6.5-2 for layer 1 and layer 2, respectively. Simulated hydraulic heads for four seasons were compared to observed hydraulic heads at 36 alluvial and 28 No. 1 Sandstone observation locations (Figures 2.5-1 to 2.5-8). The observed data were, in general, collected quarterly from second quarter 1992 through first quarter 1993. Data from other years were used in the comparison when the data in the specified period were not available. Simulated heads are the transient calibration results for the beginning of the simulation period (beginning of May), the end of July, the end of October, the end of March, and the end of April in the second year, completing an annual hydrologic cycle (Tables 6.5-1 and 6.5-2).

Three different comparisons between simulated and observed well hydrographs were performed as follows: (1) comparison of the initial heads for transient calibration with the observed heads measured in second quarter 1992, (2) comparison of the magnitude of the decrease in hydraulic heads during the drying period, and (3) comparison of the magnitude of the rise in hydraulic head during the recharge period.

In comparison (1), simulated initial heads match observed data at most locations (Tables 6.5-1 and 6.5-2, shown as Year 1 Quarter 2). These results from the steady state calibration do not match everywhere due, in part, to differences between actual observed well data and the regridded potentiometric surface elevations used as the target for steady state calibration. In addition, constraints of hydraulic conductivity (Section 6.3.4) may contribute to residuals.

Comparison (2) is applicable to Year 1 Quarter 2 through Year 2 Quarter 1 (Tables 6.5-1 and 6.5-2). The observed heads in alluvium dropped during the drying season in the range of 1 to 12 feet. For layer 1, simulated decreases in heads for the majority of the model area east of column 60 match observed values within 1 to 3 feet. In the area west of column 60, simulated decreases in heads are less than those observed at several locations.

In the No. 1 Sandstone, observed heads dropped during the drying season in the range of 1 to 15 feet. Simulated heads in layer 2 for the drying period, in general, match observed values within 1 to 3 feet. The drop in heads in the north hillside boundary area was less than observed values.

Comparison (3) applies to Year 2 Quarter 2 (Tables 6.5-1 and 6.5-2). Based on the assumption that groundwater levels rise and fall following an annual cycle, the magnitude of the rise in head from recharge should be equal to the fall in head experienced during the drying period. Simulated heads following the month of recharge were compared to the initial simulated heads, and the simulated recovery of water levels was compared to the observed decrease in heads due to drying. In general, alluvial hydraulic heads recovered approximately

3 feet to 11 feet, in response to simulated recharge. The range of observed decreases in head was approximately 1 to 15 feet.

In the No. 1 Sandstone, the simulated increases in head ranged from about 3 feet to 13 feet in response to recharge, while the observed head increases ranges of 1 to 15 feet. In the vicinity of wells 12691, 12491, and 12391 (located northeast and east of the Northeast Trenches Area) the simulated recovery following the recharge period is less than the fall of the water surface in magnitude. Therefore, the heads in that area following the recharge period do not match well with the initial (Year 1 Quarter 2) hydraulic heads.

6.5.3 Simulated Seasonal Flow Rates

Simulated seasonal flow rates, including seep flow, flow out of the model domain, and downward vertical leakage, are the result of temporal and spatial re-distribution of the hydraulic heads in response to groundwater recharge. Although measured flow rates were not available for comparison with simulated results, it was necessary to determine if simulated flow rates are consistent with the qualitative understanding of the flow conditions. Simulated seasonal flow rates are displayed with the simulated hydraulic head distributions in Figures 6.5-1 through 6.5-6. They are also listed in Table 6.5-3. Note that these rates are the rates at the end of the simulation period, rather than averages rates for the simulation period.

Simulated flow rates suggest that the majority of the groundwater discharge out of the OU2 shallow groundwater system occurs through the No. 1 Sandstone seeps along 4,000 feet of the north hillside of the South Walnut Creek drainage, at a rate ranging from 2.5 gpm to 8.2 gpm. The spatial distribution of the simulated seeps is displayed in Figures 6.5-4 through 6.5-6. The variation in seep rates on the north hillside of the drainage was qualitatively estimated based on vegetation conditions (Figure 3.6-1, Phase II RFI/RI Report [DOE 1995a]), which are an indication of sandstone seep flow rates. A substantial sandstone discharge area appears to occur in the area south of Ponds B-1 and B-2.

The second highest simulated rate of discharge from the groundwater system occurred at the surface drainage gully alluvial seep, with a flow rate ranging from 0.5 to 2.5 gpm. This range is consistent with the measured seep flow rates (0.2 to 1 gpm) at that location (Section 2.5).

The flow rate at the southwest area alluvial seep was simulated to range from 0.08 gpm to 1.6 gpm, reflecting the observed seasonal variation of seep flow conditions at that location. During high flow periods, groundwater breaches the south paleoridge activating many seeps on the north hillside of Woman Creek just southeast of the 903 Pad (Figure 2.5-4). During low flow periods, most seeps dry out (Figure 2.5-3).

The simulated seep flow rate from the No. 1 Sandstone on the south hillside of the Woman Creek drainage is minimal, with a range of 0.07 gpm to 0.5 gpm.

The simulated total seep flow rate from the alluvium and No. 1 Sandstone in the model domain ranges from 3.2 to 13.1 gpm.

Simulated vertical leakage from the alluvium to the No. 1 Sandstone is considered significant compared to the flow rate out of the No. 1 Sandstone, which ranges from 1.0 to 5.0 gpm. The ratio of vertical leakage rate versus the total discharge rate from the No. 1 Sandstone ranges from 40 percent to 65 percent. Half of the simulated discharge from the No. 1 Sandstone is received from the alluvium as vertical leakage. Much of the remaining simulated discharge originates as direct infiltration to the sandstone in OU2. Minor discharge occurs as inflow in the sandstone across the western boundary of OU2.

6.5.4 Simulated Annual Water Budget Analysis

An analysis of the annual water budget for the groundwater flow system was performed to evaluate the transient calibration results. Based on the model assumptions, the total annual volume of water into the system, including recharge and flux from the upgradient boundary, should be equal to the total annual volume of water out of the system, which is the total volume of water flowing out of the drain cells. The total volume of water out of the system for the one-year transient simulation was 6 percent more than the total volume of water into the system, which was considered within an acceptable range. Note that the MODFLOW water budget calculated at the end of each time step was always less than 1 percent. The MODFLOW water budget takes into account the change in aquifer storage, as well as the difference between the total volume of water in and out of the system.

TABLE 6.2-1
RELATIVE RECHARGE RATES FOR RECHARGE ZONES

Zone No.	Description	Relative Recharge Rate	
		Steady State Calibration[a]	Transient Calibration[b]
1	Baseline recharge area	1.0 x SRCH	1.0 x TRCH
2	Impervious area	0.2 x SRCH	0.2 x TRCH
3	Concentrated recharge zone due to subsurface collection effect	1.5 x SRCH	1.5 x TRCH
4	Hillside	0.5 x SRCH	0.5 x TRCH
5	Area where caliche layer causes recharge delay effect[c]	0.4 x SRCH	1.0 x TRCH
6	Direct recharge to No. 1 Sandstone underlying claystone and unsaturated alluvium	0.8 x SRCH	0.8 x TRCH
7	Ditch/Trench	2.0/5.0 x SRCH	2.0/5.0 x TRCH

Explanation:

a. SRCH = 0.83 x 10^{-2} inches/day (3 inches/year)

b. TRCH = 0.4 x 10^{-1} inches/day (1.2 inches/month), applied continuously for one month, except for Zone 5.

c. To simulate the delayed recharge effect associated with caliche layers, 60 percent of recharge is applied in the first stress period, May and June. 40 percent of recharge is applied in the fourth stress period, April.

TABLE 6.3-1
STEADY STATE CALIBRATION RESULTS
COMPARISON OF OBSERVED AND SIMULATED HEADS FOR LAYER 1

Well Number	Model Row	Model Column	Observed Head (ft-MSL)	Interpreted Head (ft-MSL)	Simulated Head (ft-MSL)	Simulated and Observed Head Difference (ft)	Simulated and Interpreted Head Difference (ft)
13291	41	23	5965	5965.5	5965.8	0.8	0.3
6791	29	25	5964	5964.8	5964.3	0.3	-0.5
7291	23	29	5960	5960.9	5960.9	0.9	0.0
6691	38	32	5963	5964.3	5964.6	1.6	0.3
7191	25	37	5959	5958.9	5959.4	0.4	0.5
9091	27	40	5959	5958.8	5959.7	0.7	0.9
8891	39	40	5962	5964.0	5964.8	2.8	0.8
13091	29	43	5959	5959.1	5959.9	0.9	0.8
6891	44	43	5967	5966.2	5966.0	-1.0	-0.2
4386	51	45	5959	5962.6	5963.1	4.1	0.5
6991	38	47	5962	5963.1	5963.4	1.4	0.3
1587	29	56	5956	5958.2	5958.2	2.2	0.0
191	37	60	5958	5958.5	5959.1	1.1	0.6
1787	44	66	5958	5956.8	5957.2	-0.8	0.4
13591	29	77	5953	5952.8	5952.7	-0.3	-0.1
B218789	37	85	5949	5949.8	5950.0	1.0	0.2
13491	41	87	5949	5949.3	5949.5	0.5	0.2
2487	53	92	5947	5948.2	5947.9	0.9	-0.3
7891	43	104	5941	5942.6	5942.7	1.7	0.1
4286	37	106	5943	5944.1	5943.8	0.8	-0.3
4191	28	114	5943	5942.6	5942.6	-0.4	0.0
7991	31	121	5937	5938.8	5938.6	1.6	-0.2
3191	47	127	5933	5933.5	5933.8	0.8	0.3
5691	52	139	5928	5928.2	5928.3	0.3	0.1
8091	31	140	5935	5936.4	5936.7	1.7	0.3
3591	48	141	5928	5928.1	5928.6	0.6	0.5
3387	37	149	5931	5933.8	5934.4	3.4	0.6
3287	14	164	5901	5901.4	5902.2	1.2	0.8
5391	45	172	5910	5910.7	5910.7	0.7	0.0
5291	34	173	5908	5908.9	5909.6	1.6	0.7
4186	15	175	5899	5899.4	5900.4	1.4	1.0
5191	29	186	5898	5898.7	5899.3	1.3	0.6
4991	8	188	5898	5898.1	5899.2	1.2	1.1
5091	24	193	5898	5897.1	5898.8	0.8	1.7
4091	66	201	5893	5892.5	5893.0	0.0	0.5
6091	45	208	5897	5896.2	5897.2	0.2	1.0
Root Mean Squared Error (RMS)						1.4	0.6

* RMS is defined as the squared differences in measured and observed heads.
ft-MSL - Feet above mean sea level.

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TABLE 6.3-2
STEADY STATE CALIBRATION RESULTS
COMPARISON OF OBSERVED AND SIMULATED HEADS FOR LAYER 2

Well Number	Model Row	Model Column	Observed Head (ft-MSL)	Interpreted Head (ft-MSL)	Simulated Head (ft-MSL)	Simulated and Observed Head Difference (ft)	Simulated and Interpreted Head Difference (ft)
987	45	15	5965.2	5966.7	5966.2	1.0	-0.5
6591	41	24	5964.6	5965.6	5965.0	0.4	-0.6
13191	42	24	5966.4	5965.5	5964.9	-1.5	-0.6
12291	60	26	5957.1	5957.3	5957.1	0.0	-0.2
1491	59	27	5956.9	5957.9	5957.5	0.6	-0.4
2387	51	47	5963.2	5963.2	5962.5	-0.7	-0.7
1891	50	53	5957.7	5960.2	5960.1	2.4	-0.1
12091	51	53	5960.2	5959.5	5959.8	-0.4	0.3
1791	54	54	5956.1	5955.6	5956.1	0.0	0.5
2291	69	66	5929.7	5929.6	5929.5	-0.2	-0.1
2091	52	76	5955.0	5955.0	5955.2	0.2	0.2
291	29	78	5946.2	5947.3	5946.8	0.6	-0.5
12991	30	78	5953.4	5948.2	5947.7	-5.7	-0.5
2491	68	81	5935.5	5935.6	5934.7	-0.8	-0.9
1991	40	88	5949.0	5948.7	5948.1	-0.9	-0.6
2587	51	92	5947.4	5946.5	5945.8	-1.6	-0.7
12191	51	103	5941.0	5938.1	5935.5	-5.5	-2.6
2991	51	104	5939.4	5936.7	5935.1	-4.3	-1.6
11891	62	109	5925.4	5925.7	5925.7	0.3	0.0
3391	63	109	5923.5	5925.0	5924.9	1.4	-0.1
3091	50	114	5923.8	5927.1	5927.5	3.7	0.4
3691	69	116	5902.7	5906.2	5906.1	3.4	-0.1
11691	66	121	5908.1	5905.4	5905.6	-2.5	0.2
3791	67	121	5902.9	5903.6	5903.7	0.8	0.1
3687	54	122	5920.3	5923.4	5923.8	3.5	0.4
12691	51	128	5925.0	5924.9	5924.9	-0.1	0.0
12491	53	138	5926.2	5924.7	5924.3	-1.9	-0.4
12391	47	172	5895.1	5897.9	5896.2	1.1	-1.7
Root Mean Squared Error (RMS)						2.3	0.8

• RMS is defined as the squared differences in measured and observed heads.

ft-MSL - Feet above mean sea level.

TABLE 6.5-1
TRANSIENT CALIBRATION RESULTS
COMPARISON OF OBSERVED AND SIMULATED HYDRAULIC HEADS FOR LAYER 1

WELL NUMBER	MODEL LAYER	MODEL ROW	MODEL COLUMN	YEAR	QUARTER	OBSERVED HEAD	SIMULATED HEAD
13291	1	41	23	1	2	5965.3	5965.9
				1	3	5962.6	5963.3
				1	4	Dry	Dry
				2	1	Dry	Dry
				2	2		5966.2
6791	1	29	25	1	2	5963.8	5964.6
				1	3	5958.8	5961.8
				1	4	5957.5	5961.4
				2	1	5957.6	5961.2
				2	2		5967.9
7291	1	23	29	1	2	5960.2	5961.5
				1	3	5957.4	5960.5
				1	4	5956.7	5960.2
				2	1	5955.9	5960.4
				2	2		5965.4
6691	1	38	32	1	2	5963.1	5964.8
				1	3	5958.3	5962.3
				1	4	5957.9	5961.4
				2	1	5958.3	5960.9
				2	2		5964.4
7191	1	25	37	1	2	5959.1	5959.7
				1	3	5956.2	5959.7
				1	4	5955.1	5959.5
				2	1	5957.4	5959.7
				2	2		5962.4
9091	1	27	40	1	2	5958.7	5959.9
				1	3	5955.4	5959.6
				1	4	5953.4	5959.4
				2	1	5953.9	5959.6
				2	2		5962.2
8891	1	39	40	1	2	5962.0	5964.9
				1	3	5957.2	5962.5
				1	4	5954.5	5960.9
				2	1	5954.5	5959.3
				2	2		5960.9
13091	1	29	43	1	2	5959.1	5960.0
				1	3	5955.3	5958.7
				1	4	5953.5	5958.5
				2	1	5954.1	5958.2
				2	2		5962.3
6891	1	44	43	1	2	5966.7	5966.0
				1	3	5966.1	5962.5
				1	4	5959.4	5960.5
				2	1	5964.7	Dry.
				2	2		5965.2

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TABLE 6.5-1
TRANSIENT CALIBRATION RESULTS
COMPARISON OF OBSERVED AND SIMULATED HYDRAULIC HEADS FOR LAYER 1

WELL NUMBER	MODEL LAYER	MODEL ROW	MODEL COLUMN	YEAR	QUARTER	OBSERVED HEAD	SIMULATED HEAD
4386	1	51	45	1	2	5959.0	5963.1
				1	3	5956.6	5960.1
				1	4	5956.3	Dry
				2	1	5956.3	Dry
				2	2		5965.2
6991	1	38	47	1	2	5961.9	5963.4
				1	3	5956.2	5959.0
				1	4	5953.6	5957.6
				2	1	5953.8	5956.3
				2	2		5964.3
1587	1	29	56	1	2	5956.3	5958.4
				1	3	5952.5	5956.1
				1	4	5947.3	5955.1
				2	1	5950.7	5954.0
				2	2		5959.6
191	1	37	60	1	2	5958.1	5959.2
				1	3	5953.0	5956.0
				1	4	5950.2	5954.5
				2	1	5949.7	5953.1
				2	2		5959.5
1787	1	44	66	1	2	5957.7	5957.2
				1	3	5950.4	5952.9
				1	4	5947.9	5950.1
				2	1	5948.2	5947.6
				2	2		5956.0
13591	1	29	77	1	2	5952.6	5952.7
				1	3	Dry	5951.0
				1	4	Dry	5950.2
				2	1	Dry	5949.5
				2	2		5955.6
21878	9 1	37	85	1	2	5948.8	5950.0
				1	3	5943.0	5945.9
				1	4	NA	5943.0
				2	1	NA	5939.9
				2	2		5949.4
13491	1	41	87	1	2	5949.2	5949.5
				1	3	5941.9	5945.2
				1	4	5939.9	5942.1
				2	1	5937.8	5939.0
				2	2		5948.4
2487	1	53	92	1	2	5947.2	5947.9
				1	3	5944.8	Dry
				1	4	Dry	Dry
				2	1	Dry	Dry
				2	2		5946.2

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TABLE 6.5-1
TRANSIENT CALIBRATION RESULTS
COMPARISON OF OBSERVED AND SIMULATED HYDRAULIC HEADS FOR LAYER 1

WELL NUMBER	MODEL LAYER	MODEL ROW	MODEL COLUMN	YEAR	QUARTER	OBSERVED HEAD	SIMULATED HEAD
7891	1	43	104	1	2	5941.3	5942.7
				1	3	5934.6	5938.4
				1	4	5932.1	5935.6
				2	1	5929.9	5932.1
				2	2		5940.5
4286	1	37	106	1	2	5943.5	5943.8
				1	3	5936.5	5939.2
				1	4	5933.5	5935.9
				2	1	5931.0	5931.9
				2	2		5943.3
4191	1	28	114	1	2	5943.0	5942.6
				1	3	5941.3	5940.0
				1	4	5940.2	5939.3
				2	1	5937.3	Dry
				2	2		5942.4
7991	1	31	121	1	2	5937.6	5938.6
				1	3	5932.9	5933.8
				1	4	5930.3	5929.3
				2	1	5928.8	Dry
				2	2		5939.4
3191	1	47	127	1	2	5933.3	5933.8
				1	3	5929.7	5929.8
				1	4	5929.3	Dry
				2	1	5928.7	Dry
				2	2		5933.1
5691	1	52	139	1	2	5927.6	5928.3
				1	3	5922.7	5923.4
				1	4	5919.9	5919.7
				2	1	5917.4	5916.0
				2	2		5925.4
8091	1	31	140	1	2	5934.8	5936.7
				1	3	5931.9	5934.1
				1	4	5930.7	5932.9
				2	1	Dry	5932.2
				2	2		5936.7
3591	1	48	141	1	2	5927.9	5928.6
				1	3	5923.7	5923.7
				1	4	5920.0	5920.0
				2	1	5918.6	5916.2
				2	2		5925.8
3387	1	37	149	1	2	5930.7	5934.4
				1	3	5926.7	5932.2
				1	4	Dry	5931.0
				2	1	Dry	Dry
				2	2		5934.3

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TABLE 6.5-1
TRANSIENT CALIBRATION RESULTS
COMPARISON OF OBSERVED AND SIMULATED HYDRAULIC HEADS FOR LAYER 1

WELL NUMBER	MODEL LAYER	MODEL ROW	MODEL COLUMN	YEAR	QUARTER	OBSERVED HEAD	SIMULATED HEAD
3287	1	14	164	1	2	5901.0	5902.2
				1	3	5901.6	5901.7
				1	4	5900.2	5900.8
				2	1	5900.4	5899.9
				2	2		5901.3
5391	1	45	172	1	2	5910.2	5910.7
				1	3	5907.5	5908.3
				1	4	5906.3	5906.1
				2	1	5906.0	Dry
				2	2		5907.9
5291	1	34	173	1	2	5908.4	5909.6
				1	3	5906.8	5907.7
				1	4	5905.9	5906.5
				2	1	5905.9	5905.9
				2	2		5909.3
4186	1	15	175	1	2	5899.4	5900.4
				1	3	5900.0	5900.0
				1	4	5898.9	5899.5
				2	1	5898.2	5898.9
				2	2		5900.2
5191	1	29	186	1	2	5898.5	5899.4
				1	3	5898.4	5899.1
				1	4	5897.1	5898.8
				2	1	5895.7	5898.5
				2	2		5899.6
4991	1	8	188	1	2	5897.6	5899.3
				1	3	5899.6	5899.1
				1	4	5898.9	5898.8
				2	1	5897.4	5898.5
				2	2		5899.6
5091	1	24	193	1	2	5898.3	5898.8
				1	3	5898.4	5898.7
				1	4	5897.2	5898.6
				2	1	5895.9	5898.4
				2	2		5899.3
4091	1	66	201	1	2	5893.0	5892.9
				1	3	5892.9	5891.4
				1	4	5892.8	5890.8
				2	1	5892.7	Dry
				2	2		5893.7
6091	1	45	208	1	2	5896.9	5897.0
				1	3	5896.6	5895.3
				1	4	5895.5	5894.1
				2	1	5894.3	5892.9
				2	2		5897.3

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TABLE 6.5-2
TRANSIENT CALIBRATION RESULTS
COMPARISON OF OBSERVED AND SIMULATED HYDRAULIC HEADS FOR LAYER 2

WELL NUMBER	MODEL LAYER	MODEL ROW	MODEL COLUMN	YEAR	QUARTER	OBSERVED HEAD	SIMULATED HEAD
987	2	45	15	1	2	5965.2	5966.5
				1	3	5963.8	5964.8
				1	4	5962.2	5963.3
				2	1	5961.3	5961.6
				2	2		5962.9
6591	2	41	24	1	2	5964.6	5965.2
				1	3	5961.0	5963.0
				1	4	5959.9	5961.8
				2	1	5959.2	5960.4
				2	2		5963.7
13191	2	42	24	1	2	5966.4	5965.1
				1	3	5961.5	5962.9
				1	4	5960.3	5961.7
				2	1	5959.6	5960.3
				2	2		5963.5
12291	2	60	26	1	2	5957.1	5957.1
				1	3	5957.1	5955.7
				1	4	5956.3	5955.5
				2	1	5956.4	5955.4
				2	2		5958.4
1491	2	59	27	1	2	5956.9	5957.6
				1	3	5956.8	5956.1
				1	4	5955.8	5955.8
				2	1	5955.9	5955.7
				2	2		5958.7
2387	2	51	47	1	2	5963.2	5962.5
				1	3	5957.1	5959.6
				1	4	5955.3	5959.0
				2	1	5956.7	5958.3
				2	2		5964.3
1891	2	50	53	1	2	5957.7	5960.2
				1	3	5956.1	5957.2
				1	4	5953.8	5955.6
				2	1	5954.8	5953.6
				2	2		5958.7
12091	2	51	53	1	2	5960.2	5959.9
				1	3	5955.7	5957.2
				1	4	5953.8	5956.0
				2	1	5954.5	5953.9
				2	2		5958.7

TABLE 6.5-2
TRANSIENT CALIBRATION RESULTS
COMPARISON OF OBSERVED AND SIMULATED HYDRAULIC HEADS FOR LAYER 2

WELL NUMBER	MODEL LAYER	MODEL ROW	MODEL COLUMN	YEAR	QUARTER	OBSERVED HEAD	SIMULATED HEAD
1791	2	54	54	1	2	5956.1	5956.4
				1	3	5953.5	5954.5
				1	4	5952.1	5952.1
				2	1	5952.7	5949.7
				2	2		5951.9
2291	2	69	66	1	2	5929.7	5929.7
				1	3	5926.8	5929.0
				1	4	5924.4	5929.2
				2	1	5923.7	5929.3
				2	2		5932.1
2091	2	52	76	1	2	5955.0	5955.2
				1	3	5944.8	5950.5
				1	4	5943.6	5944.6
				2	1	5944.4	5940.5
				2	2		5953.7
291	2	29	78	1	2	5946.2	5946.9
				1	3	5940.7	5943.8
				1	4	5939.3	5942.0
				2	1	5937.8	5939.8
				2	2		5944.6
12991	2	30	78	1	2	5953.4	5947.7
				1	3	5945.9	5944.6
				1	4	5944.6	5942.6
				2	1	5942.9	5940.2
				2	2		5945.5
2491	2	68	81	1	2	5935.5	5934.8
				1	3	5932.2	5932.8
				1	4	5929.3	5931.3
				2	1	5930.3	5929.8
				2	2		5934.0
1991	2	40	88	1	2	5949.0	5948.2
				1	3	5941.9	5944.5
				1	4	5939.8	5941.5
				2	1	5937.7	5938.3
				2	2		5946.7
2587	2	51	92	1	2	5947.4	5946.1
				1	3	5937.8	5942.2
				1	4	5934.3	5938.4
				2	1	5932.6	5934.4
				2	2		5942.3

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TABLE 6.5-2
TRANSIENT CALIBRATION RESULTS
COMPARISON OF OBSERVED AND SIMULATED HYDRAULIC HEADS FOR LAYER 2

WELL NUMBER	MODEL LAYER	MODEL ROW	MODEL COLUMN	YEAR	QUARTER	OBSERVED HEAD	SIMULATED HEAD
12191	2	51	103	1	2	5941.0	5935.8
				1	3	5933.9	5933.7
				1	4	5932.0	5929.9
				2	1	5930.0	5925.1
				2	2		5933.5
2991	2	51	104	1	2	5939.4	5935.2
				1	3	5933.7	5933.2
				1	4	5931.4	5929.5
				2	1	5929.4	5924.7
				2	2		5932.9
11891	2	62	109	1	2	5925.4	5925.7
				1	3	5922.9	5923.3
				1	4	5921.4	5921.1
				2	1	5921.1	5918.3
				2	2		5922.2
3391	2	63	109	1	2	5923.5	5924.9
				1	3	5921.8	5922.6
				1	4	5920.3	5920.5
				2	1	5919.3	5917.8
				2	2		5921.6
3091	2	50	114	1	2	5923.8	5927.5
				1	3	5920.3	5925.0
				1	4	5918.4	5922.0
				2	1	5917.1	5918.2
				2	2		5923.6
3691	2	69	116	1	2	5902.7	5906.1
				1	3	5901.4	5905.2
				1	4	5900.7	5906.3
				2	1	5900.4	5907.1
				2	2		5909.2
11691	2	66	121	1	2	5908.1	5905.6
				1	3	5907.3	5905.4
				1	4	5906.1	5906.0
				2	1	5905.4	5906.5
				2	2		5907.0
3791	2	67	121	1	2	5902.9	5903.6
				1	3	5901.1	5904.0
				1	4	5899.7	5904.8
				2	1	5899.1	5905.8
				2	2		5905.6

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TABLE 6.5-2
TRANSIENT CALIBRATION RESULTS
COMPARISON OF OBSERVED AND SIMULATED HYDRAULIC HEADS FOR LAYER 2

WELL NUMBER	MODEL LAYER	MODEL ROW	MODEL COLUMN	YEAR	QUARTER	OBSERVED HEAD	SIMULATED HEAD
3687	2	54	122	1	2	5920.3	5923.8
				1	3	5917.9	5921.0
				1	4	5915.7	5918.5
				2	1	5914.1	5915.2
				2	2		5920.4
12691	2	51	128	1	2	5925.0	5924.9
				1	3	5920.7	5921.7
				1	4	5917.9	5918.9
				2	1	5915.6	5915.4
				2	2		5919.5
12491	2	53	138	1	2	5926.2	5924.3
				1	3	5921.7	5920.6
				1	4	5919.0	5917.6
				2	1	5916.6	5913.9
				2	2		5917.3
12391	2	47	172	1	2	5895.1	5896.2
				1	3	5895.7	5895.0
				1	4	5894.3	5893.0
				2	1	5892.8	5889.2
				2	2		5889.8

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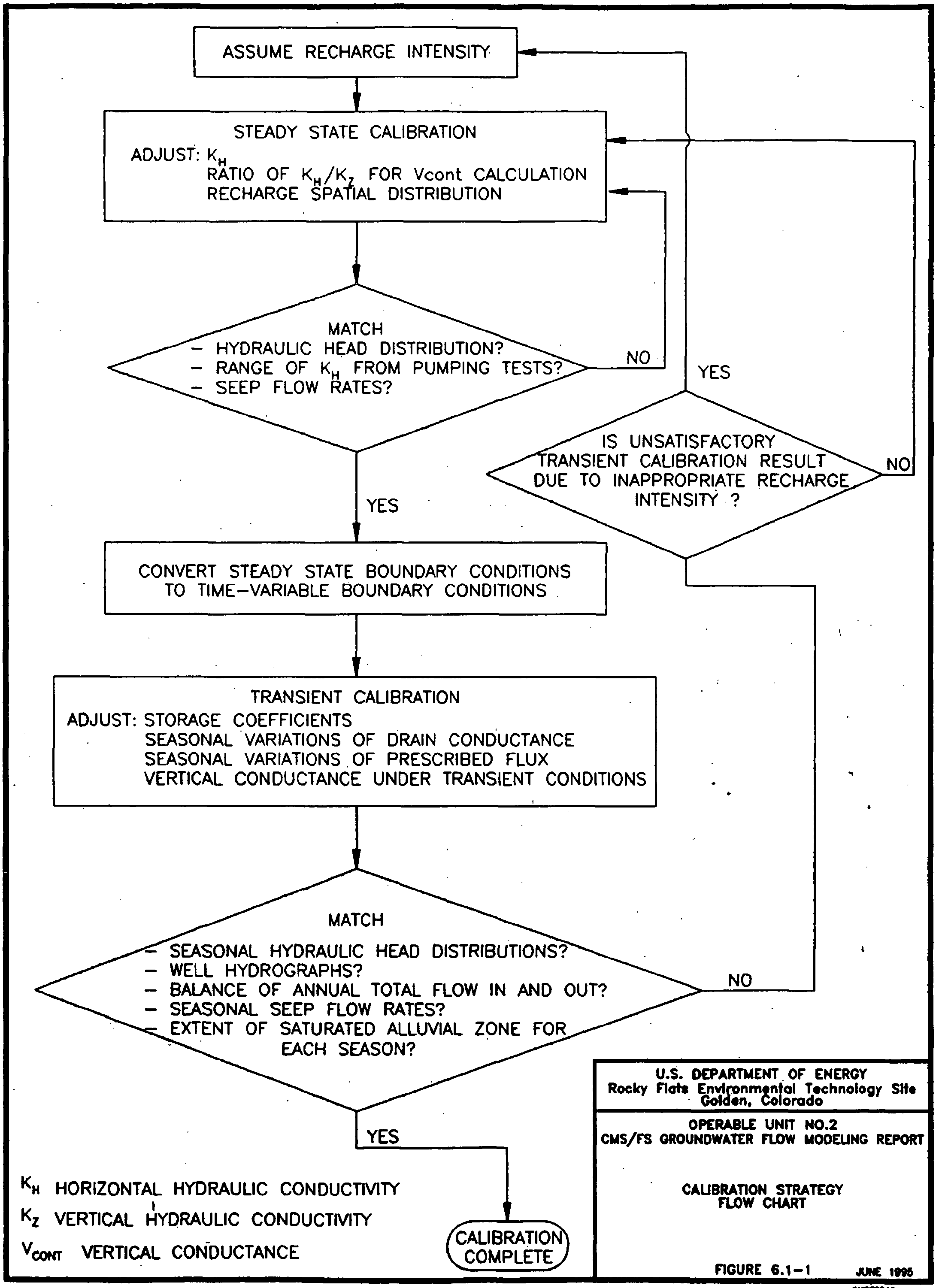
TABLE 6.5-3
SIMULATED SEASONAL FLOW RATES
(Unit = Gallons per Minute)

Flow Location	Second Quarter Year 1	Third Quarter Year 1	Fourth Quarter Year 1	First Quarter Year 2	Second Quarter Year 2
Southwest Alluvial Seeps	1.1	0.2	0.2	0.08	1.6
Alluvial Surface Drainage Gully Seep	1.9	0.9	1.0	0.5	2.5
No. 1 Sandstone Seeps along North Hillside	5.8	3.2	3.6	2.5	8.2
No. 1 Sandstone Seeps along South Hillside	0.6	0.2	0.2	0.1	0.8
Total seep rate	9.4	4.5	5	3.2	13.1

Flow out of East model boundary in alluvium	1.3	0.6	0.6	0.3	1.8
Flow out of East model boundary in Sandstone	0.3	0.08	0.09	0.05	0.4
Vertical leakage from alluvium to sandstone	4.2	2.3	1.6	1.0	5.0



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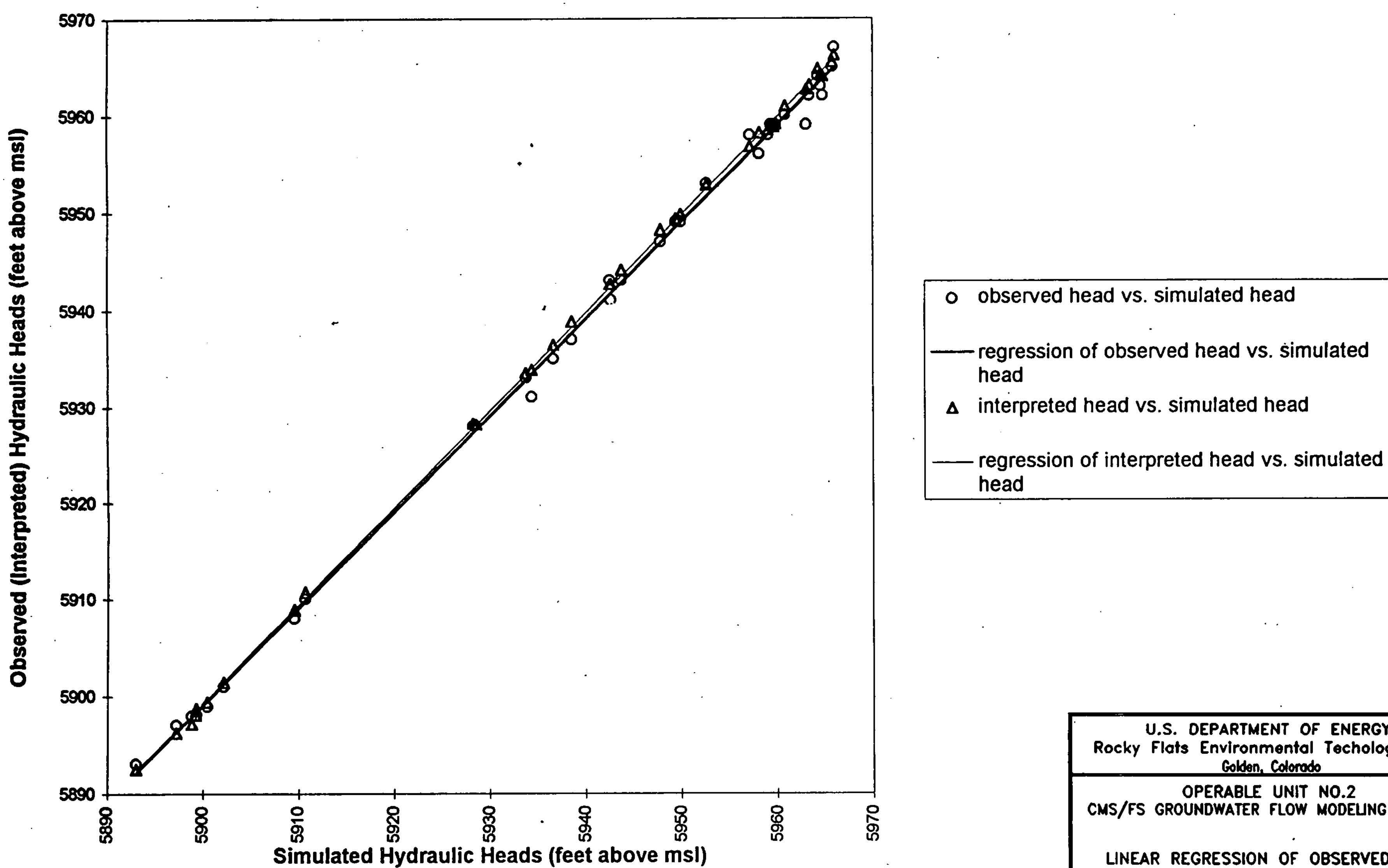
CALIBRATION STRATEGY FLOW CHART

FIGURE 6.1–1 JUNE 1995

OU2FS040



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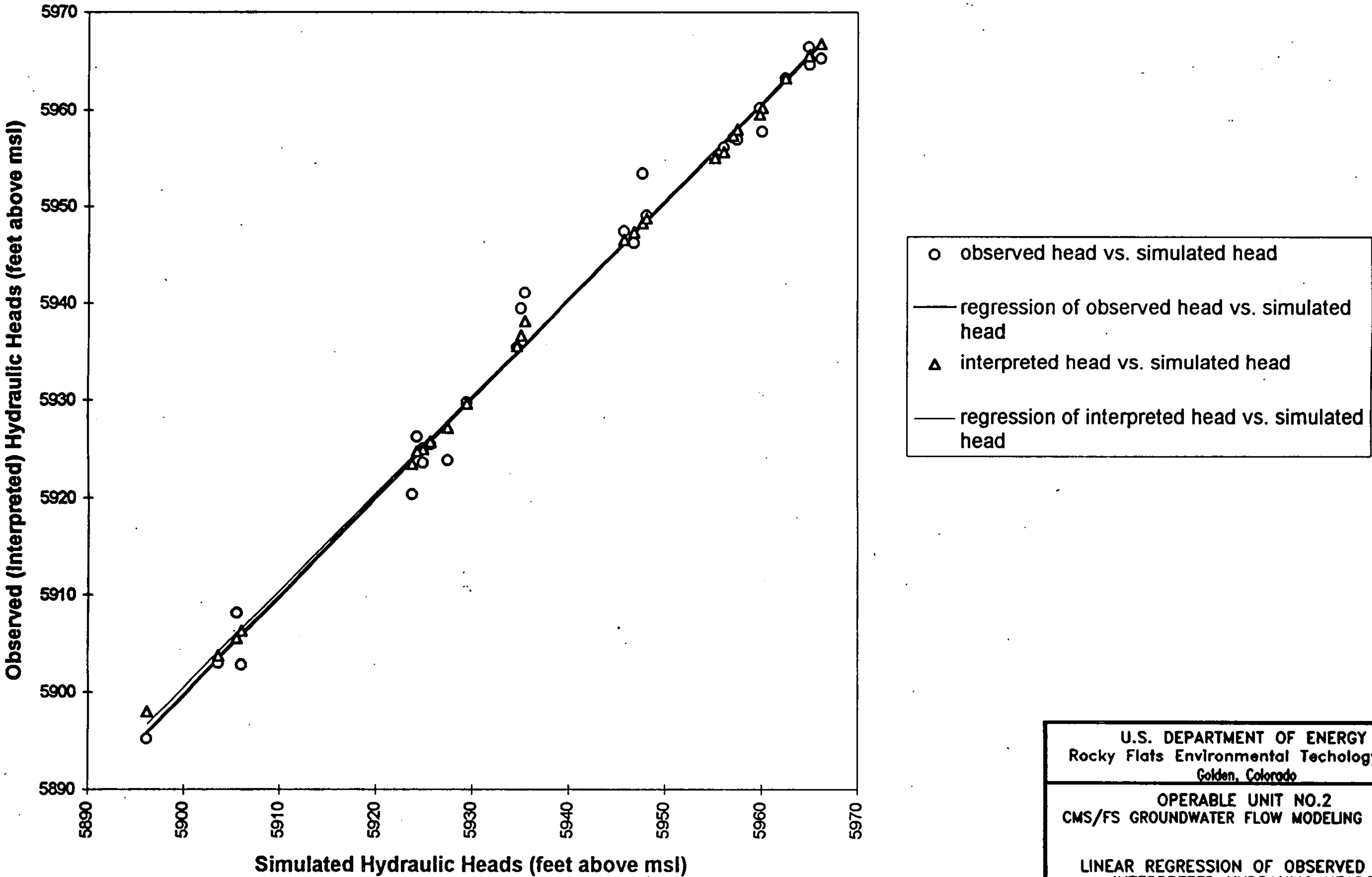
LINEAR REGRESSION OF OBSERVED AND INTERPRETED HYDRAULIC HEADS VS. SIMULATED HYDRAULIC HEADS ROCKY FLATS ALLUVIUM (STEADY STATE CALIBRATION)

FIGURE 6.3-7 JUNE 1995

OU2FS041 1=1



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Golden, Colorado

OPERABLE UNIT NO.2
CMS/FS GROUNDWATER FLOW MODELING REPORT

LINEAR REGRESSION OF OBSERVED AND INTERPRETED HYDRAULIC HEADS VS. SIMULATED HYDRAULIC HEADS NO. 1 SANDSTONE (STEADY STATE CALIBRATION)

FIGURE 6.3-8 JUNE 1995

OU2FS042 1=1

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7.0
MODEL TESTING

Testing of the CMS/FS groundwater flow model was performed to verify its satisfactory performance for simulation of typical remedial action scenarios during the CMS/FS. The testing was performed for three of the scenarios discussed in Sections 7.1 through 7.4. For the fourth scenario, information was available to indicate testing was not necessary.

7.1 NO ACTION SCENARIO

The OU2 groundwater model was tested for a No Action remedial alternative by running a continuous five-year simulation. In this scenario, groundwater recharge was applied in the same manner as in the transient calibration, with the same recharge rates and distribution. Hydraulic heads fell and rose following an annual cycle. The results show that most of the simulated hydraulic heads recovered to approximately the same elevations at the beginning of each year. Hydrographs of the simulated results for five years were prepared for 15 alluvial and 15 No. 1 Sandstone wells to illustrate the results (Figures 7.1-1 through 7.1-2).

Analysis of the annual water budget for the five-year simulation showed that the annual simulated total volume of water out of the groundwater system was balanced with the total volume of water into the system, with an error percentage decreasing from 10 percent at year 2 to 3 percent at year 5.

7.2 EXTRACTION WELL SCENARIO

Pumping of four extraction wells in the groundwater flow system was simulated simultaneously to test if a pumping scenario could be simulated by the model without major numerical difficulties. One extraction well was simulated in layer 1 about 200 feet upgradient of the Northeast Trenches, in the medial paleoscour. Three additional wells were simulated in layer 2 in the Northeast Trenches Area, in the vicinity of IHSS 110. Locations for simulated wells are shown on Figures 7.2-1 and 7.2-2. Locations and pumping rates are listed in Table 7.2-1. The pumping rates were similar to rates applied during OU2 pumping tests and the SVE IM/IRA pilot test (DOE 1992; DOE 1995b).

Extraction well pumping was simulated for 60 days in two stress periods: the first stress period was 30 days long and recharge was applied during the period; the second stress period was also 30 days and was simulated without recharge. Two different recharge rates were simulated in the first stress period; the first rate (high recharge rate) is equal to the rate applied during the last month of transient calibration (1.2 inches/month), and the second rate is equal to half of the high recharge rate (0.6 inches/month).

Results of well pumping simulations for both recharge scenarios are plotted in Figures 7.2-3 through 7.2-6. Under the high recharge scenario, none of the extraction wells were dry after 60 days of continuous pumping, i.e., the saturated units did not become dewatered. But under the low recharge condition, all of the wells became dry during the late stages of the simulation period. The results in the second layer are consistent with the results of pumping tests conducted at Site 1 (DOE 1992) and the SVE site (DOE 1995b), as well as the results of the pilot test at the SVE site (Section 6.3.4).

7.3 RECHARGE REDUCTION SCENARIO

Reduction in groundwater recharge, another potential remedial alternative that may reduce groundwater seepage rates, was simulated. This scenario was simulated by reducing the recharge rate for all recharge zones by 50 percent during the month of annual recharge (April) for a simulation period of two years. The testing period began under high flow conditions (the beginning of May) using the same high flow initial hydraulic head distribution that was used for the transient model calibration. The first 11 months of the simulation was a drying period. Recharge was then applied at the reduced rate for one month following the 11 months of drying. This pattern was then repeated during the second year of the model testing simulation.

At the end of the second 11 month period of drying (end of March), the simulated hydraulic heads were 2 to 3 feet lower than transient calibration results for the same season (Figures 7.3-1 to 7.3-2). The simulated hydraulic heads at the end of the second recharge period (end of April) were 5 to 10 feet lower than transient calibration results for the same season (Figures 7.3-3 and 7.3-4). Simulated seepage flow rates were approximately 20 percent lower at the end of March in the second year than at the end of March during the second year of the transient calibration. Simulated seepage flow rates at the end of the two year reduced recharge period (end of April) were approximately 35 percent lower than rates at the end of the transient calibration period.

Limitations of the simulation results for the recharge reduction scenario were analyzed. At the end of the second year, the annual water budget was not balanced; the storage lost from the flow system was about 50 percent greater than the storage gain to the system, indicating that seepage out of the system was much greater than recharge into the system. A cause of this effect is believed to be that drain cell conductance values, corresponding to high recharge conditions calibrated in transient calibration, were too high, allowing for high seepage rates under the reduced recharge conditions. The causes of the limitations are discussed in Section 8.0 (Model Limitations) in detail. Due to these limitations, drain conductance values should be modified to conduct further recharge reduction scenarios. The modifications may include further reducing drain conductance to reduce the seep flow rate until total annual flow out of the system equals total annual flow into the system.

7.4 SLURRY WALL SCENARIO

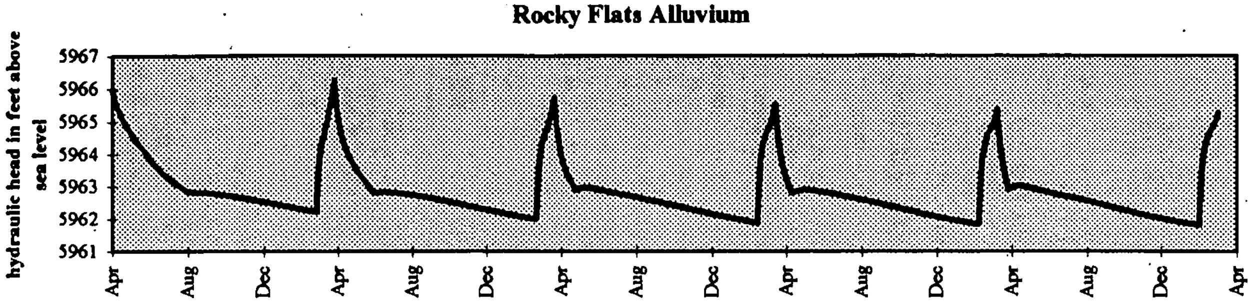
Another remedial alternative for the OU2 groundwater system is the emplacement of a hydraulic barrier (slurry wall) at the western boundary of the system. This barrier would limit inflow to the No. 1 Sandstone and reduce groundwater storage in the system. After model calibration, it was found that the simulated flow into the No. 1 Sandstone was minimal, occurring at a rate of 0.08 gpm under high flow (May 1992) conditions. The accumulated volume of inflow for one year was only approximately 200 ft^3. Because inflow at the western boundary is minimal, the potential effect of a slurry wall is expected to be insignificant. Therefore, no simulation of a slurry wall was conducted.

TABLE 7.2-1
SIMULATED PUMPING RATES UNDER EXTRACTION WELL SCENARIO

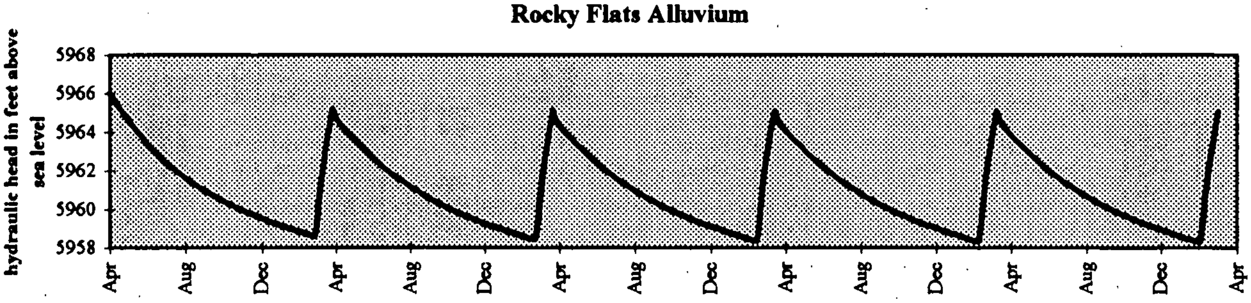
PUMPING WELL LOCATION			PUMPING RATES	
Model Layer	Model Row	Model Column	(ft^3/d)	(gpm)
1	45	90	192.5	1
2	52	102	288.75	1.5
2	45	100	96.25	0.5
2	56	120	385	2

FIGURE 7.1-1
NO ACTION SCENARIO
FIVE-YEAR SIMULATED HYDROGRAPHS
(ALLUVIAL)

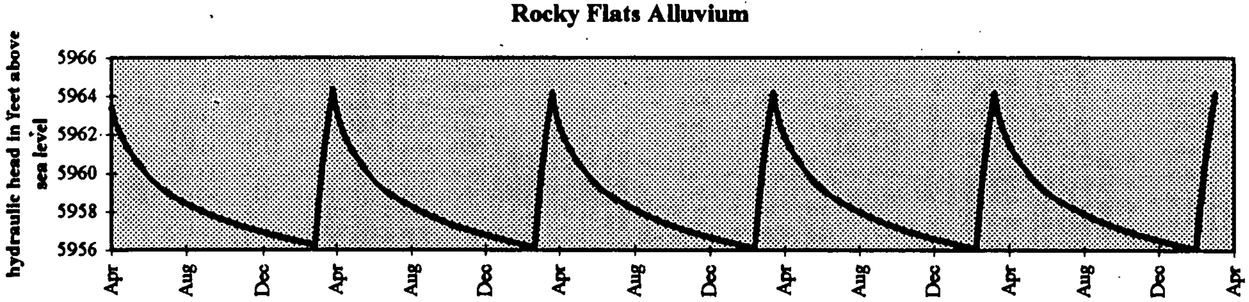
Simulated Hydrograph at Well 13291,
Rocky Flats Alluvium



Simulated Hydrograph at Well 6891,
Rocky Flats Alluvium



Simulated Hydrograph at Well 6991,
Rocky Flats Alluvium



Simulated Hydrograph at Well 1587,
Rocky Flats Alluvium

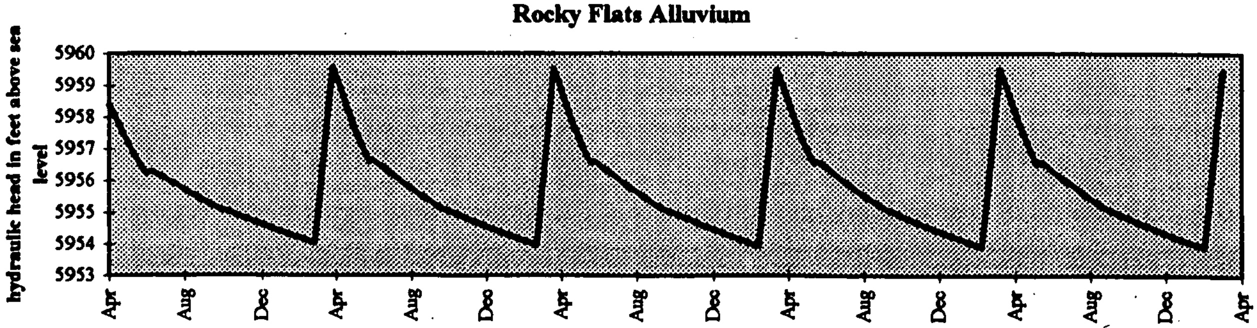


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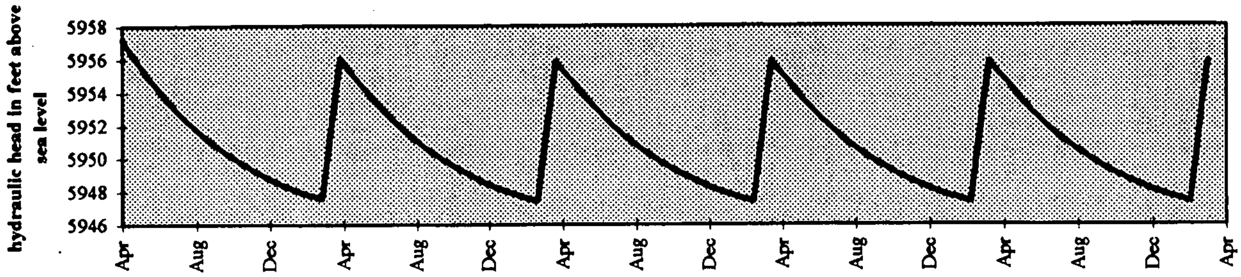
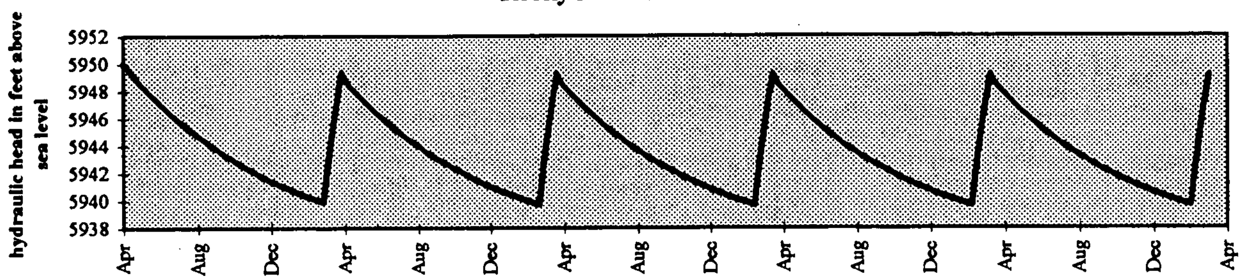
FIGURE 7.1-1
NO ACTION SCENARIO
FIVE-YEAR SIMULATED HYDROGRAPHS
(ALLUVIAL)

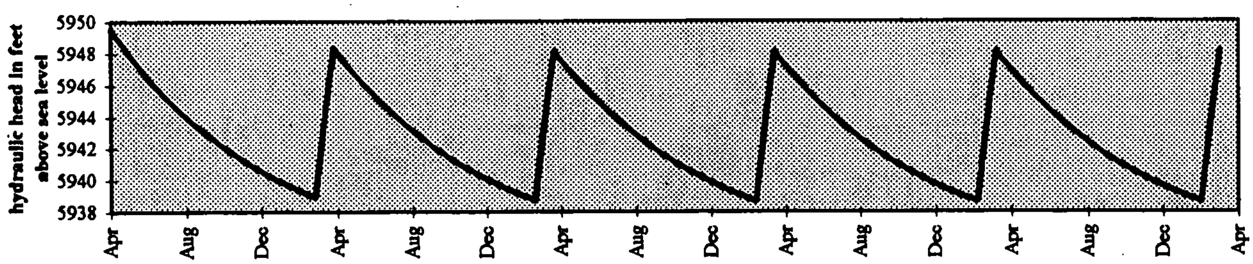
Simulated Hydrograph at Well 1787,
Rocky Flats Alluvium



Simulated Hydrograph at Well 218789,
Rocky Flats Alluvium



Simulated Hydrograph at Well 13491,
Rocky Flats Alluvium



Simulated Hydrograph at Well 7891,
Rocky Flats Alluvium

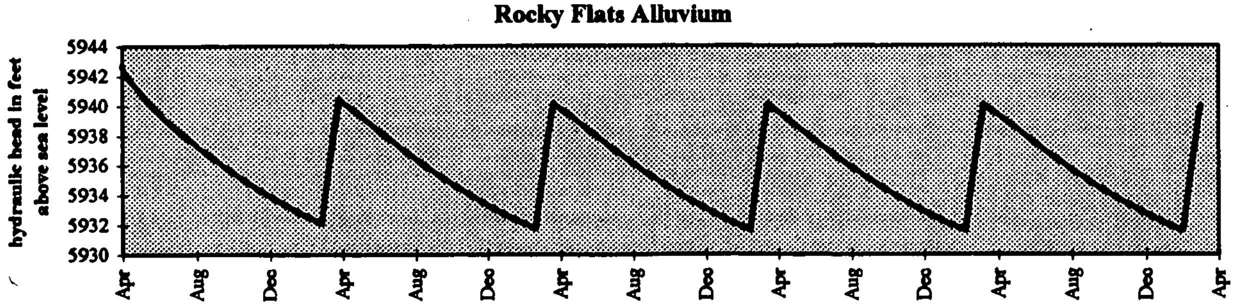


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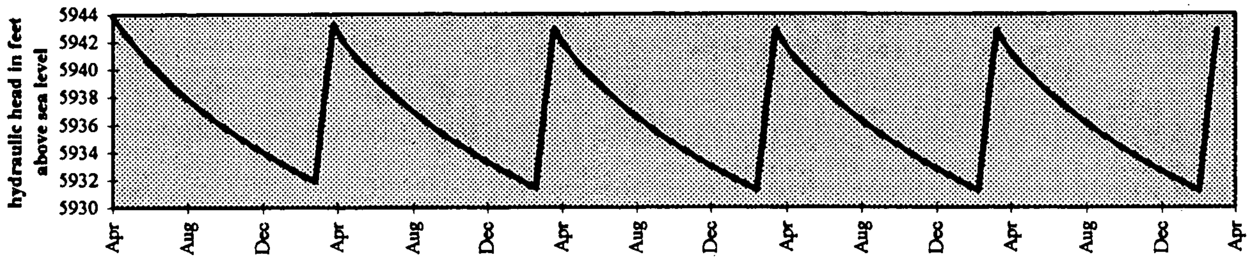
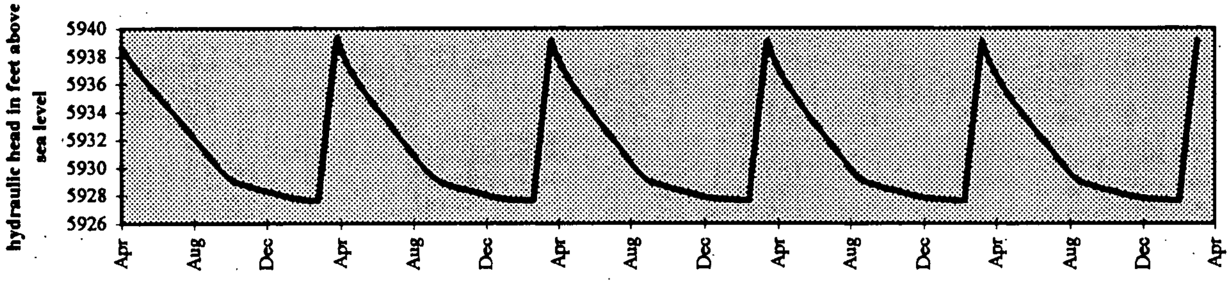
FIGURE 7.1-1
NO ACTION SCENARIO
FIVE-YEAR SIMULATED HYDROGRAPHS
(ALLUVIAL)

Simulated Hydrograph at Well 4286,
Rocky Flats Alluvium



Simulated Hydrograph at Well 7991,
Rocky Flats Alluvium



Simulated Hydrograph at Well 3191,
Rocky Flats Alluvium

Simulated Hydrograph at Well 5691,
Rocky Flats Alluvium

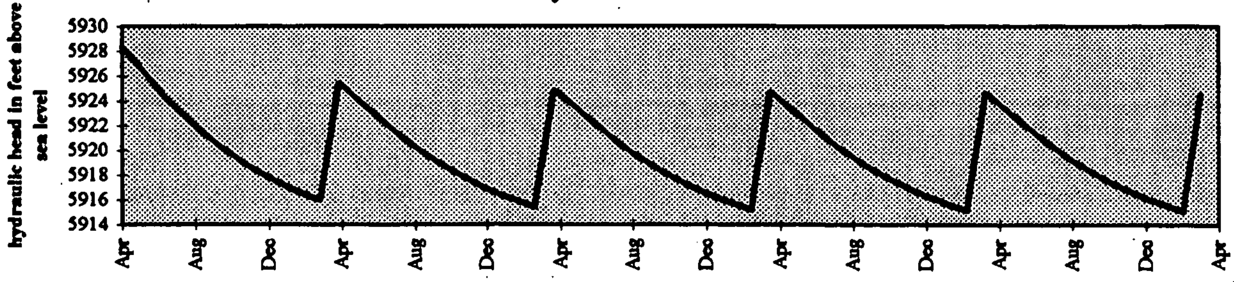


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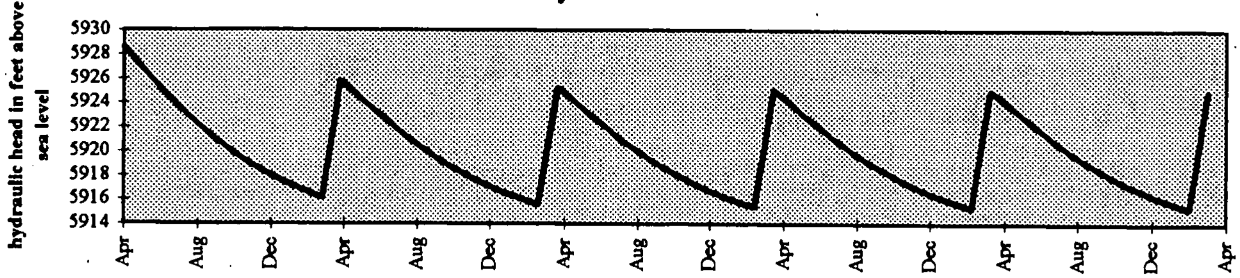
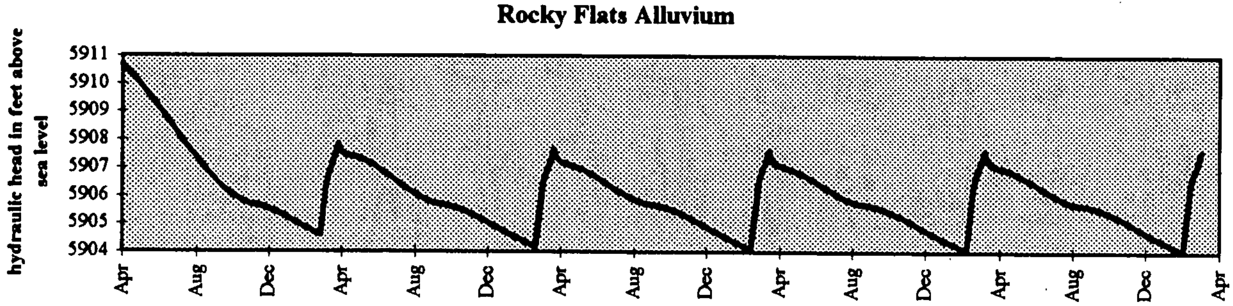
FIGURE 7.1-1
NO ACTION SCENARIO
FIVE-YEAR SIMULATED HYDROGRAPHS
(ALLUVIAL)

Simulated Hydrograph at Well 3591, Rocky Flats Alluvium



Simulated Hydrograph at Well 5391, Rocky Flats Alluvium



Simulated Hydrograph at Well 6091, Rocky Flats Alluvium

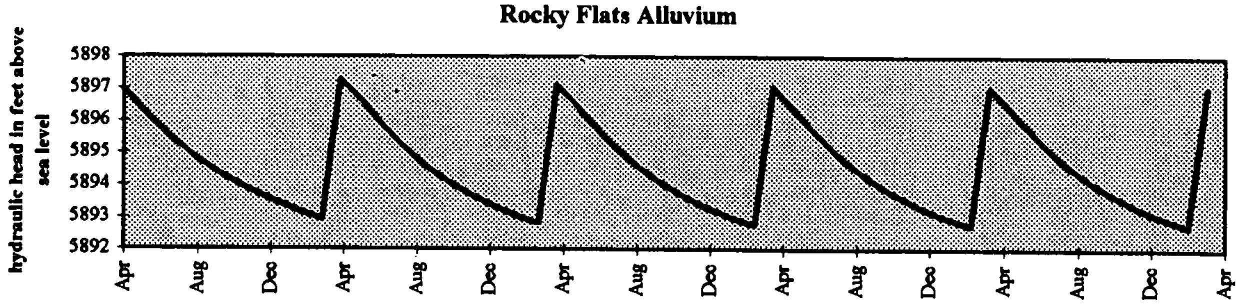


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FIGURE 7.1-2
NO ACTION SCENARIO
FIVE-YEAR SIMULATED HYDROGRAPHS
(NO. 1 SANDSTONE)

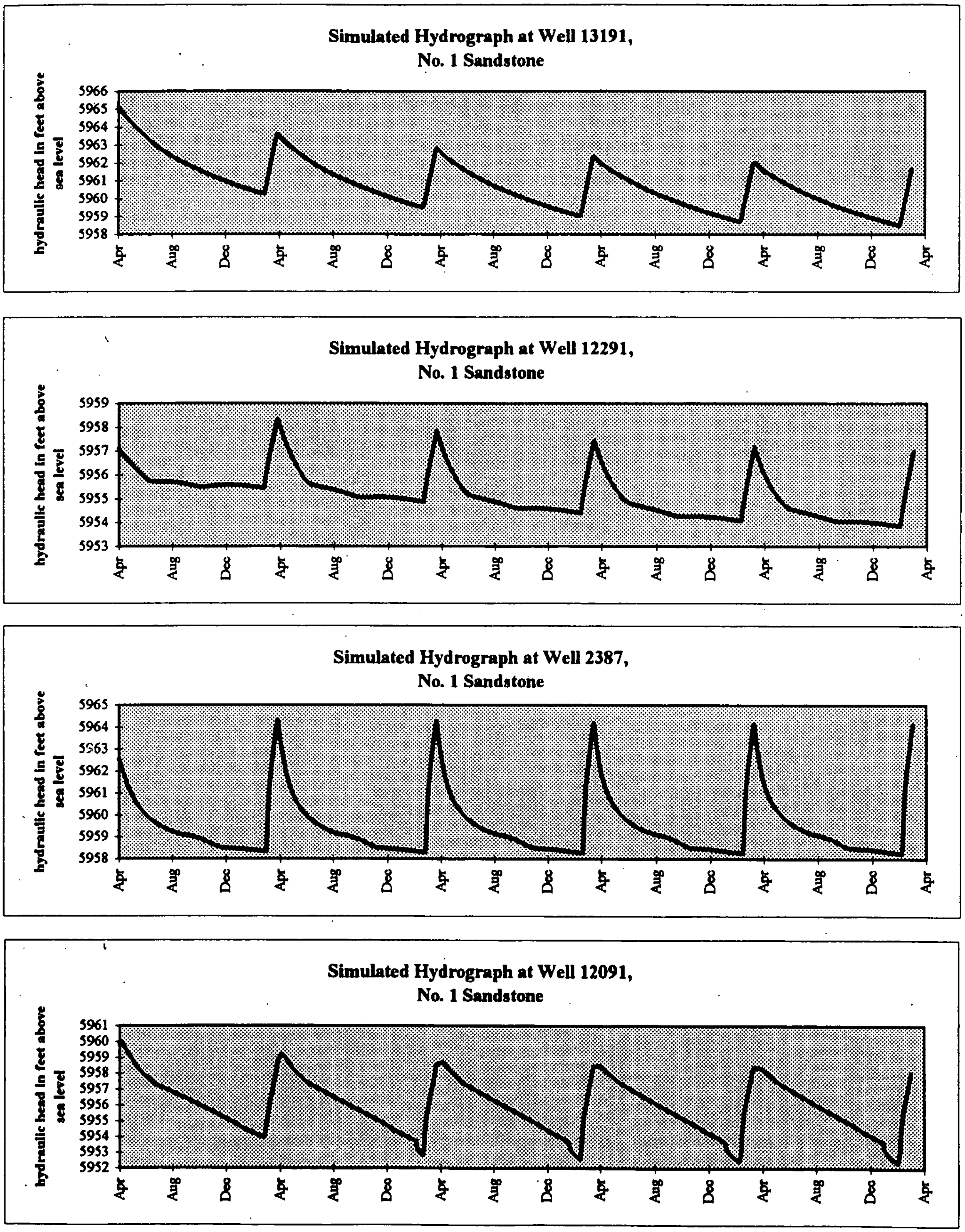

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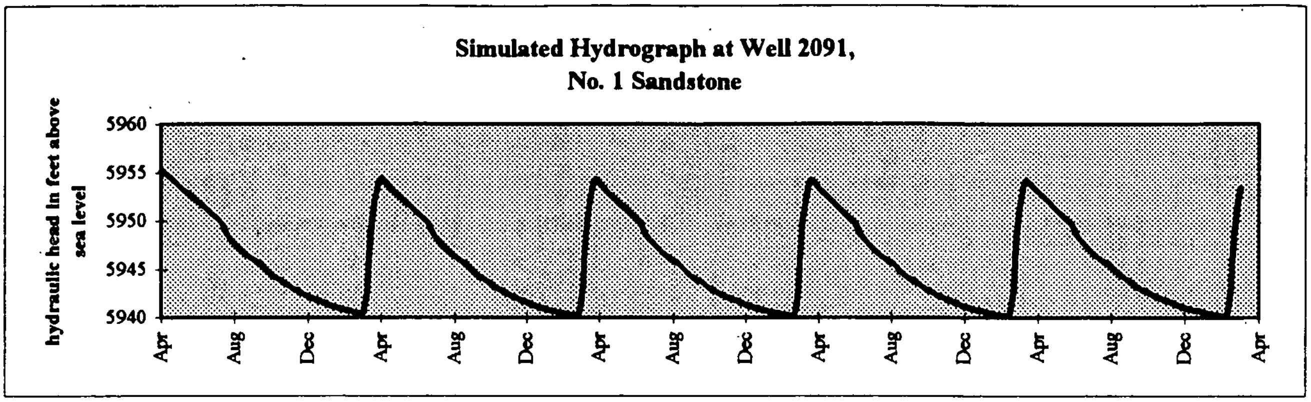
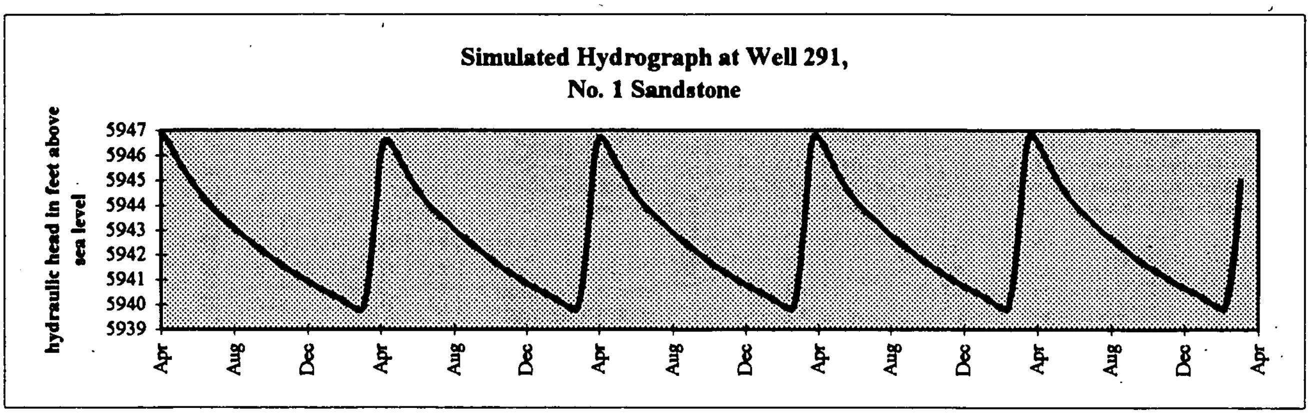
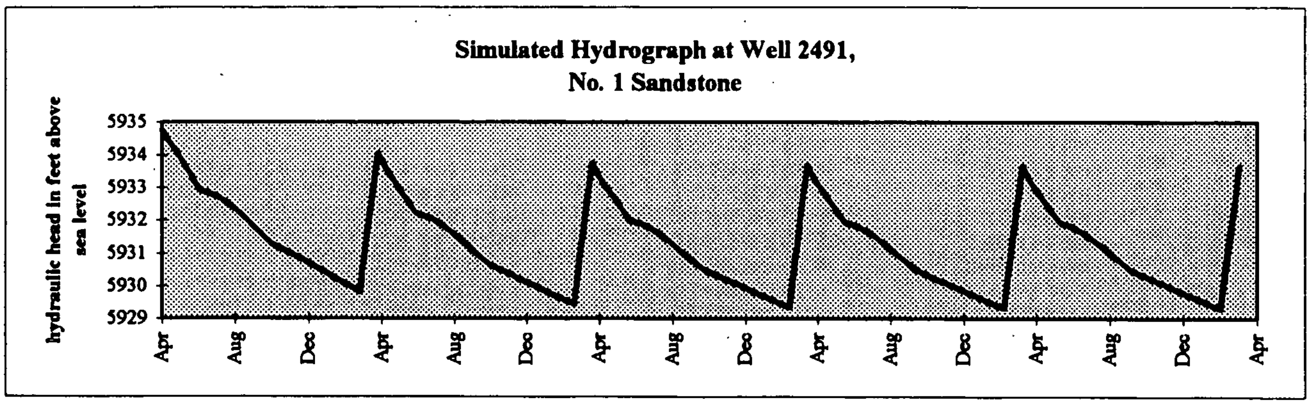
FIGURE 7.1-2
NO ACTION SCENARIO
FIVE-YEAR SIMULATED HYDROGRAPHS
(NO. 1 SANDSTONE)







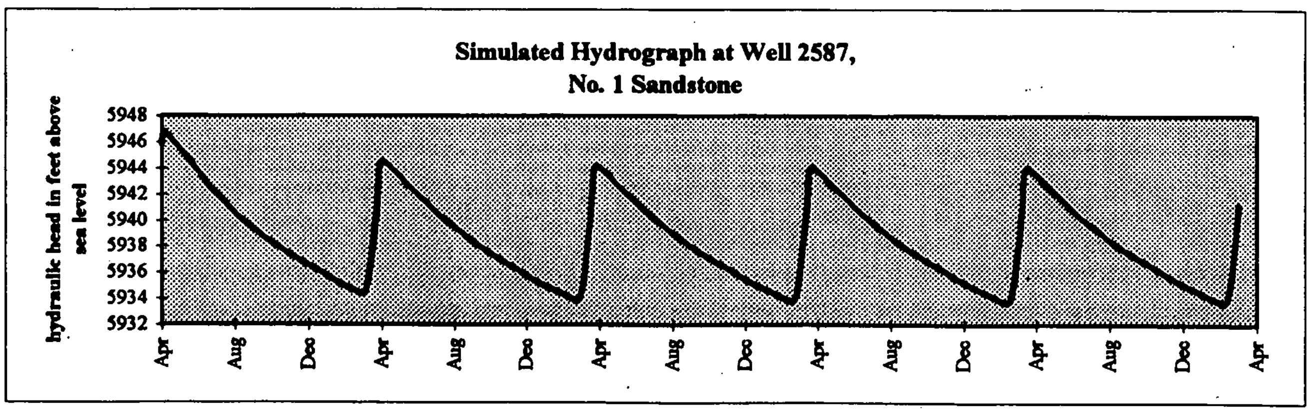


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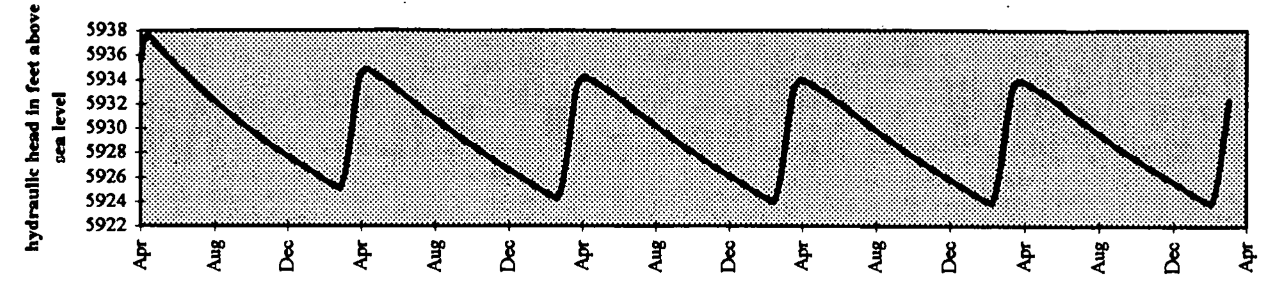
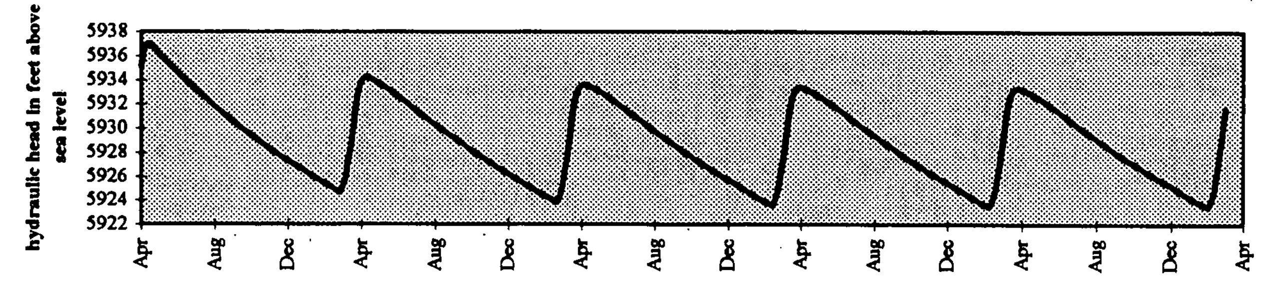
FIGURE 7.1-2
NO ACTION SCENARIO
FIVE-YEAR SIMULATED HYDROGRAPHS
(NO. 1 SANDSTONE)

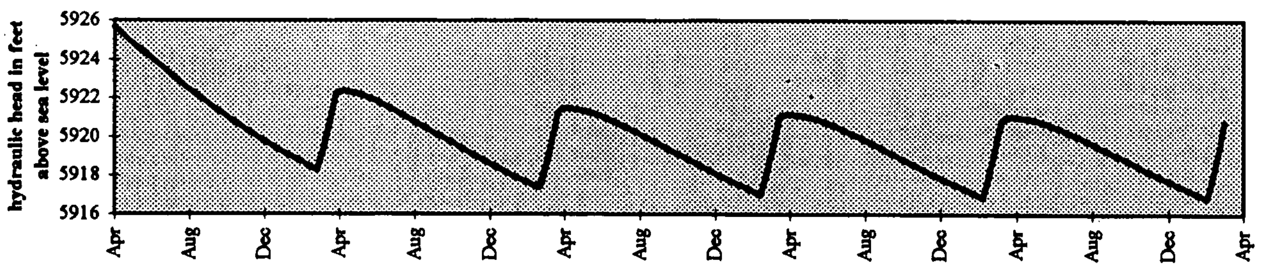
Simulated Hydrograph at Well 12191,
No. 1 Sandstone



Simulated Hydrograph at Well 2991,
No. 1 Sandstone



Simulated Hydrograph at Well 11891,
No. 1 Sandstone



Simulated Hydrograph at Well 3091,
No. 1 Sandstone

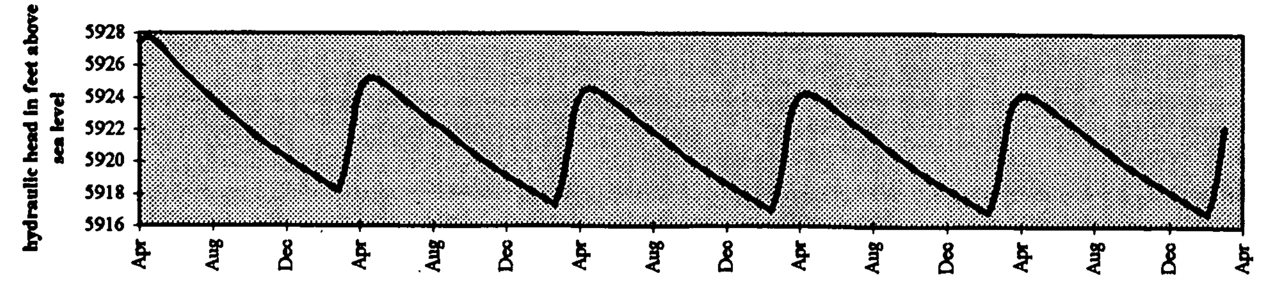


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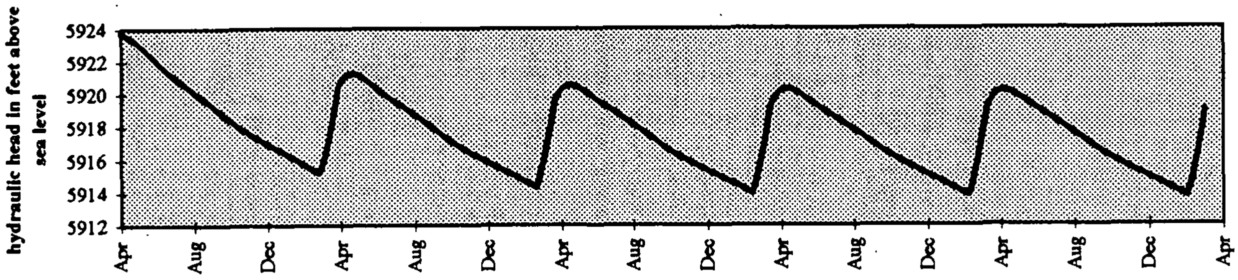
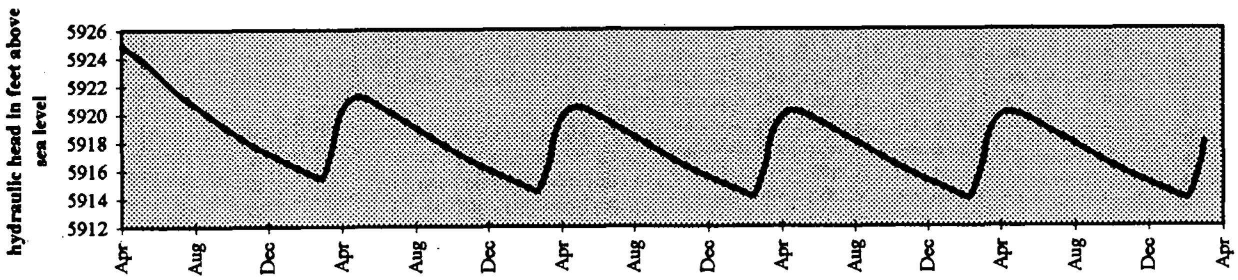
FIGURE 7.1-2
NO ACTION SCENARIO
FIVE-YEAR SIMULATED HYDROGRAPHS
(NO. 1 SANDSTONE)

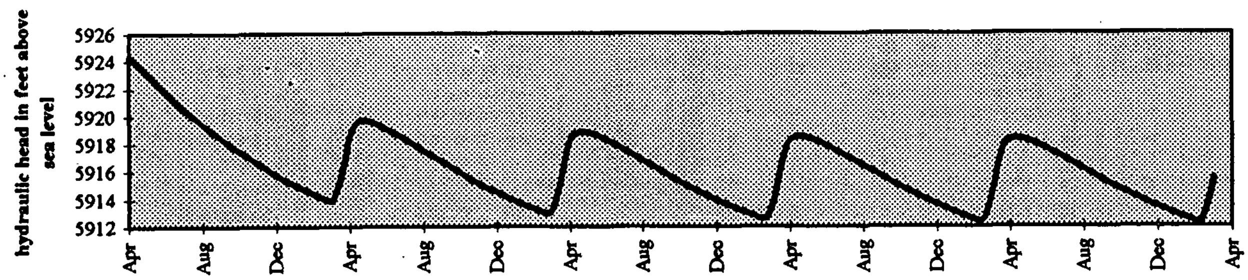
Simulated Hydrograph at Well 3687,
No. 1 Sandstone



Simulated Hydrograph at Well 12691,
No. 1 Sandstone

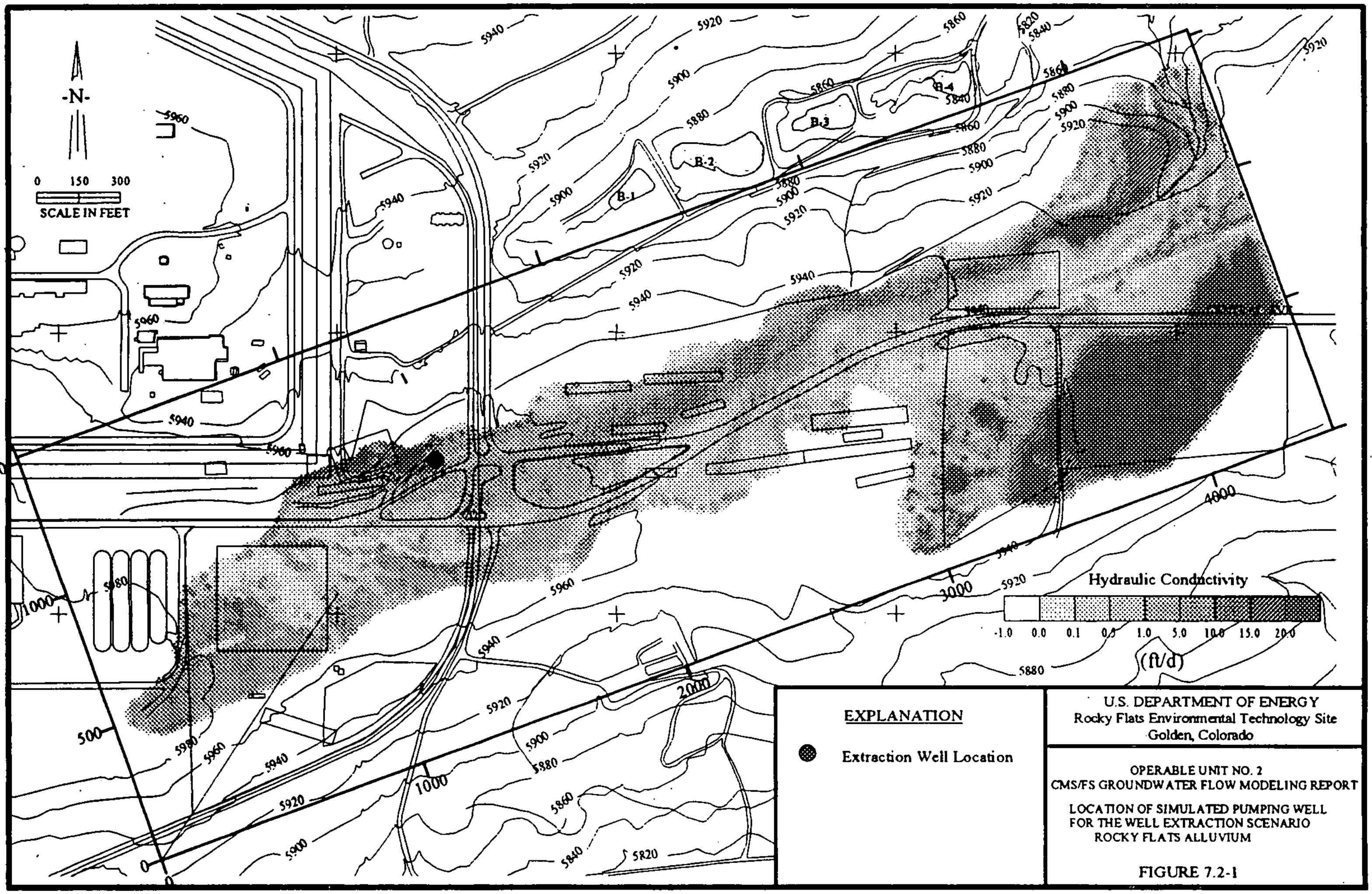


Simulated Hydrograph at Well 12491,
No. 1 Sandstone



144

145



EXPLANATION

Extraction Well Location

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LOCATION OF SIMULATED PUMPING WELL
FOR THE WELL EXTRACTION SCENARIO
ROCKY FLATS ALLUVIUM

FIGURE 7.2-1

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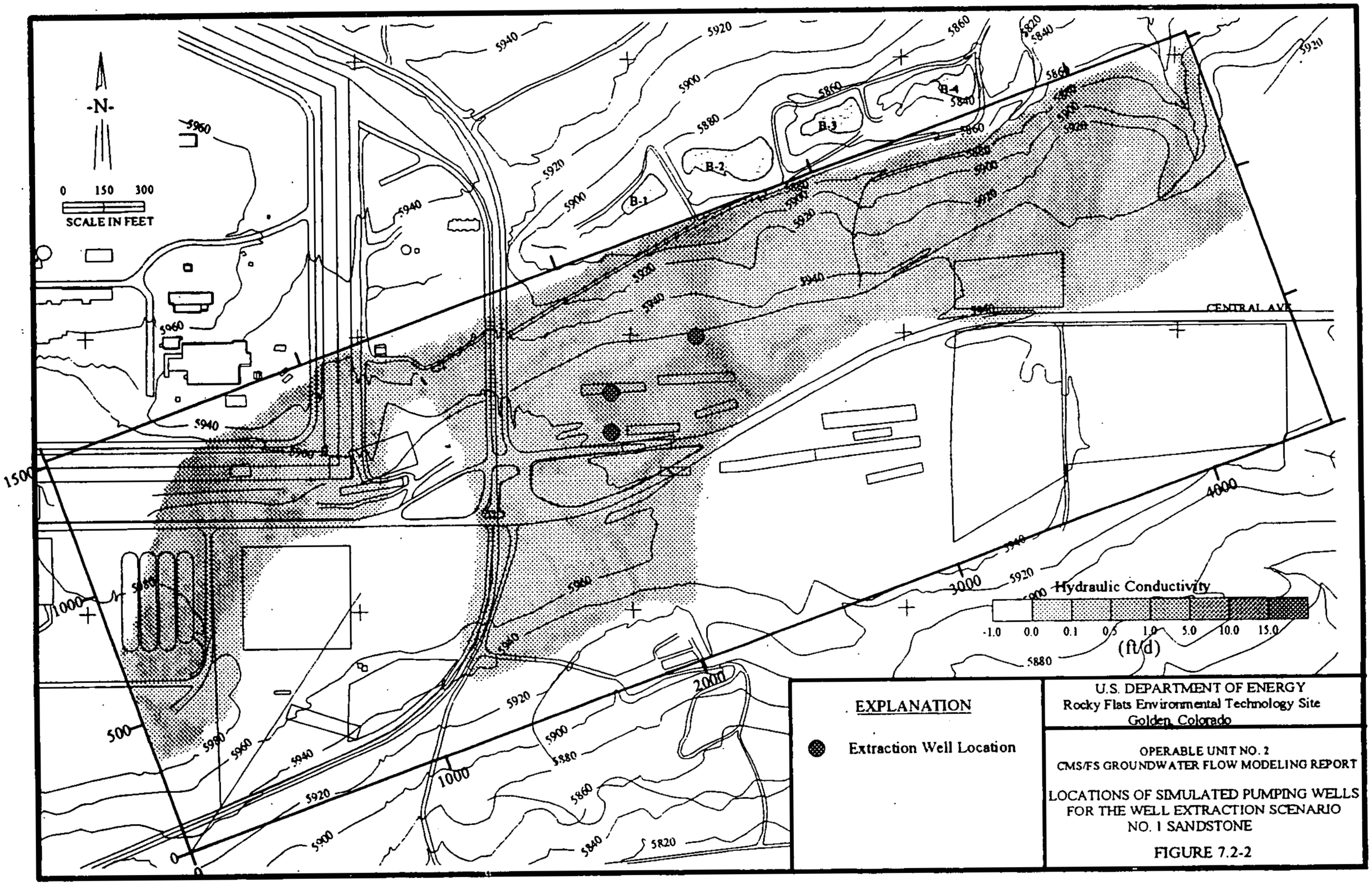

EXPLANATION

Extraction Well Location

U.S. DEPARTMENT OF ENERGY
Rocky Flats Environmental Technology Site
Golden, Colorado

OPERABLE UNIT NO. 2
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LOCATIONS OF SIMULATED PUMPING WELLS FOR THE WELL EXTRACTION SCENARIO NO. 1 SANDSTONE

FIGURE 7.2-2

147

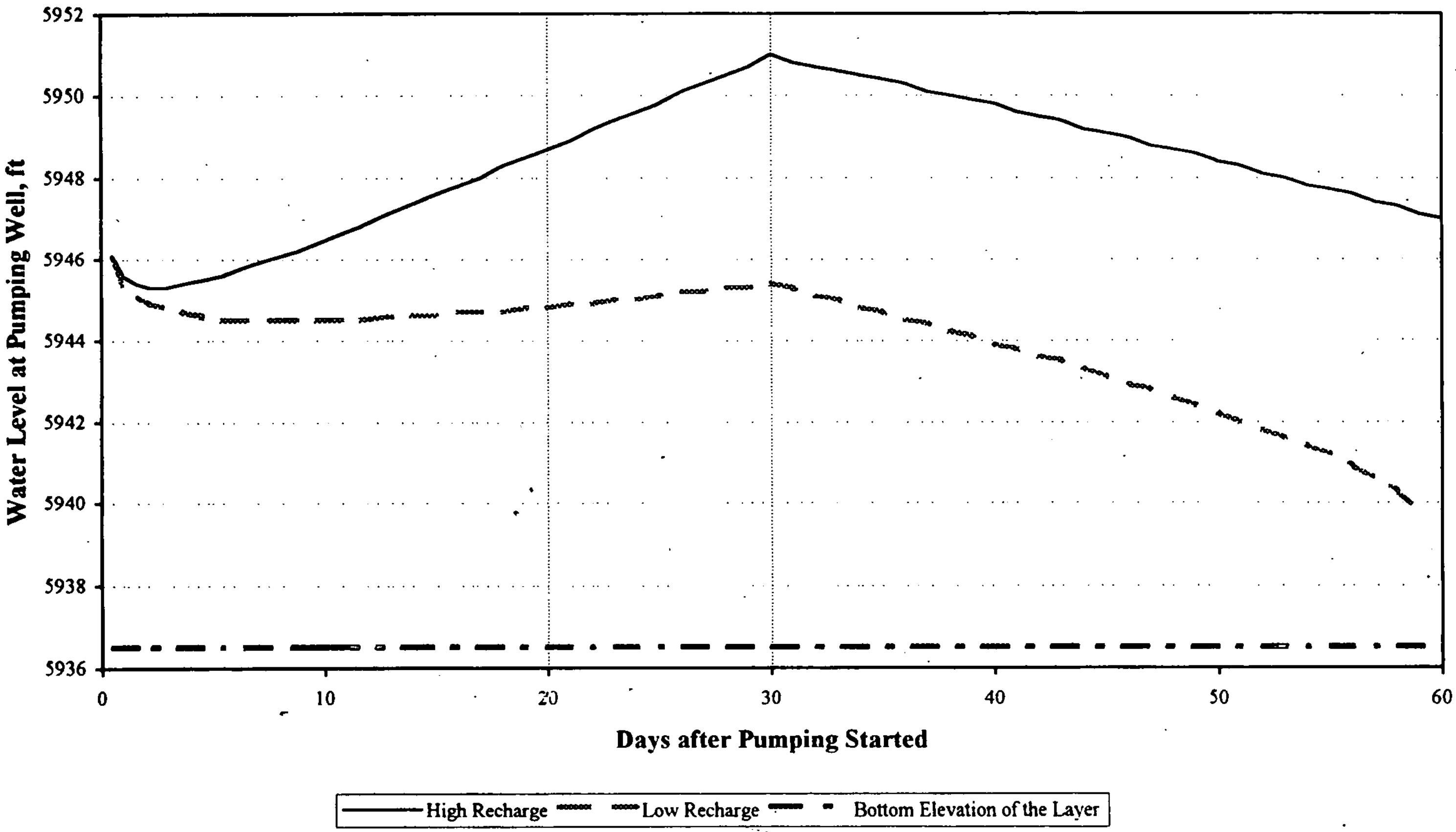

FIGURE 7.2-3
EXTRACTION WELL SCENARIO
SIMULATED RESULTS OF PUMPING AT LOCATION (LAYER 1, MODEL ROW 45, MODEL COLUMN 90)
(DISCHARGE RATE = 1 GPM)

4053/003 PUMP-HI.XLS graph 1 (6/28/95-4:50 PM)

142

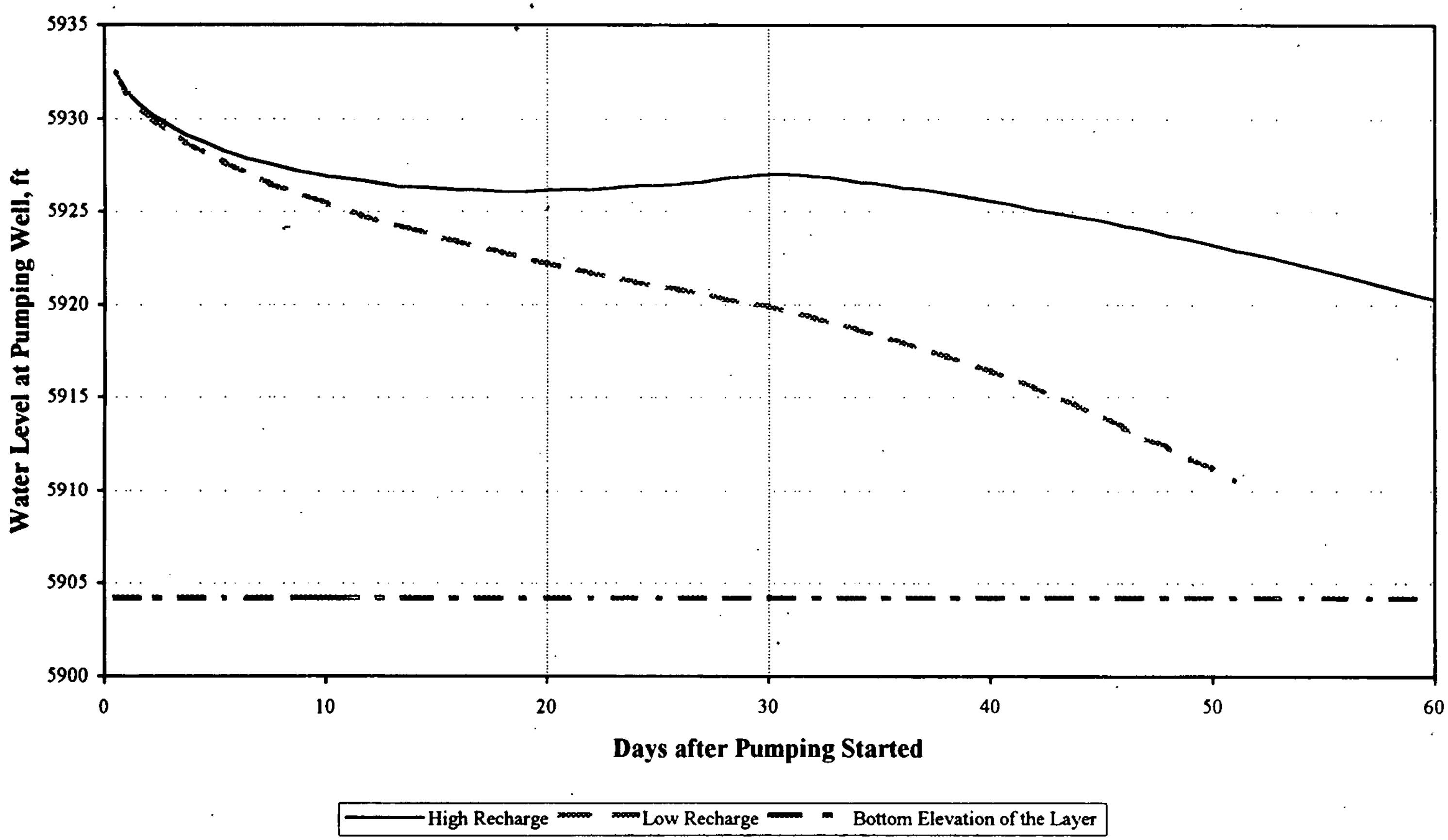

FIGURE 7.2-4
EXTRACTION WELL SCENARIO
SIMULATED RESULTS OF PUMPING AT LOCATION (LAYER 2, MODEL ROW 52, MODEL COLUMN 102)
(DISCHARGE RATE = 1.5 GPM)

4053/003 PUMP-HI.XLS graph 2 (6/28/95-4:50 PM)

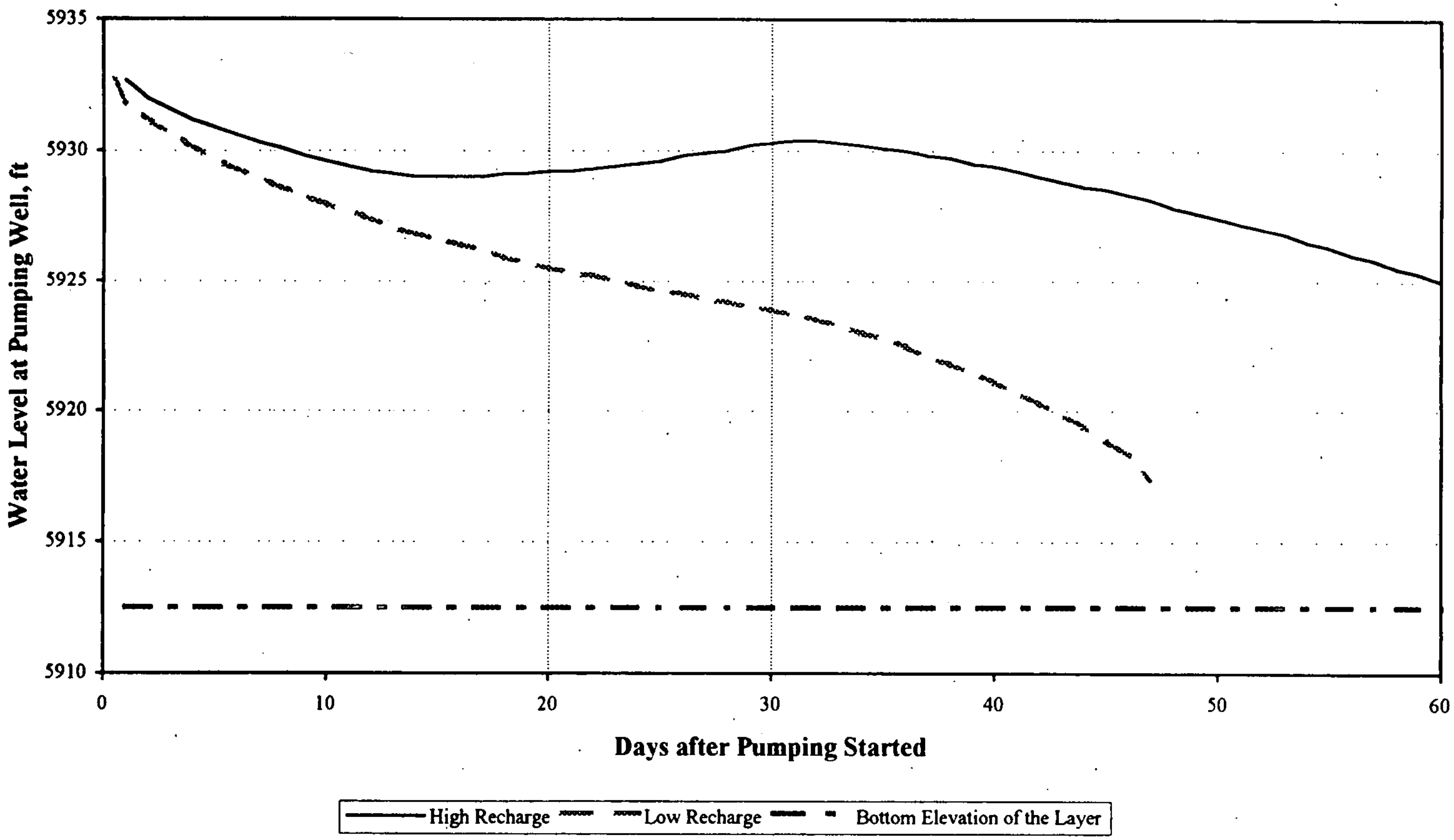

FIGURE 7.2-5

EXTRACTION WELL SCENARIO

SIMULATED RESULTS OF PUMPING AT LOCATION (LAYER 2, MODEL ROW 45, MODEL COLUMN 100)

(DISCHARGE RATE = 0.5 GPM)

4053/003 PUMP-HI.XLS graph 3 (6/28/95-4:50 PM)

150

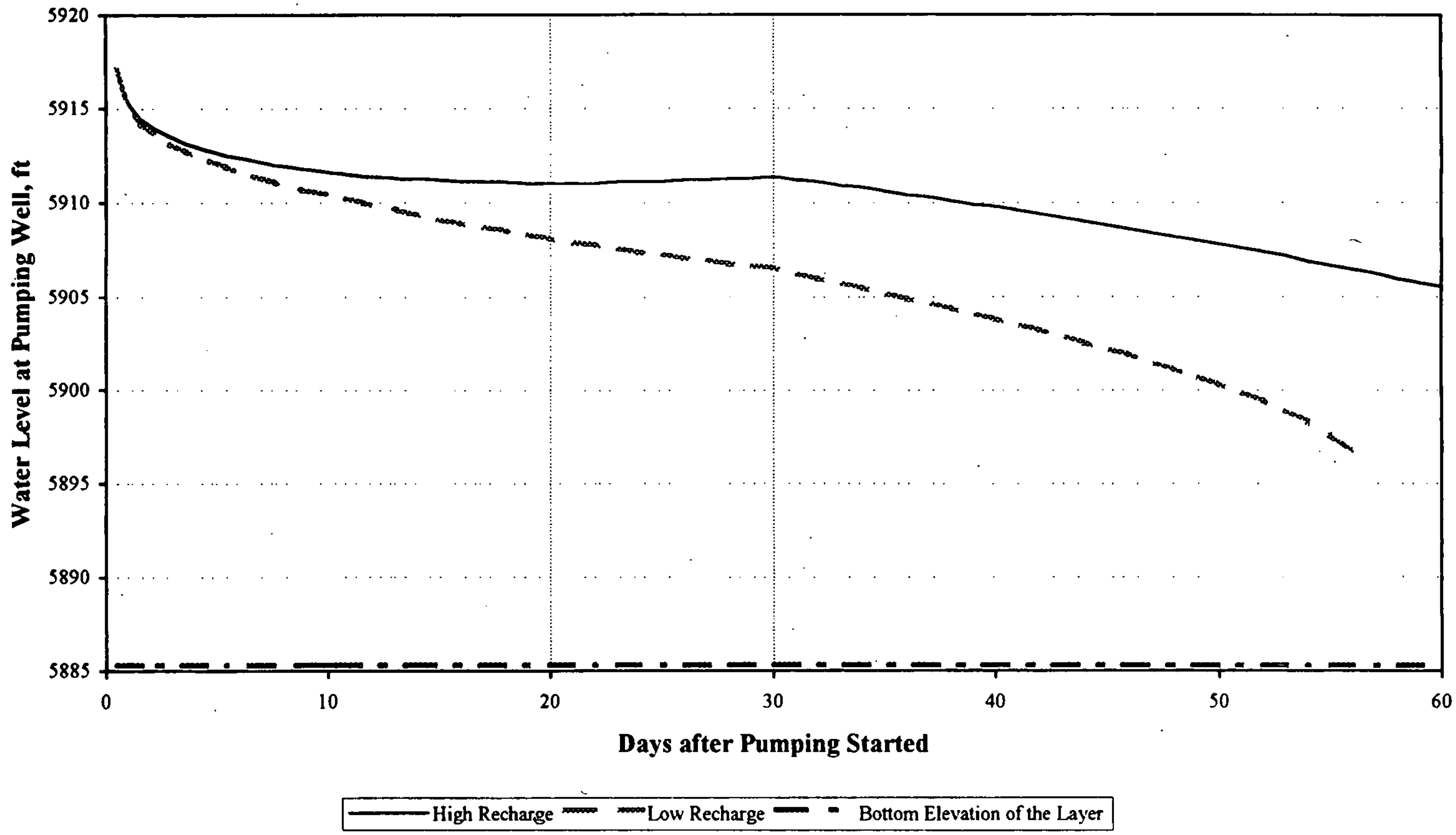

FIGURE 7.2-6

EXTRACTION WELL SCENARIO

SIMULATED RESULTS OF PUMPING AT LOCATION (LAYER 2, MODEL ROW 56, MODEL COLUMN 120)

(DISCHARGE RATE = 2 GPM)

151

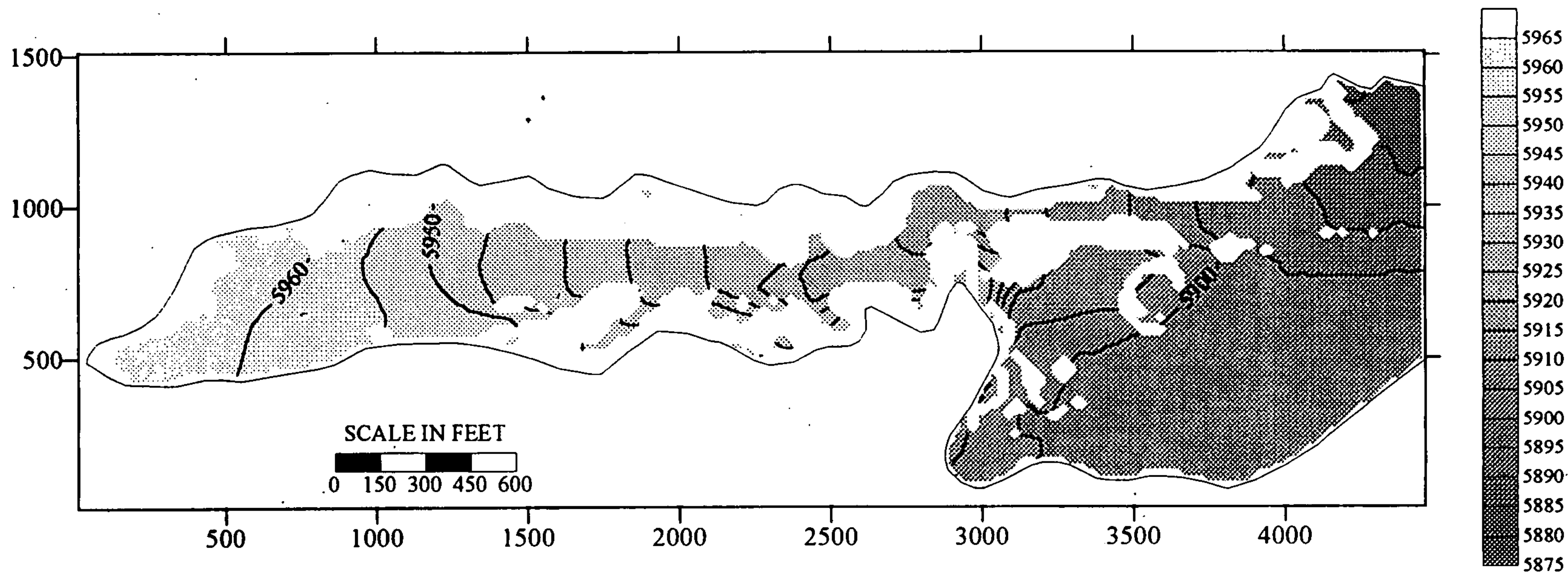

FIGURE 7.3-1
Simulated Hydraulic Head Distribution at the End of March, Second Year
Rocky Flats Alluvium, OU-2
Reduction of Recharge Scenario

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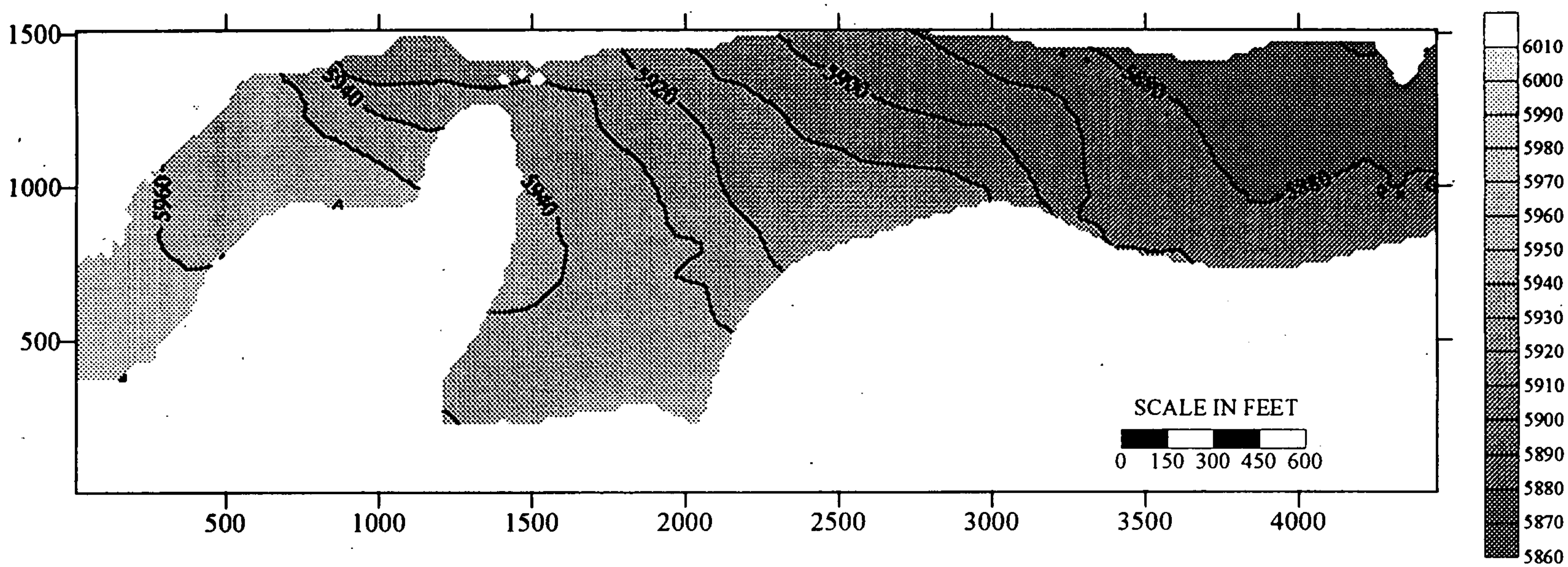

FIGURE 7.3-2
Simulated Hydraulic Head Distribution at the End of March, Second Year
No. 1 Sandstone, OU-2
Reduction of Recharge Scenario

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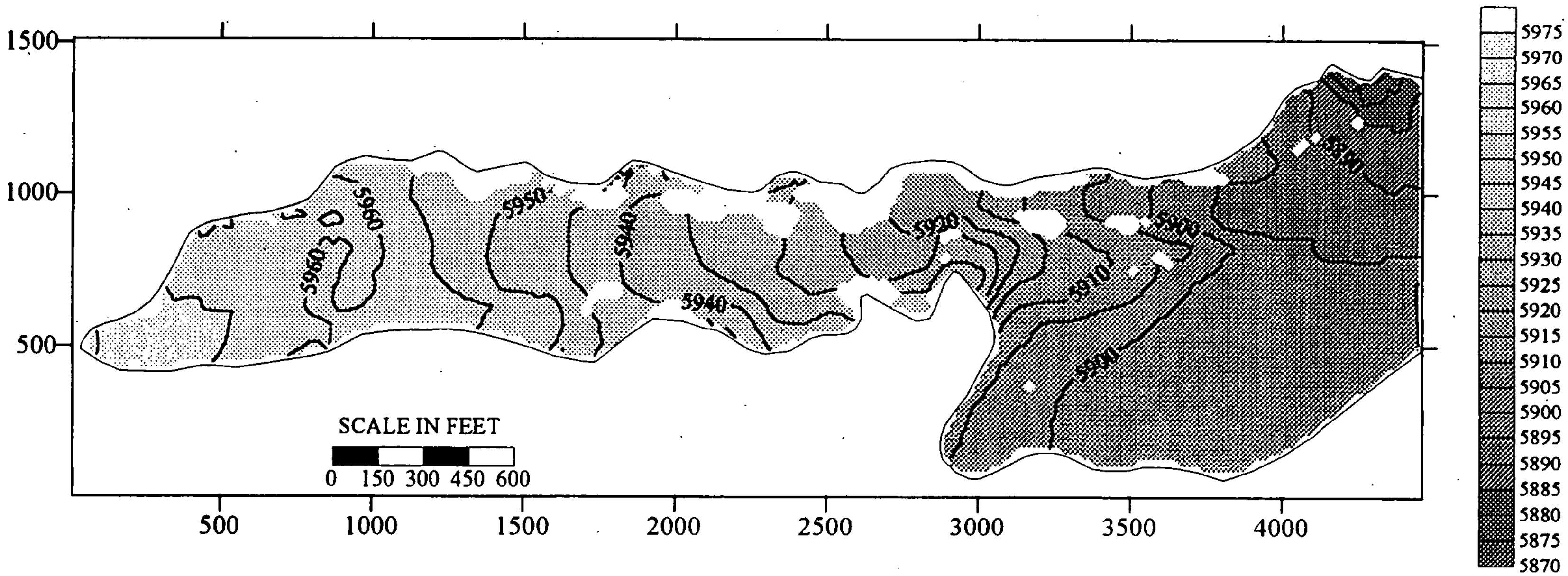

FIGURE 7.3-3
Simulated Hydraulic Head Distribution at the End of April, Second Year
Rocky Flats Alluvium, OU-2
Reduction of Recharge Scenario

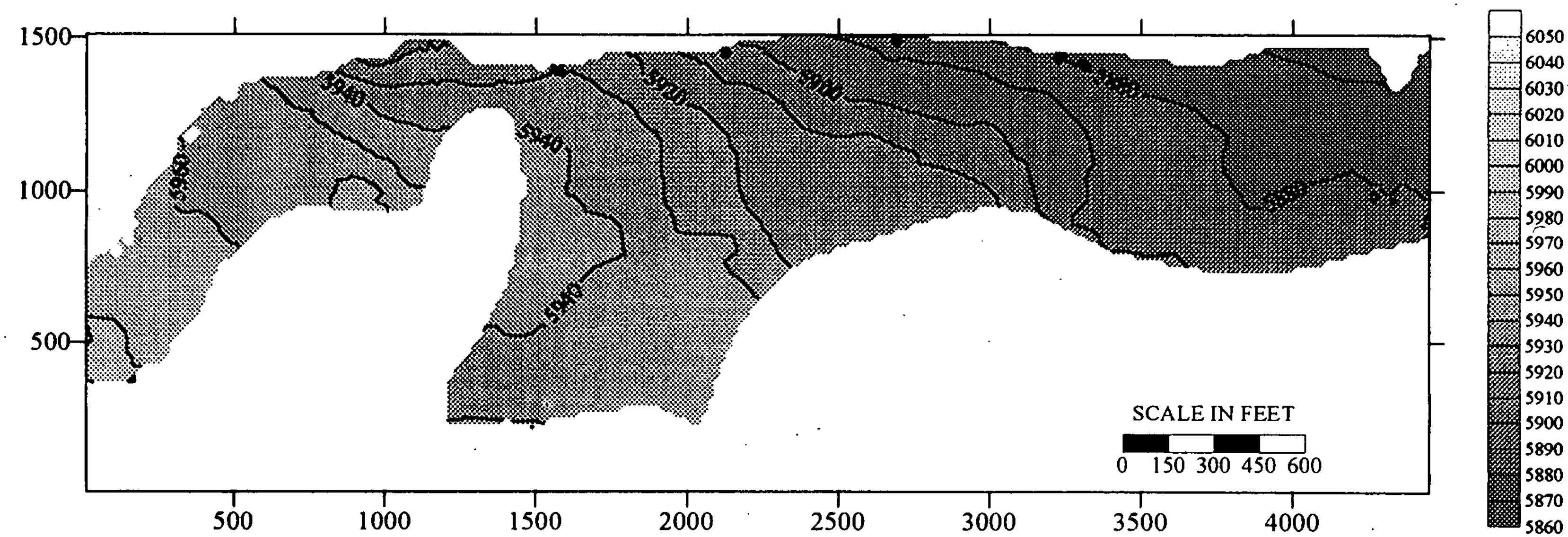

FIGURE 7.3-4
Simulated Hydraulic Head Distribution at the End of April, Second Year
No. 1 Sandstone, OU-2
Reduction of Recharge Scenario

8.0 MODEL LIMITATIONS

This model was developed based on interpreted geologic and hydrogeologic data, and calibrated to the interpreted hydraulic head distributions, under the constraints of prior information on hydraulic conductivity. Calibration results were evaluated from different aspects with substantial information. In general, this model should be representative of the general site hydrogeologic conditions under normal climatic conditions, i.e., normal groundwater recharge conditions.

However, the model may have limitations when used under certain circumstances. There are two major potential limitations:

1. Calibrated conductance values for drain cells are only representative when the hydraulic heads at the seeps are not significantly different from the conditions simulated in the model calibration. The major factor that potentially affects the hydraulic heads at the seeps is groundwater recharge.

   This limitation is primarily due to the non-rigorous calculation of drain conductance using MODFLOW (Anderson and Woessner 1994), which does not incorporate transient calculation of drain conductance as a function of seepage face.

   In future use of this model, if hydraulic heads at drain cells are significantly different from the heads used in model calibration, the seepage flow estimated by drain conductance may not be representative.

   This situation may occur when area recharge is reduced substantially. The recommendation for obtaining an approximate solution is to reduce drain conductance by adjusting the percentages for each stress period as discussed in Section 7.3. The impact on the hydraulic heads at the seep boundary due to pumping of extraction wells is expected to be limited, because the hydraulic conductivity (and transmissivity) in both saturated units is relatively low. The simulated pumping of extraction wells results indicated that the cone of depression was about 100 to 200 feet across, corresponding to a drawdown of one third of the saturated thickness at the pumping cell. The cone of depression does not reach the boundary drain cells, therefore, limitations of non-rigorous calculation of drain conductance may be negligible in the well extraction remediation scenario results.

2. Values of calibrated vertical conductance under transient conditions may only be representative under conditions assumed in the calibration, i.e., similar hydraulic head distributions in space (both vertical and horizontal) and in time.

   This limitation is due to the inability of the MODFLOW code (Anderson and Woessner 1994) to calculate transient vertical conductance, and the lack of clear information about the claystone layers and interbeds. The lack of information about claystone precluded the use of the new MODFLOW module TLK1 package for calculating time-variable vertical leakage.

   In future use of the model, if pumping does not significantly increase the vertical interaction between the alluvium and the sandstone, the simulated vertical leakage using the calibrated vertical conductance should be acceptable. This phenomenon should be evaluated if vertical leakage is considered critical in remediation.

9.0
SUMMARY

The OU2 CMS/FS groundwater flow model was developed based on thorough characterization of the site geologic and hydrologic conditions, which were determined from the results of extensive site investigation. Design of the numerical model for this complex system preserved the nature of the geometry of the hydrogeologic units, the boundary conditions, and the temporal variation of the system. Groundwater recharge was estimated independently from previous detailed hydrologic analysis.

The numerical model was calibrated by an iterative process of repeated steady state and transient calibrations. In the steady state calibration, a detailed hydraulic conductivity distribution was calibrated against the hydraulic head distribution for May 1992, which was assumed to be a steady state condition. Transient calibration simulated the transient processes of the groundwater system (i.e., the falling and rising of hydraulic head and change in the extent of saturated alluvium) in response to groundwater recharge for a one-year period. Parameters calibrated in the transient calibration included: storage coefficient, vertical hydraulic conductance under transient conditions, and variation of drain conductance (representing seepage conductance).

Calibration results show that under specified typical groundwater recharge conditions, the model can simulate the spatial and temporal hydraulic head and flow distributions very well in the key areas of the UHSU, with a reasonable water budget result. The calibrated model is representative of the typical UHSU hydrodynamic system at OU2 with calibrated parameters that characterize the major features of the system.

Limitations of the model are primarily due to the limitations of the MODFLOW code. These limitations will only be applied under certain circumstances, such as significant reduction of recharge over the entire model domain.

In summary, the calibration results provide a representative hydrodynamic environment suitable for use in the CMS/FS. The effect of remedial alternatives can be evaluated using this model. The detailed hydraulic conductivity distribution and the detailed simulation of the transient flow field provide a good basis for contaminant fate and transport simulation.

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APPENDIX A
EVALUATION OF BLOCK CENTERED FLOW (2) (BCF2) MODULE CODE MODIFICATIONS

As described in Section 4.0 of this report, modifications were made to the BCF2 module of the MODFLOW code for use in developing the OU2 CMS/FS groundwater flow model. The FORTRAN code for the subroutines of the BCF2 module that were modified are included in this Appendix as Attachment A. Modifications to the code are identified using comment lines that read 'cmz---'. These comment lines bracket the modified lines of code. Note that the dimension of the new array (cvlbry) is specific to this model. If these same modifications are made for use in other applications of the BCF2 module, dimensions should be general or specified for the model in question.

The modifications were made to keep "dry" cells from becoming inactive and to eliminate unrealistic upward groundwater flux in the "dry" cells while simulating the drying and re-wetting processes during transient simulation. The modified BCF2 module was used only in the transient simulations of the model and not during steady state simulations.

The effect on MODFLOW simulation results using the modified BCF2 module were evaluated by comparing the results from the unmodified BCF2 and the modified BCF2 modules. Model simulations of the eleven month drying period were conducted using the calibrated input parameters. The hydraulic head distributions and water budgets for the two simulations were compared and differences in results were not significant. The residual hydraulic heads between the two simulations are generally less than 1.0 feet (Figures A-1 through A-6). The comparison of the water budgets for the two simulations indicated that each of the related parameters (e.g., storage, total volume of drain flow) agreed within 1 percent.

To achieve a solution convergence, the simulation using the unmodified BCF2 module required a smaller time step (1 day time step) and a smaller acceleration parameter value (0.1) than the simulation using the modified BCF2 module (3 day time step and 0.3 acceleration parameter).

As stated above, the drying period of the annual transient flow cycle was used to compare results using the modified BCF2 and unmodified BCF2 modules. The period of recharge was not simulated in the comparison because of the difficulty, associated with re-wetting of cells, expected in achieving a solution convergence using the unmodified BCF2 module.

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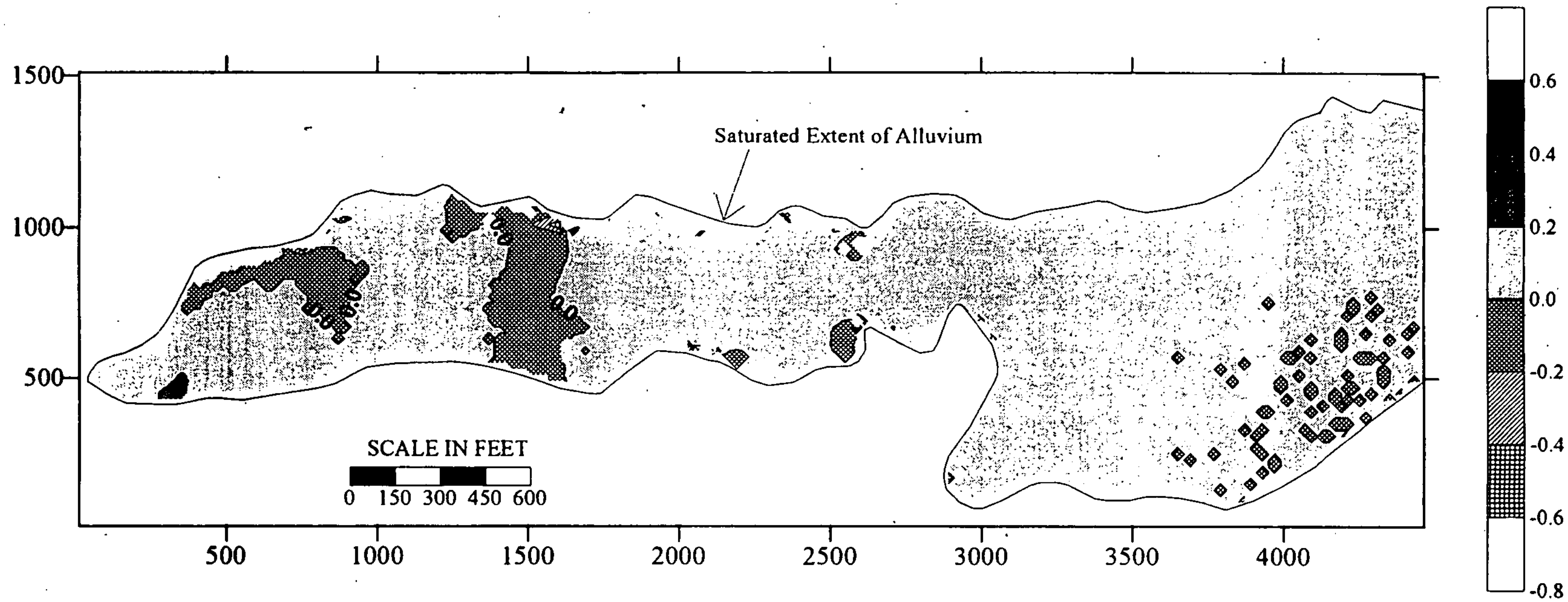

Figure A-1
Difference of Simulated Heads using Modified BCF2 and Unmodified BCF2
Rocky Flats Alluvium, End of Stress Period 1

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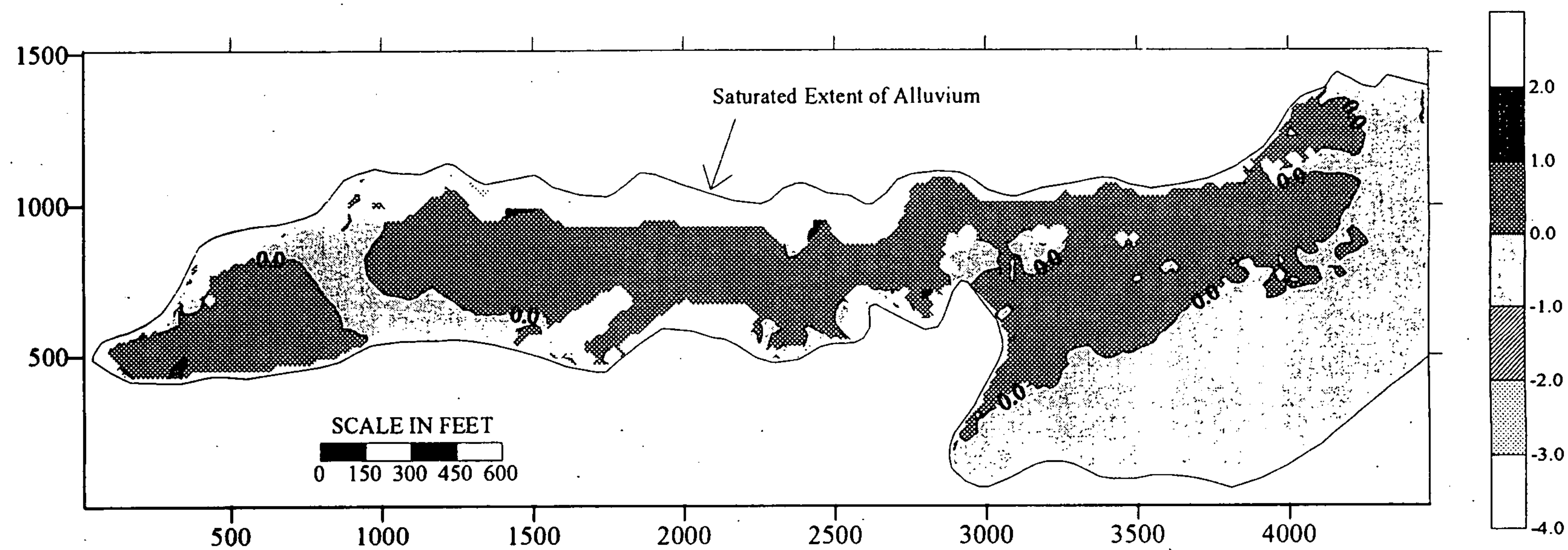

Figure A-2
Difference of Simulated Heads using Modified BCF2 and Unmodified BCF2
Rocky Flats Alluvium, End of Stress Period 2

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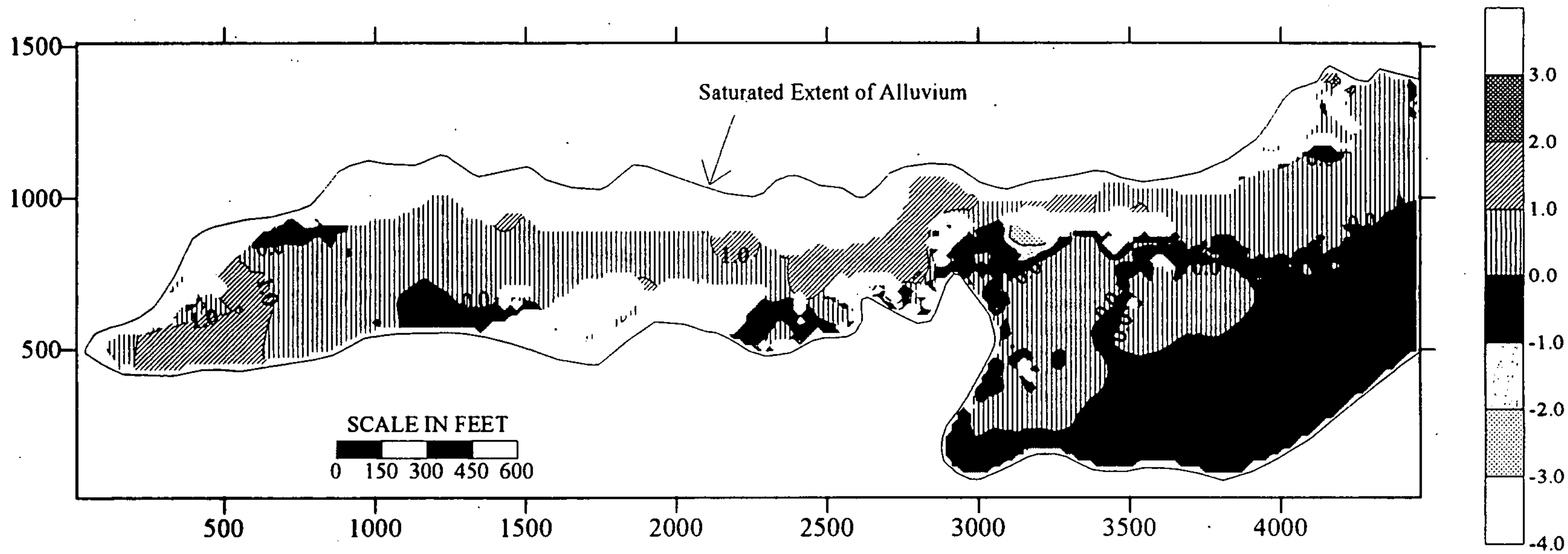

Figure A-3
Difference of Simulated Heads using Modified BCF2 and Unmodified BCF2
Rocky Flats Alluvium, End of Stress Period 3

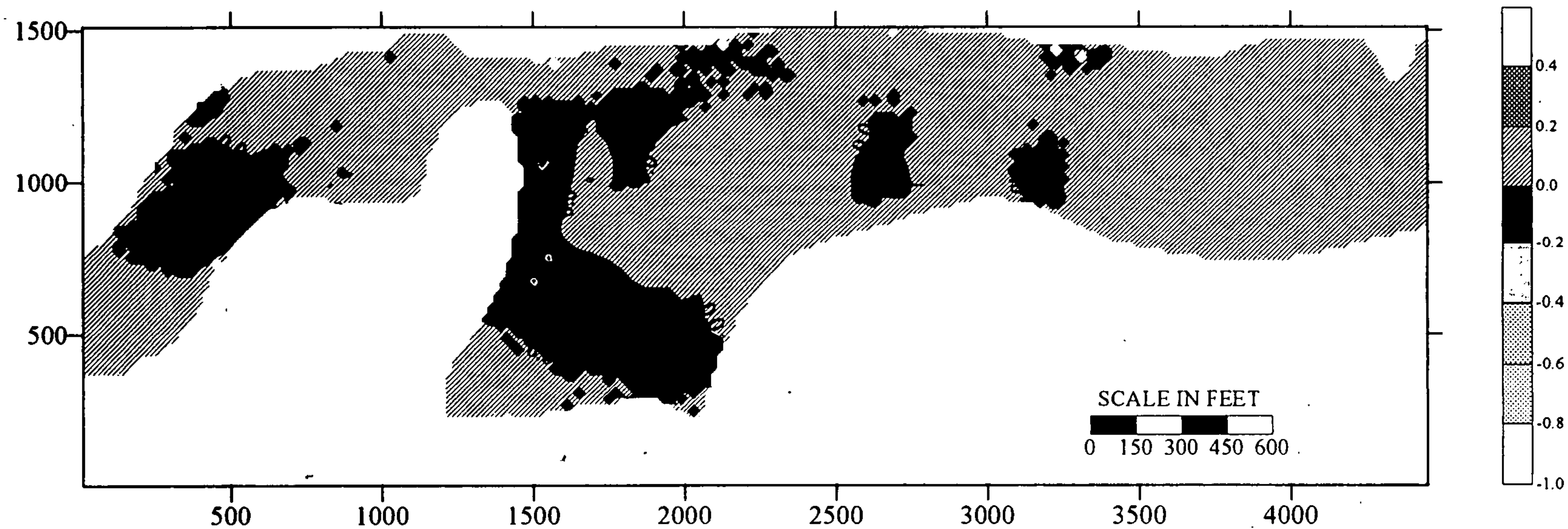

Figure A-4
Difference of Simulated Heads using Modified BCF2 and Unmodified BCF2
No.1 Sandstone, End of Stress Period 1

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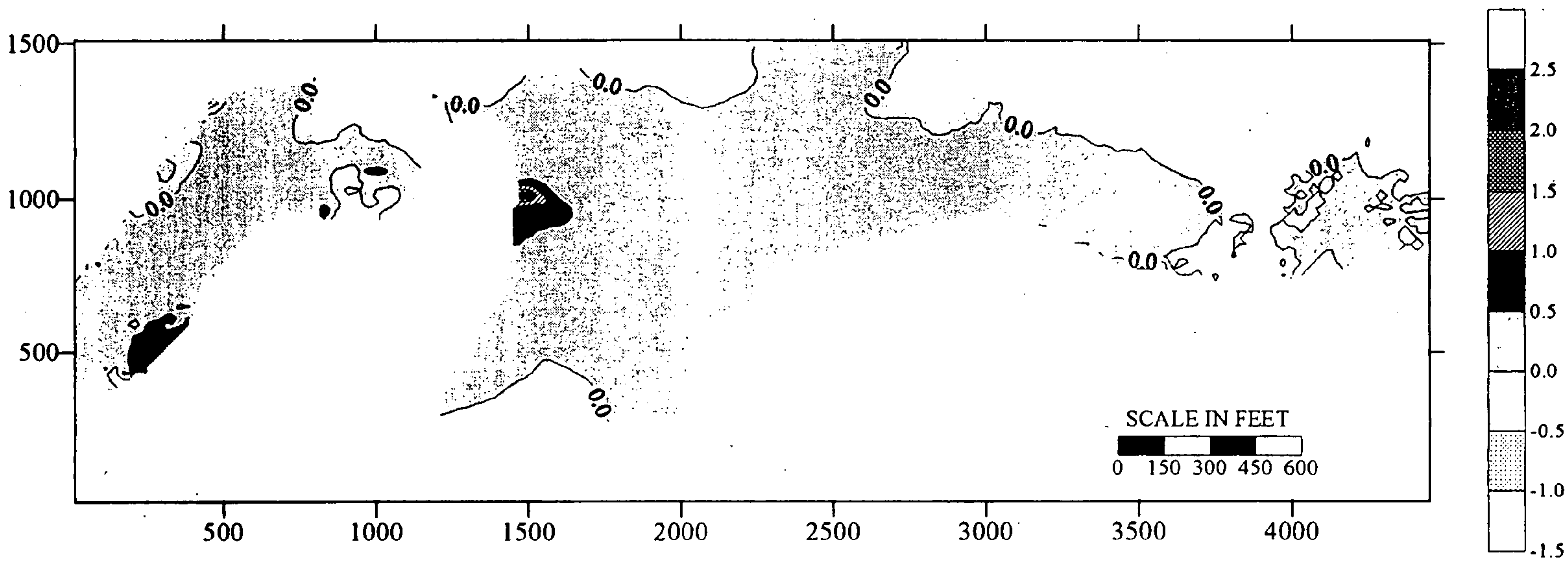

Figure A-5
Difference of Simulated Heads using Modified BCF2 and Unmodified BCF2
No.1 Sandstone, End of Stress Period 2

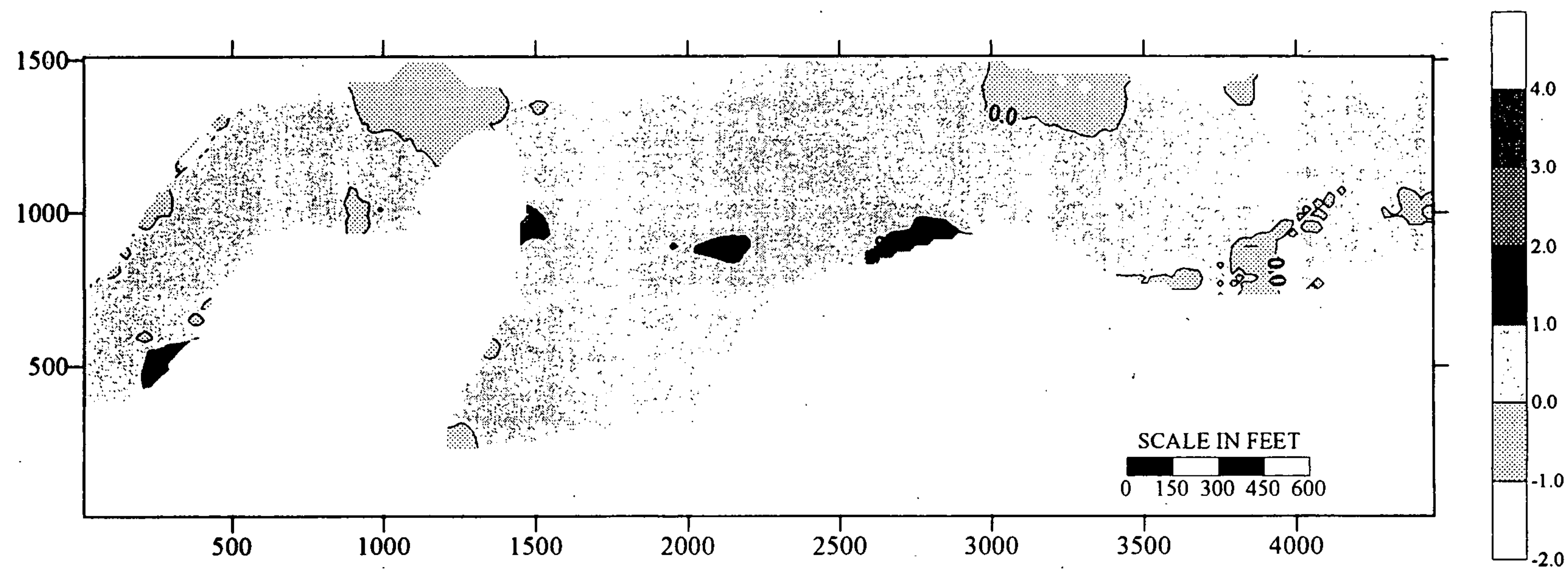

Figure A-6
Difference of Simulated Heads using Modified BCF2 and Unmodified BCF2
No. 1 Sandstone, End of Stress Period 3

ATTACHMENT A

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```
      SUBROUTINE BCF2RP(IBOUND,HNEW,SC1,HY,CR,CC,CV,DELR,DELC,BOT,TOP,
     1 SC2,TRPY,IN,ISS,NCOL,NROW,NLAY,NODES,IOUT,WETDRY,IWDFLG,CVWD)
C
C-----VERSION 1275 6JUNE1991 BCF2RP
C     ******************************************************************
C     READ AND INITIALIZE DATA FOR BLOCK-CENTERED FLOW PACKAGE,
C     VERSION 2
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      CHARACTER*4 ANAME
      DOUBLE PRECISION HNEW
C
      DIMENSION HNEW(NODES),SC1(NODES),HY(NODES),CR(NODES),CC(NODES),
     1          CV(NODES),ANAME(6,11),DELR(NCOL),DELC(NROW),BOT(NODES),
     1          TOP(NODES),SC2(NODES),TRPY(NLAY),IBOUND(NODES),
     1          WETDRY(NODES),CVWD(NODES)
C
      COMMON /FLWCOM/LAYCON(80)
C
cmz---
      common /cvcom/cvlbry(33896)
cmz---

      DATA ANAME(1,1),ANAME(2,1),ANAME(3,1),ANAME(4,1),ANAME(5,1),
     1 ANAME(6,1) /'    ','PRIM','ARY ','STOR','AGE ','COEF'/
      DATA ANAME(1,2),ANAME(2,2),ANAME(3,2),ANAME(4,2),ANAME(5,2),
     1 ANAME(6,2) /'    ','TRAN','SMIS','. AL','ONG ','ROWS'/
      DATA ANAME(1,3),ANAME(2,3),ANAME(3,3),ANAME(4,3),ANAME(5,3),
     1 ANAME(6,3) /'   H','YD. ','COND','. AL','ONG ','ROWS'/
      DATA ANAME(1,4),ANAME(2,4),ANAME(3,4),ANAME(4,4),ANAME(5,4),
     1 ANAME(6,4) /'VERT',' HYD',' CON','D /T','HICK','NESS'/
      DATA ANAME(1,5),ANAME(2,5),ANAME(3,5),ANAME(4,5),ANAME(5,5),
     1 ANAME(6,5) /'    ','    ','    ','    ','  BO','TTOM'/
      DATA ANAME(1,6),ANAME(2,6),ANAME(3,6),ANAME(4,6),ANAME(5,6),
     1 ANAME(6,6) /'    ','    ','    ','    ','    ',' TOP'/
      DATA ANAME(1,7),ANAME(2,7),ANAME(3,7),ANAME(4,7),ANAME(5,7),
     1 ANAME(6,7) /'  SE','COND','ARY ','STOR','AGE ','COEF'/
      DATA ANAME(1,8),ANAME(2,8),ANAME(3,8),ANAME(4,8),ANAME(5,8),
     1 ANAME(6,8) /'COLU','MN T','O RO','W AN','ISOT','ROPY'/
      DATA ANAME(1,9),ANAME(2,9),ANAME(3,9),ANAME(4,9),ANAME(5,9),
     1 ANAME(6,9) /'    ','    ','    ','    ','    ','DELR'/
      DATA ANAME(1,10),ANAME(2,10),ANAME(3,10),ANAME(4,10),ANAME(5,10),
     1 ANAME(6,10) /'    ','    ','    ','    ','    ','DELC'/
      DATA ANAME(1,11),ANAME(2,11),ANAME(3,11),ANAME(4,11),ANAME(5,11),
     1 ANAME(6,11) /'    ','    ','WETD','RY P','ARAM','ETER'/
C     ------------------------------------------------------------------
C
```

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```
C1------CALCULATE NUMBER OF NODES IN A LAYER AND READ TRPY,DELR,DELC
      NIJ=NCOL*NROW
C
      CALL U1DREL(TRPY,ANAME(1,8),NLAY,IN,IOUT)
      CALL U1DREL(DELR,ANAME(1,9),NCOL,IN,IOUT)
      CALL U1DREL(DELC,ANAME(1,10),NROW,IN,IOUT)
C
C2------READ ALL PARAMETERS FOR EACH LAYER
      KT=0
      KB=0
      DO 200 K=1,NLAY
      KK=K
C
C2A-----FIND ADDRESS OF EACH LAYER IN THREE DIMENSION ARRAYS.
      IF(LAYCON(K).EQ.1 .OR. LAYCON(K).EQ.3) KB=KB+1
      IF(LAYCON(K).EQ.2 .OR. LAYCON(K).EQ.3) KT=KT+1
      LOC=1+(K-1)*NIJ
      LOCB=1+(KB-1)*NIJ
      LOCT=1+(KT-1)*NIJ
C
C2B-----READ PRIMARY STORAGE COEFFICIENT INTO ARRAY SC1 IF TRANSIENT
      IF(ISS.EQ.0)CALL U2DREL(SC1(LOC),ANAME(1,1),NROW,NCOL,KK,IN,IOUT)
C
C2C-----READ TRANSMISSIVITY INTO ARRAY CC IF LAYER TYPE IS 0 OR 2
      IF(LAYCON(K).EQ.3 .OR. LAYCON(K).EQ.1) GO TO 100
      CALL U2DREL(CC(LOC),ANAME(1,2),NROW,NCOL,KK,IN,IOUT)
      GO TO 110
C
C2D-----READ HYDRAULIC CONDUCTIVITY(HY) AND BOTTOM ELEVATION(BOT)
C2D-----IF LAYER TYPE IS 1 OR 3
  100 CALL U2DREL(HY(LOCB),ANAME(1,3),NROW,NCOL,KK,IN,IOUT)
      CALL U2DREL(BOT(LOCB),ANAME(1,5),NROW,NCOL,KK,IN,IOUT)
C
C2E-----READ VERTICAL HYCOND/THICK INTO ARRAY CV IF NOT BOTTOM LAYER
C2E----- READ AS HYCOND/THICKNESS -- CONVERTED TO CONDUCTANCE LATER
  110 IF(K.EQ.NLAY) GO TO 120
      CALL U2DREL(CV(LOC),ANAME(1,4),NROW,NCOL,KK,IN,IOUT)
C
C2F-----READ SECONDARY STORAGE COEFFICIENT INTO ARRAY SC2 IF TRANSIENT
C2F-----AND LAYER TYPE IS 2 OR 3
  120 IF(LAYCON(K).NE.3 .AND. LAYCON(K).NE.2) GO TO 130
      IF(ISS.EQ.0)CALL U2DREL(SC2(LOCT),ANAME(1,7),NROW,NCOL,KK,IN,IOUT)
C
C2G-----READ TOP ELEVATION(TOP) IF LAYER TYPE IS 2 OR 3
      CALL U2DREL(TOP(LOCT),ANAME(1,6),NROW,NCOL,KK,IN,IOUT)
C
C2H-----READ WETDRY CODES IF LAYER TYPE IS 1 OR 3 AND WETTING
C2H-----CAPABILITY HAS BEEN INVOKED (IWDFLG NOT 0)
  130 IF(LAYCON(K).NE.3.AND.LAYCON(K).NE.1)GO TO 200
```

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```
      IF(IWDFLG.EQ.0)GO TO 200
      CALL U2DREL(WETDRY(LOCB),ANAME(1,11),NROW,NCOL,KK,IN,IOUT)
  200 CONTINUE
C
C3------PREPARE AND CHECK BCF DATA
      CALL SBCF2N(HNEW,IBOUND,SC1,SC2,CR,CC,CV,HY,TRPY,DELR,DELC,ISS,
     1          NCOL,NROW,NLAY,IOUT,WETDRY,IWDFLG,CVWD)
C
C4------RETURN
      RETURN
      END
```

```
      SUBROUTINE BCF2FM(HCOF,RHS,HOLD,SC1,HNEW,IBOUND,CR,CC,CV,HY,TRPY,
     1                  BOT,TOP,SC2,DELR,DELC,DELT,ISS,KITER,KSTP,KPER,
     2                  NCOL,NROW,NLAY,IOUT,WETDRY,IWDFLG,CVWD,
     3                  WETFCT,IWETIT,IHDWET,HDRY)
C-----VERSION 1104 5MAY1991 BCF2FM
C     ******************************************************************
C     ADD LEAKAGE CORRECTION AND STORAGE TO HCOF AND RHS, AND CALCULATE
C     CONDUCTANCE AS REQUIRED, VERSION 2
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
      DOUBLE PRECISION HNEW
C
      DIMENSION HCOF(NCOL,NROW,NLAY),RHS(NCOL,NROW,NLAY),
     1    HOLD(NCOL,NROW,NLAY),SC1(NCOL,NROW,NLAY),HNEW(NCOL,NROW,NLAY),
     2    IBOUND(NCOL,NROW,NLAY),CR(NCOL,NROW,NLAY),
     3    CC(NCOL,NROW,NLAY),CV(NCOL,NROW,NLAY),HY(NCOL,NROW,NLAY),
     4    TRPY(NLAY),BOT(NCOL,NROW,NLAY),TOP(NCOL,NROW,NLAY),DELR(NCOL),
     5    DELC(NROW),SC2(NCOL,NROW,NLAY),WETDRY(NCOL,NROW,NLAY),
     6    CVWD(NCOL,NROW,NLAY)
C
      COMMON /FLWCOM/LAYCON(80)
cmz---
      common /cvcom/cvlbry(223,76,2)
cmz---
C     ------------------------------------------------------------------
      KB=0
      KT=0
C
C1------FOR EACH LAYER: IF T VARIES CALCULATE HORIZONTAL CONDUCTANCES
      DO 100 K=1,NLAY
      KK=K
      IF(LAYCON(K).EQ.3 .OR. LAYCON(K).EQ.2) KT=KT+1
C
C1A-----IF LAYER TYPE IS NOT 1 OR 3 THEN SKIP THIS LAYER.
      IF(LAYCON(K).NE.3 .AND. LAYCON(K).NE.1) GO TO 100
      KB=KB+1
C
C1B-----FOR LAYER TYPES 1 & 3 CALL SBCF2H TO CALCULATE
C1B-----HORIZONTAL CONDUCTANCES.
      CALL SBCF2H(HNEW,IBOUND,CR,CC,CV,HY,TRPY,DELR,DELC,BOT,TOP,
     1  KK,KB,KT,KITER,KSTP,KPER,NCOL,NROW,NLAY,IOUT,WETDRY,IWDFLG,
     2  CVWD,WETFCT,IWETIT,IHDWET,HDRY)
  100 CONTINUE
C
C2------IF THE SIMULATION IS TRANSIENT ADD STORAGE TO HCOF AND RHS
      IF(ISS.NE.0) GO TO 201
      TLED=1./DELT
```

```
      KT=0
      DO 200 K=1,NLAY
C
C3------SEE IF THIS LAYER IS CONVERTIBLE OR NON-CONVERTIBLE.
      IF(LAYCON(K).EQ.3 .OR. LAYCON(K).EQ.2) GO TO 150
C4------NON-CONVERTIBLE LAYER, SO USE PRIMARY STORAGE
      DO 140 I=1,NROW
      DO 140 J=1,NCOL
      IF(IBOUND(J,I,K).LE.0) GO TO 140
      RHO=SC1(J,I,K)*TLED
      HCOF(J,I,K)=HCOF(J,I,K)-RHO
      RHS(J,I,K)=RHS(J,I,K)-RHO*HOLD(J,I,K)
  140 CONTINUE
      GO TO 200
C
C5------A CONVERTIBLE LAYER, SO CHECK OLD AND NEW HEADS TO DETERMINE
C5------WHEN TO USE PRIMARY AND SECONDARY STORAGE
  150 KT=KT+1
      DO 180 I=1,NROW
      DO 180 J=1,NCOL
C
C5A-----IF THE CELL IS EXTERNAL THEN SKIP IT.
      IF(IBOUND(J,I,K).LE.0) GO TO 180
      TP=TOP(J,I,KT)
      RHO2=SC2(J,I,KT)*TLED
      RHO1=SC1(J,I,K)*TLED
C
C5B-----FIND STORAGE FACTOR AT START OF TIME STEP.
      SOLD=RHO2
      IF(HOLD(J,I,K).GT.TP) SOLD=RHO1
C
C5C-----FIND STORAGE FACTOR AT END OF TIME STEP.
      HTMP=HNEW(J,I,K)
      SNEW=RHO2
      IF(HTMP.GT.TP) SNEW=RHO1
C
C5D-----ADD STORAGE TERMS TO RHS AND HCOF.
      HCOF(J,I,K)=HCOF(J,I,K)-SNEW
      RHS(J,I,K)=RHS(J,I,K) - SOLD*(HOLD(J,I,K)-TP) - SNEW*TP
C
  180 CONTINUE
C
  200 CONTINUE
C
C6------FOR EACH LAYER DETERMINE IF CORRECTION TERMS ARE NEEDED FOR
C6------FLOW DOWN INTO PARTIALLY SATURATED LAYERS.
  201 KT=0
      DO 300 K=1,NLAY
C
```

```
C7------SEE IF CORRECTION IS NEEDED FOR LEAKAGE FROM ABOVE.
      IF(LAYCON(K).NE.3 .AND. LAYCON(K).NE.2) GO TO 250
      KT=KT+1
      IF(K.EQ.1) GO TO 250
C
C7A-----FOR EACH CELL MAKE THE CORRECTION IF NEEDED.
      DO 220 I=1,NROW
      DO 220 J=1,NCOL
C
C7B-----IF THE CELL IS EXTERNAL(IBOUND<=0) THEN SKIP IT.
      IF(IBOUND(J,I,K).LE.0) GO TO 220
      HTMP=HNEW(J,I,K)
C
C7C-----IF HEAD IS ABOVE TOP THEN CORRECTION NOT NEEDED
      IF(HTMP.GE.TOP(J,I,KT)) GO TO 220
C
C7D-----WITH HEAD BELOW TOP ADD CORRECTION TERMS TO RHS.
      RHS(J,I,K)=RHS(J,I,K) + CV(J,I,K-1)*(TOP(J,I,KT)-HTMP)
  220 CONTINUE
C
C8------SEE IF THIS LAYER MAY NEED CORRECTION FOR LEAKAGE TO BELOW.
  250 IF(K.EQ.NLAY) GO TO 300
      IF(LAYCON(K+1).NE.3 .AND. LAYCON(K+1).NE.2) GO TO 300
      KTT=KT+1
C
C8A-----FOR EACH CELL MAKE THE CORRECTION IF NEEDED.
      DO 280 I=1,NROW
      DO 280 J=1,NCOL
C
C8B-----IF CELL IS EXTERNAL (IBOUND<=0) THEN SKIP IT.
      IF(IBOUND(J,I,K).LE.0) GO TO 280
C
C8C-----IF HEAD IN THE LOWER CELL IS LESS THAN TOP ADD CORRECTION
C8C-----TERM TO RHS.
      HTMP=HNEW(J,I,K+1)
      IF(HTMP.LT.TOP(J,I,KTT)) RHS(J,I,K)=RHS(J,I,K)
     1                         - CV(J,I,K)*(TOP(J,I,KTT)-HTMP)
  280 CONTINUE
  300 CONTINUE
C
C9------RETURN
      RETURN
      END
```

```
      SUBROUTINE SBCF1B(HNEW,IBOUND,CR,CC,CV,TOP,NCOL,NROW,NLAY,
     1      KSTP,KPER,IBCFCB,BUFF,IOUT)
C
C-----VERSION 1548 12MAY1987 SBCF1B
C
C     ******************************************************************
C     COMPUTE FLOW ACROSS EACH CELL WALL
C     ******************************************************************
C
C     SPECIFICATIONS:
C     ------------------------------------------------------------------
      CHARACTER*4 TEXT
      DOUBLE PRECISION HNEW,HD
C
      DIMENSION HNEW(NCOL,NROW,NLAY), IBOUND(NCOL,NROW,NLAY),
     1     CR(NCOL,NROW,NLAY), CC(NCOL,NROW,NLAY),
     2     CV(NCOL,NROW,NLAY), TOP(NCOL,NROW,NLAY),
     3     BUFF(NCOL,NROW,NLAY)
C
      COMMON /FLWCOM/LAYCON(80)
C
      DIMENSION TEXT(12)
C
      DATA TEXT(1),TEXT(2),TEXT(3),TEXT(4),TEXT(5),TEXT(6),TEXT(7),
     1  TEXT(8),TEXT(9),TEXT(10),TEXT(11),TEXT(12)
     2  /'FLOW',' RIG','HT F','ACE ',
     2   'FLOW',' FRO','NT F','ACE ','FLOW',' LOW','ER F','ACE '/
C     ------------------------------------------------------------------
C
      NCM1=NCOL-1
      IF(NCM1.LT.1) GO TO 405
C
C1-----CLEAR THE BUFFER
      DO 310 K=1,NLAY
      DO 310 I=1,NROW
      DO 310 J=1,NCOL
      BUFF(J,I,K)=0.
  310 CONTINUE
C
C2-----FOR EACH CELL CALCULATE FLOW THRU RIGHT FACE & STORE IN BUFFER
      DO 400 K=1,NLAY
      DO 400 I=1,NROW
      DO 400 J=1,NCM1
      IF((IBOUND(J,I,K).LE.0) .AND. (IBOUND(J+1,I,K).LE.0)) GO TO 400
      HDIFF=HNEW(J,I,K)-HNEW(J+1,I,K)
      BUFF(J,I,K)=HDIFF*CR(J,I,K)
  400 CONTINUE
C
C3-----RECORD CONTENTS OF BUFFER
```

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```
      CALL UBUDSV(KSTP,KPER,TEXT(1),IBCFCB,BUFF,NCOL,NROW,NLAY,IOUT)
C
C4-----CLEAR THE BUFFER
  405 NRM1=NROW-1
      IF(NRM1.LT.1) GO TO 505
      DO 410 K=1,NLAY
      DO 410 I=1,NROW
      DO 410 J=1,NCOL
      BUFF(J,I,K)=0.
  410 CONTINUE
C
C5-----FOR EACH CELL CALCULATE FLOW THRU FRONT FACE & STORE IN BUFFER
      DO 500 K=1,NLAY
      DO 500 I=1,NRM1
      DO 500 J=1,NCOL
      IF((IBOUND(J,I,K).LE.0) .AND. (IBOUND(J,I+1,K).LE.0)) GO TO 500
      HDIFF=HNEW(J,I,K)-HNEW(J,I+1,K)
      BUFF(J,I,K)=HDIFF*CC(J,I,K)
  500 CONTINUE
C
C6-----RECORD CONTENTS OF BUFFER.
      CALL UBUDSV(KSTP,KPER,TEXT(5),IBCFCB,BUFF,NCOL,NROW,NLAY,IOUT)
  505 NLM1=NLAY-1
      IF(NLM1.LT.1) GO TO 1000
C
C7-----CLEAR THE BUFFER
      DO 510 K=1,NLAY
      DO 510 I=1,NROW
      DO 510 J=1,NCOL
      BUFF(J,I,K)=0.
  510 CONTINUE
C
C8-----FOR EACH CELL CALCULATE FLOW THRU LOWER FACE & STORE IN BUFFER
      KT=0
      DO 600 K=1,NLM1
      IF(LAYCON(K).EQ.3 .OR. LAYCON(K).EQ.2) KT=KT+1
      DO 600 I=1,NROW
      DO 600 J=1,NCOL
      IF((IBOUND(J,I,K).LE.0) .AND. (IBOUND(J,I,K+1).LE.0)) GO TO 600
      HD=HNEW(J,I,K+1)
      IF(LAYCON(K+1).NE.3 .AND. LAYCON(K+1).NE.2) GO TO 580
      TMP=HD
      IF(TMP.LT.TOP(J,I,KT+1)) HD=TOP(J,I,KT+1)
cmz---
      IF(hnew(j,i,k).lt.top(j,i,kt+1)) hd=hnew(j,i,k)
cmz---
  580 HDIFF=HNEW(J,I,K)-HD
      BUFF(J,I,K)=HDIFF*CV(J,I,K)
  600 CONTINUE
```

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```
C
C9-----RECORD CONTENTS OF BUFFER.
      CALL UBUDSV(KSTP,KPER,TEXT(9),IBCFCB,BUFF,NCOL,NROW,NLAY,IOUT)
C
C10----RETURN
 1000 RETURN
      END
```

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```
      SUBROUTINE SBCF2H(HNEW,IBOUND,CR,CC,CV,HY,TRPY,DELR,DELC
     1,BOT,TOP,K,KB,KT,KITER,KSTP,KPER,NCOL,NROW,NLAY,IOUT
     2,WETDRY,IWDFLG,CVWD,WETFCT,IWETIT,IHDWET,HDRY)
C-----VERSION 1345 23MAY1991 SBCF2H
C
C     ******************************************************************
C     COMPUTE CONDUCTANCE FOR ONE LAYER FROM SATURATED THICKNESS AND
C     HYDRAULIC CONDUCTIVITY, VERSION 2
C     ******************************************************************
C
C      SPECIFICATIONS:
C     ------------------------------------------------------------------
      DOUBLE PRECISION HNEW
C
      DIMENSION HNEW(NCOL,NROW,NLAY),IBOUND(NCOL,NROW,NLAY)
     1,CR(NCOL,NROW,NLAY), CC(NCOL,NROW,NLAY), CV(NCOL,NROW,NLAY)
     2,HY(NCOL,NROW,NLAY), TRPY(NLAY), DELR(NCOL), DELC(NROW)
     3,BOT(NCOL,NROW,NLAY),TOP(NCOL,NROW,NLAY),WETDRY(NCOL,NROW,NLAY)
     4,CVWD(NCOL,NROW,NLAY)
      CHARACTER*4 ACNVRT
      DIMENSION ICNVRT(8),JCNVRT(8),ACNVRT(8)
C
      COMMON /FLWCOM/LAYCON(80)
cmz---
      common /cvcom/cvlbry(223,76,2)
cmz---
C     ------------------------------------------------------------------
C
C1------LOOP THROUGH EACH CELL IN LAYER AND CALCULATE TRANSMISSIVITY AT
C1------EACH ACTIVE CELL.
      NCNVRT=0
      IHDCNV=0
      ITFLG=1
      IF(IWDFLG.NE.0) ITFLG=MOD(KITER,IWETIT)
      DO 200 I=1,NROW
      DO 200 J=1,NCOL
C
C2------IF CELL IS ACTIVE, THEN SKIP TO CODE THAT CALCULATES SATURATED
C2------THICKNESS.
      IF(IBOUND(J,I,K).NE.0) GO TO 20
C
C3------DETERMINE IF THE CELL CAN CONVERT BETWEEN CONFINED AND
C3------UNCONFINED.  IF NOT, SKIP TO CODE THAT SETS TRANSMISSIVITY TO 0.
      IF(ITFLG.NE.0) GO TO 6
      IF(WETDRY(J,I,KB).EQ.0.0)GO TO 6
      WD=WETDRY(J,I,KB)
      IF(WD.LT.0.) WD=-WD
      TURNON=BOT(J,I,KB)+WD
C
```

```
C3A-----CHECK HEAD IN CELL BELOW TO SEE IF WETTING THRESHOLD HAS BEEN
C3A-----REACHED.
      IF(K.EQ.NLAY)GO TO 2
      HTMP=HNEW(J,I,K+1)
      IF(IBOUND(J,I,K+1).GT.0.AND.HTMP.GE.TURNON)GO TO 9
C
C3B-----CHECK HEAD IN ADJACENT HORIZONTAL CELLS TO SEE IF WETTING
C3B-----THRESHOLD HAS BEEN REACHED.
    2 IF(WETDRY(J,I,KB).LT.0.) GO TO 6
      IF(J.EQ.1)GO TO 3
      HTMP=HNEW(J-1,I,K)
      IF(IBOUND(J-1,I,K).GT.0.AND.IBOUND(J-1,I,K).NE.30000.AND.
     1                          HTMP.GE.TURNON)GO TO 9
    3 IF(J.EQ.NCOL)GO TO 4
      HTMP=HNEW(J+1,I,K)
      IF(IBOUND(J+1,I,K).GT.0.AND.HTMP.GE.TURNON)GO TO 9
    4 IF(I.EQ.1)GO TO 5
      HTMP=HNEW(J,I-1,K)
      IF(IBOUND(J,I-1,K).GT.0.AND.IBOUND(J,I-1,K).NE.30000.AND.
     1                           HTMP.GE.TURNON)GO TO 9
    5 IF(I.EQ.NROW)GO TO 6
      HTMP=HNEW(J,I+1,K)
      IF(IBOUND(J,I+1,K).GT.0.AND.HTMP.GE.TURNON)GO TO 9
C
C3C-----CELL IS DRY AND STAYS DRY.  SET TRANSMISSIVITY TO 0 AND SKIP
C3C-----TO THE NEXT CELL.
    6 CC(J,I,K)=0.
      GO TO 200
C
C4------CELL BECOMES WET.  SET INITIAL HEAD AND VERTICAL CONDUCTANCE.
    9 IF(IHDWET.NE.0) HNEW(J,I,K)=BOT(J,I,KB)+WETFCT*WD
      IF(IHDWET.EQ.0) HNEW(J,I,K)=BOT(J,I,KB)+WETFCT*(HTMP-BOT(J,I,KB))
      IF(K.EQ.NLAY) GO TO 12
      IF(IBOUND(J,I,K+1).NE.0) CV(J,I,K)= CVWD(J,I,K)
   12 IF(K.EQ.1) GO TO 14
      IF(IBOUND(J,I,K-1).NE.0) CV(J,I,K-1)= CVWD(J,I,K-1)
   14 IBOUND(J,I,K)=30000
C
C4A-----PRINT MESSAGE SAYING CELL HAS BEEN CONVERTED TO WET.
      NCNVRT=NCNVRT+1
      ICNVRT(NCNVRT)=I
      JCNVRT(NCNVRT)=J
      ACNVRT(NCNVRT)=' WET'
      IF(NCNVRT.LT.8) GO TO 20
         IF(IHDCNV.EQ.0) WRITE(IOUT,17) KITER,K,KSTP,KPER
   17    FORMAT(1H0,'CELL CONVERSIONS FOR ITERATION=',I3,'  LAYER=',
     1    I2,'  TIME STEP=',I3,'  STRESS PERIOD=',I3,'     (ROW,COL)')
         IHDCNV=1
         WRITE(IOUT,18) (ACNVRT(L),ICNVRT(L),JCNVRT(L),L=1,NCNVRT)
```

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```
   18     FORMAT(1X,8(A4,'(',I3,',',I3,')   '))
          NCNVRT=0
C
C5------CALCULATE SATURATED THICKNESS.
   20 HD=HNEW(J,I,K)
      IF(LAYCON(K).EQ.1) GO TO 50
      IF(HD.GT.TOP(J,I,KT)) HD=TOP(J,I,KT)
   50 THCK=HD-BOT(J,I,KB)
cmz.......A threshod is set for recalculate vertical conductance
      if(thck.gt.1.0) then
        cv(j,i,kb) = cvlbry(j,i,kb)
      endif
cmz.. --Modification was according to John Dorherty in James Cook Univ. in Alstralia
      IF(THCK.LE.0.1) then
        THCK = 0.1
        cv(j,i,kb) = 0.0
      endif
cmz...
C
C6------CHECK TO SEE IF SATURATED THICKNESS IS GREATER THAN ZERO.
      IF(THCK.LE.0.) GO TO 100
C
C6A-----IF SATURATED THICKNESS>0 THEN TRANSMISSIVITY IS HYDRAULIC
C6A-----CONDUCTIVITY TIMES SATURATED THICKNESS.
      CC(J,I,K)=THCK*HY(J,I,KB)
      GO TO 200
C
C6B-----WHEN SATURATED THICKNESS < 0, PRINT A MESSAGE AND SET
C6B-----TRANSMISSIVITY, IBOUND, AND VERTICAL CONDUCTANCE =0
  100 NCNVRT=NCNVRT+1
      ICNVRT(NCNVRT)=I
      JCNVRT(NCNVRT)=J
      ACNVRT(NCNVRT)=' DRY'
      IF(NCNVRT.LT.8) GO TO 150
         IF(IHDCNV.EQ.0) WRITE(IOUT,17) KITER,K,KSTP,KPER
         IHDCNV=1
         WRITE(IOUT,18) (ACNVRT(L),ICNVRT(L),JCNVRT(L),L=1,NCNVRT)
         NCNVRT=0
  150 HNEW(J,I,K)=HDRY
      CC(J,I,K)=0.
      IF(IBOUND(J,I,K).GE.0) GO TO 160
         WRITE(IOUT,151)
  151    FORMAT(1H0,'CONSTANT-HEAD CELL WENT DRY -- SIMULATION ABORTED')
         WRITE(IOUT,152) K,I,J,KITER,KSTP,KPER
  152    FORMAT(1X,'LAYER=',I2,'   ROW=',I3,'   COLUMN=',I3,
     1    '   ITERATION=',I3,'   TIME STEP=',I3,'   STRESS PERIOD=',I3)
         STOP
  160 IBOUND(J,I,K)=0
      IF(K.LT.NLAY) CV(J,I,K)=0.
```

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```
      IF(K.GT.1) CV(J,I,K-1)=0.
  200 CONTINUE
C
C7------PRINT ANY REMAINING CELL CONVERSIONS NOT YET PRINTED
      IF(NCNVRT.EQ.0) GO TO 203
         IF(IHDCNV.EQ.0) WRITE(IOUT,17) KITER,K,KSTP,KPER
         IHDCNV=1
         WRITE(IOUT,18) (ACNVRT(L),ICNVRT(L),JCNVRT(L),L=1,NCNVRT)
         NCNVRT=0
C
C8------CHANGE IBOUND VALUE FOR CELLS THAT CONVERTED TO WET THIS
C8------ITERATION FROM 30000 to 1.
  203 IF(IWDFLG.EQ.0) GO TO 210
      DO 205 I=1,NROW
      DO 205 J=1,NCOL
      IF(IBOUND(J,I,K).EQ.30000) IBOUND(J,I,K)=1
  205 CONTINUE
C
C9------COMPUTE HORIZONTAL BRANCH CONDUCTANCES FROM TRANSMISSIVITY.
  210 CALL SBCF1C(CR,CC,TRPY,DELR,DELC,K,NCOL,NROW,NLAY)
C
C10-----RETURN
      RETURN
      END
```

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```
      SUBROUTINE SBCF2N(HNEW,IBOUND,SC1,SC2,CR,CC,CV,HY,TRPY,DELR,DELC,
     1    ISS,NCOL,NROW,NLAY,IOUT,WETDRY,IWDFLG,CVWD)
C
C-----VERSION 1107 5MAY1991 SBCF2N
C
C     ******************************************************************
C     INITIALIZE AND CHECK BCF DATA, VERSION 2
C     ******************************************************************
C
C        SPECIFICATIONS:
C     ------------------------------------------------------------------
C
      DOUBLE PRECISION HNEW,HCNV
C
      DIMENSION HNEW(NCOL,NROW,NLAY),IBOUND(NCOL,NROW,NLAY)
     1    ,SC1(NCOL,NROW,NLAY),CR(NCOL,NROW,NLAY)
     2    ,CC(NCOL,NROW,NLAY),CV(NCOL,NROW,NLAY)
     3    ,HY(NCOL,NROW,NLAY),TRPY(NLAY),DELR(NCOL),DELC(NROW)
     4    ,SC2(NCOL,NROW,NLAY),WETDRY(NCOL,NROW,NLAY)
     5    ,CVWD(NCOL,NROW,NLAY)
C
      COMMON /FLWCOM/LAYCON(80)
cmz---
      common /cvcom/cvlbry(223,76,2)
cmz---
C     ------------------------------------------------------------------
C
C1------MULTIPLY VERTICAL LEAKANCE BY AREA TO MAKE CONDUCTANCE
      IF(NLAY.EQ.1) GO TO 20
      K1=NLAY-1
      DO 10 K=1,K1
      DO 10 I=1,NROW
      DO 10 J=1,NCOL
      CV(J,I,K)=CV(J,I,K)*DELR(J)*DELC(I)
   10 CONTINUE
C
C2------IF WETTING CAPABILITY IS ACTIVATED, SAVE CV IN CVWD FOR USE WHEN
C2------WETTING CELLS.
      IF(IWDFLG.EQ.0) GO TO 20
      DO 15 K=1,K1
      DO 15 I=1,NROW
      DO 15 J=1,NCOL
      CVWD(J,I,K)=CV(J,I,K)
   15 CONTINUE
C
C3------IF IBOUND=0, SET CV=0 AND CC=0.
   20 DO 30 K=1,NLAY
      DO 30 I=1,NROW
      DO 30 J=1,NCOL
```

```
      IF(IBOUND(J,I,K).NE.0) GO TO 30
      IF(K.NE.NLAY) CV(J,I,K)=0.
      IF(K.NE.1) CV(J,I,K-1)=0.
      CC(J,I,K)=0.
   30 CONTINUE
C
C4------INSURE THAT EACH ACTIVE CELL HAS AT LEAST ONE NON-ZERO
C4------TRANSMISSIVE PARAMETER.
      HCNV=888.88
      KB=0
      DO 60 K=1,NLAY
      IF(LAYCON(K).EQ.1 .OR. LAYCON(K).EQ.3) GO TO 50
C
C4A-----WHEN LAYER TYPE IS 0 OR 2, TRANSMISSIVITY OR CV MUST BE NONZERO
      DO 45 I=1,NROW
      DO 45 J=1,NCOL
      IF(IBOUND(J,I,K).EQ.0) GO TO 45
      IF(CC(J,I,K).NE.0.) GO TO 45
      IF(K.EQ.NLAY) GO TO 41
      IF(CV(J,I,K).NE.0.) GO TO 45
   41 IF(K.EQ.1) GO TO 42
      IF(CV(J,I,K-1).NE.0.) GO TO 45
   42 IBOUND(J,I,K)=0
      HNEW(J,I,K)=HCNV
      WRITE(IOUT,43) K,I,J
   43 FORMAT(1X,'NODE (LAYER,ROW,COL)',3I4,
     1      ' ELIMINATED BECAUSE ALL CONDUCTANCES TO NODE ARE 0')
   45 CONTINUE
      GO TO 60
C
C4B-----WHEN LAYER TYPE IS 1 OR 3, HY OR CV MUST BE NONZERO
   50 KB=KB+1
      DO 59 I=1,NROW
      DO 59 J=1,NCOL
C
C4B1----IF WETTING CAPABILITY IS ACTIVE, CHECK CVWD
      IF(IWDFLG.EQ.0) GO TO 55
      IF(WETDRY(J,I,KB).EQ.0.) GO TO 55
      IF(K.EQ.NLAY) GO TO 51
      IF(CVWD(J,I,K).NE.0.) GO TO 59
   51 IF(K.EQ.1) GO TO 57
      IF(CV(J,I,K-1).NE.0.) GO TO 59
C
C4B2----WETTING CAPABILITY IS INACTIVE, SO CHECK CV AT ACTIVE CELLS
   55 IF(IBOUND(J,I,K).EQ.0) GO TO 59
      IF(K.EQ.NLAY) GO TO 56
      IF(CV(J,I,K).NE.0.) GO TO 59
   56 IF(K.EQ.1) GO TO 57
      IF(CV(J,I,K-1).NE.0.) GO TO 59
```

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```
C
C4B3----CHECK HYDRAULIC CONDUCTIVITY
   57 IF(HY(J,I,KB).NE.0.) GO TO 59
C
C4B4----HY AND CV ARE ALL 0, SO CONVERT CELL TO NO FLOW
      IBOUND(J,I,K)=0
      HNEW(J,I,K)=HCNV
      IF(IWDFLG.NE.0) WETDRY(J,I,KB)=0.
      WRITE(IOUT,43) K,I,J
   59 CONTINUE
   60 CONTINUE
C
C5------CALCULATE HOR. CONDUCTANCE(CR AND CC) FOR CONSTANT T LAYERS
      DO 70 K=1,NLAY
      KK=K
      IF(LAYCON(K).EQ.3 .OR. LAYCON(K).EQ.1) GO TO 70
      CALL SBCF1C(CR,CC,TRPY,DELR,DELC,KK,NCOL,NROW,NLAY)
   70 CONTINUE
C
C6------IF TRANSIENT, LOOP THROUGH LAYERS AND CALCULATE STORAGE CAPACITY
      IF(ISS.NE.0) GO TO 100
      KT=0
      DO 90 K=1,NLAY
C
C6A-----MULTIPLY PRIMARY STORAGE COEFFICIENT BY DELR & DELC TO GET
C6A-----PRIMARY STORAGE CAPACITY.
      DO 80 I=1,NROW
      DO 80 J=1,NCOL
      SC1(J,I,K)=SC1(J,I,K)*DELR(J)*DELC(I)
   80 CONTINUE
C
C6B-----IF LAYER IS CONF/UNCONF MULTIPLY SECONDARY STORAGE COEFFICIENT
C6B-----BY DELR AND DELC TO GET SECONDARY STORAGE CAPACITY(SC2).
      IF(LAYCON(K).NE.3 .AND. LAYCON(K).NE.2) GO TO 90
      KT=KT+1
      DO 85 I=1,NROW
      DO 85 J=1,NCOL
      SC2(J,I,KT)=SC2(J,I,KT)*DELR(J)*DELC(I)
   85 CONTINUE
   90 CONTINUE
C

cmz-----store vertical conductance in a libray array cvlbry
      IF(NLAY.EQ.1) GO TO 100
      K1=NLAY-1
      DO 110 K=1,K1
      DO 110 I=1,NROW
      DO 110 J=1,NCOL
      cvlbry(J,I,K)=CV(J,I,K)
```

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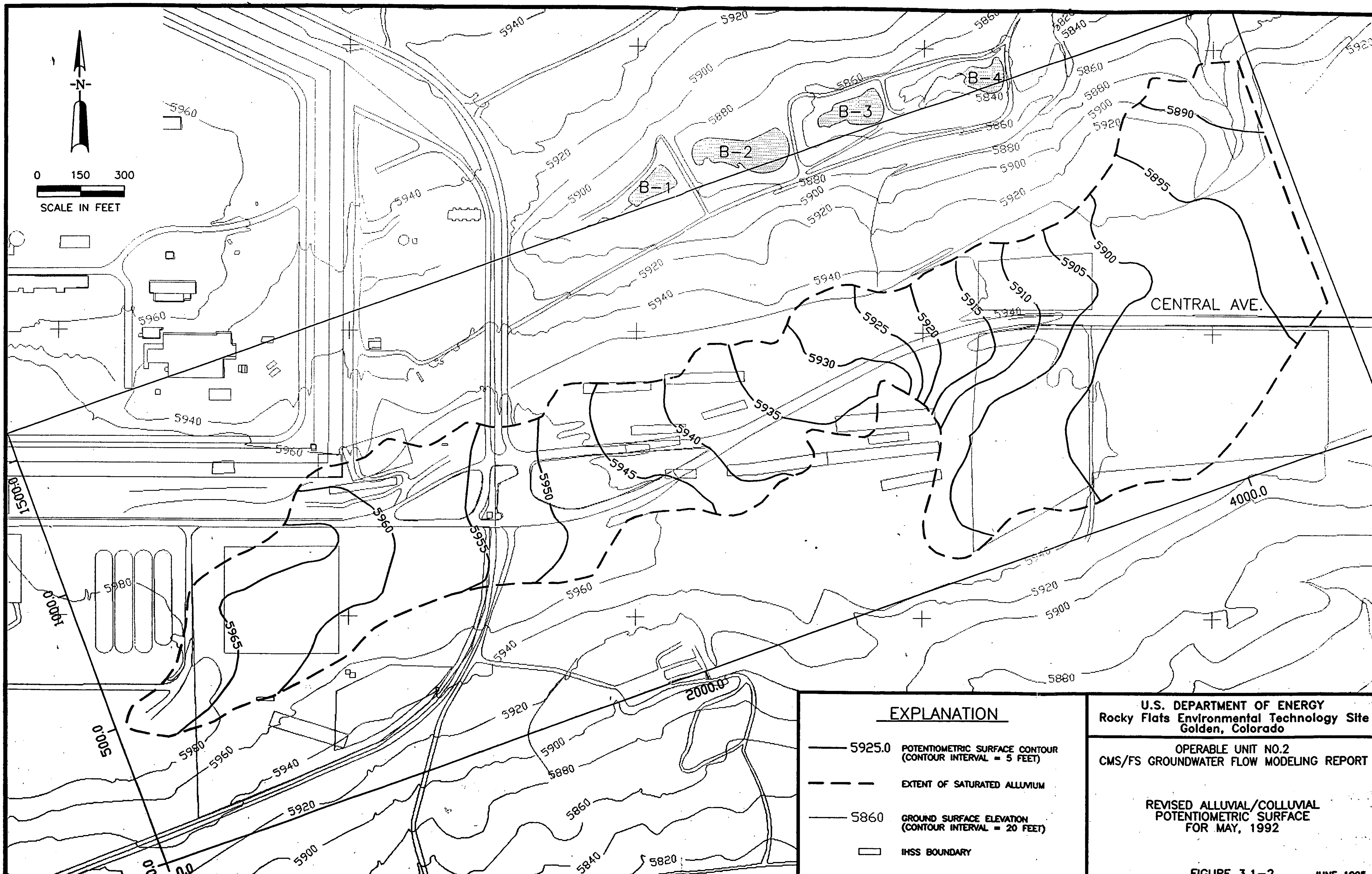
```
  110 CONTINUE
cmz---
C
C7------RETURN
  100 RETURN
      END
```

186/186



EXPLANATION

5925.0 POTENTIOMETRIC SURFACE CONTOUR (CONTOUR INTERVAL = 5 FEET)

EXTENT OF SATURATED ALLUVIUM

5860 GROUND SURFACE ELEVATION (CONTOUR INTERVAL = 20 FEET)

IHSS BOUNDARY

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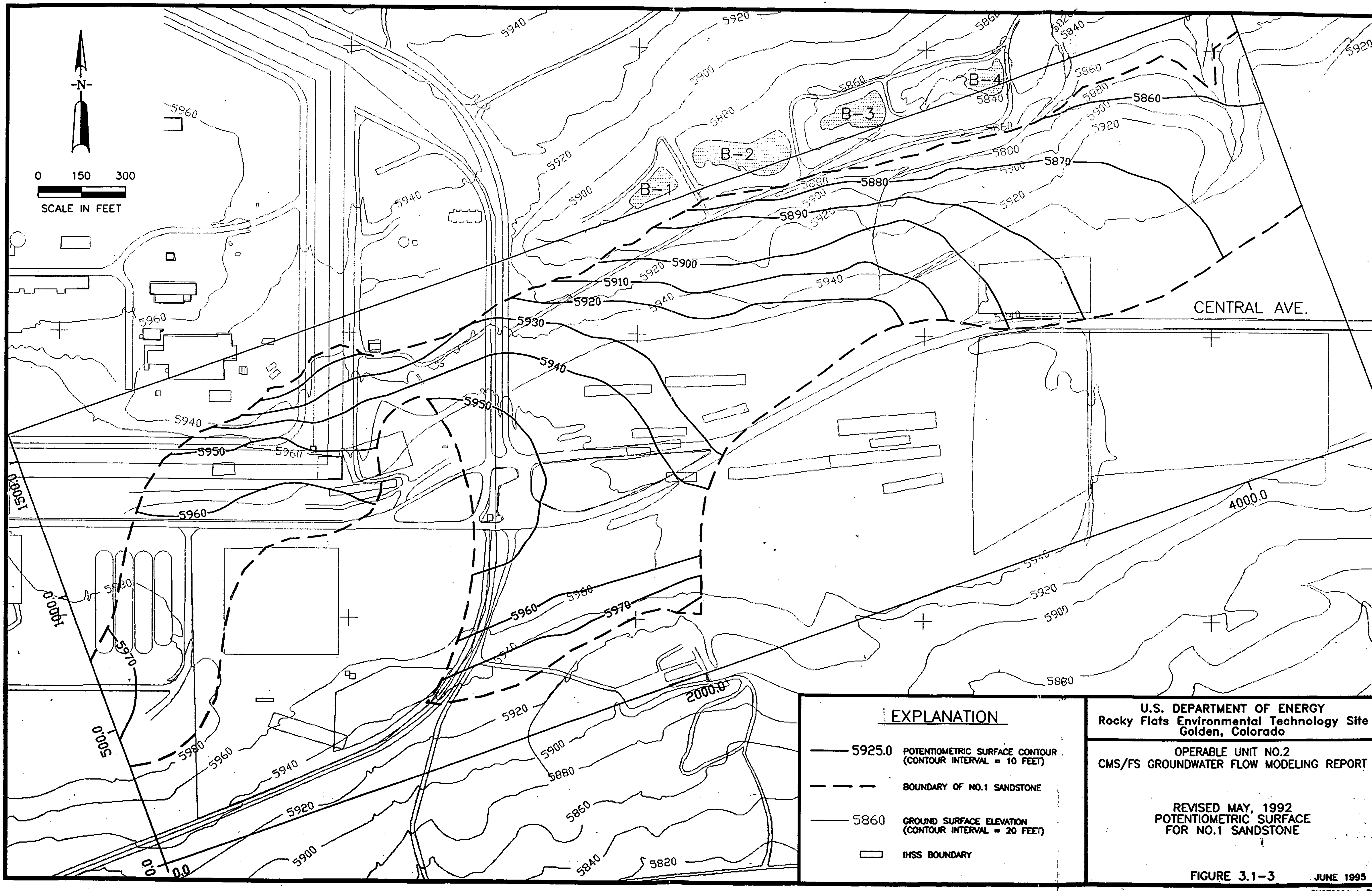
REVISED ALLUVIAL/COLLUVIAL POTENTIOMETRIC SURFACE FOR MAY, 1992

FIGURE 3.1-2

JUNE 1995

OU2FS002 1=300

32


-N-
0 150 300
SCALE IN FEET
CENTRAL AVE.
B-1
B-2
B-3
B-4
5960
5940
5920
5900
5880
5870
5860
5840
5820
5890
5910
5930
5950
5970
5980
0.0
500.0
1000.0
1500.0
2000.0
4000.0
EXPLANATION
5925.0 POTENTIOMETRIC SURFACE CONTOUR (CONTOUR INTERVAL = 10 FEET)
BOUNDARY OF NO.1 SANDSTONE
5860 GROUND SURFACE ELEVATION (CONTOUR INTERVAL = 20 FEET)
IHSS BOUNDARY
U.S. DEPARTMENT OF ENERGY
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Golden, Colorado
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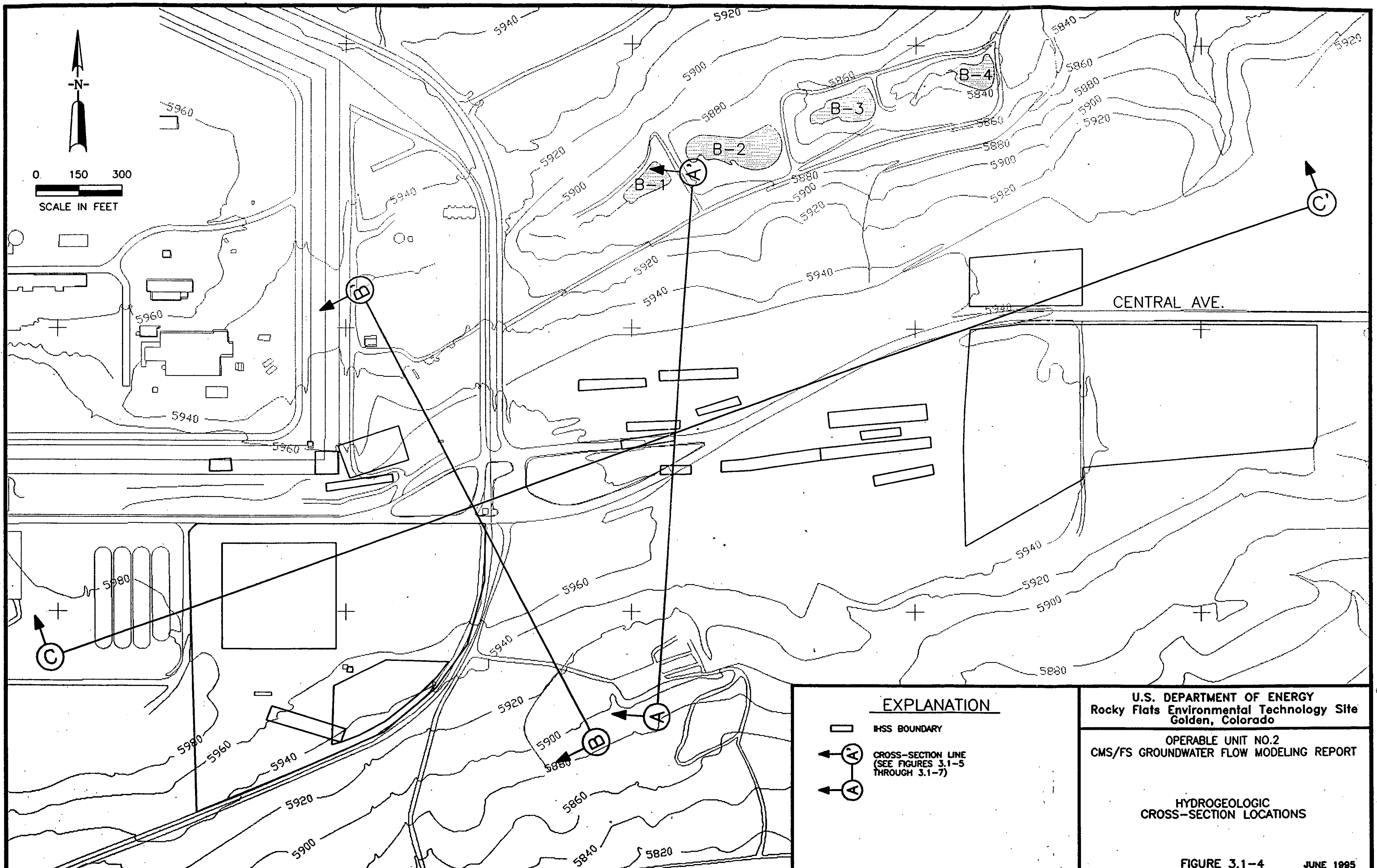
REVISED MAY, 1992
POTENTIOMETRIC SURFACE
FOR NO.1 SANDSTONE
FIGURE 3.1-3
JUNE 1995
0U2FS004 1=300

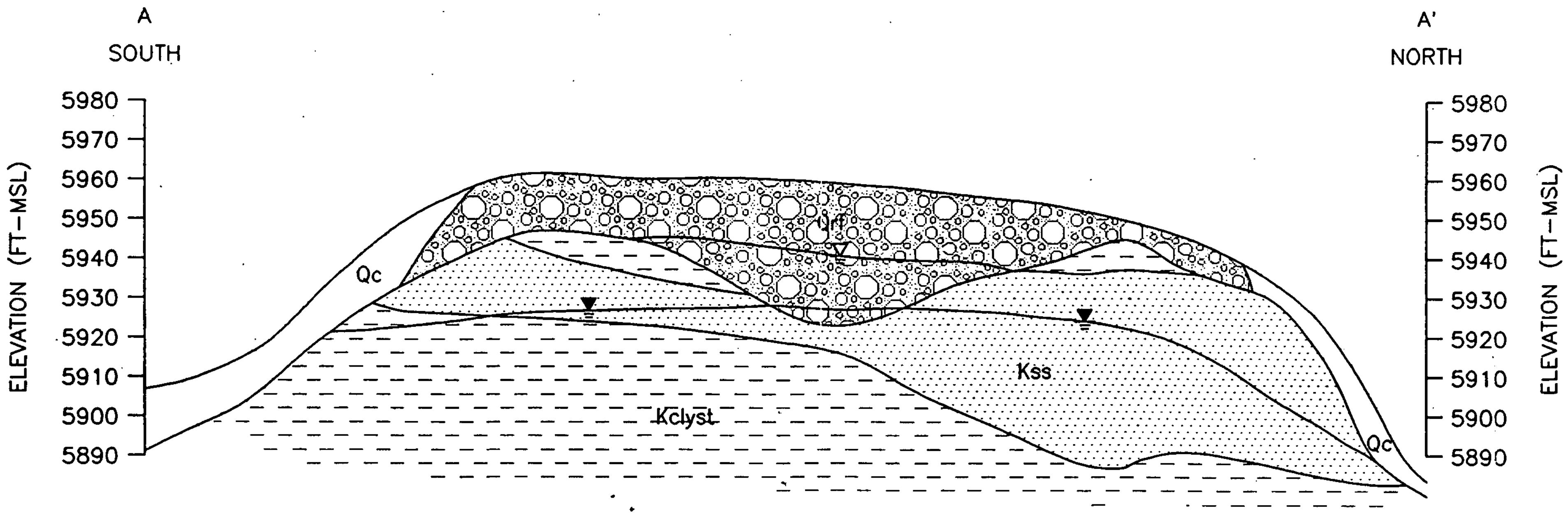
33

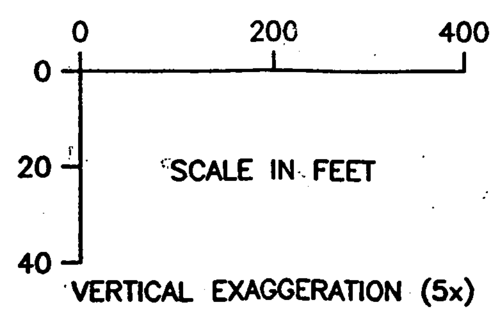


HYDROGEOLOGIC CROSS-SECTION LOCATIONS

FIGURE 3.1-4

OU2FS040 1=300





EXPLANATION

- Qc COLLUVIUM
- Qrf ROCKY FLATS ALLUVIUM
- Kss ARAPAHOE NO.1 SANDSTONE
- Kclyst ARAPAHOE/LARAMIE CLAYSTONE
- ALLUVIAL POTENTIOMETRIC SURFACE
- NO.1 SANDSTONE POTENTIOMETRIC SURFACE

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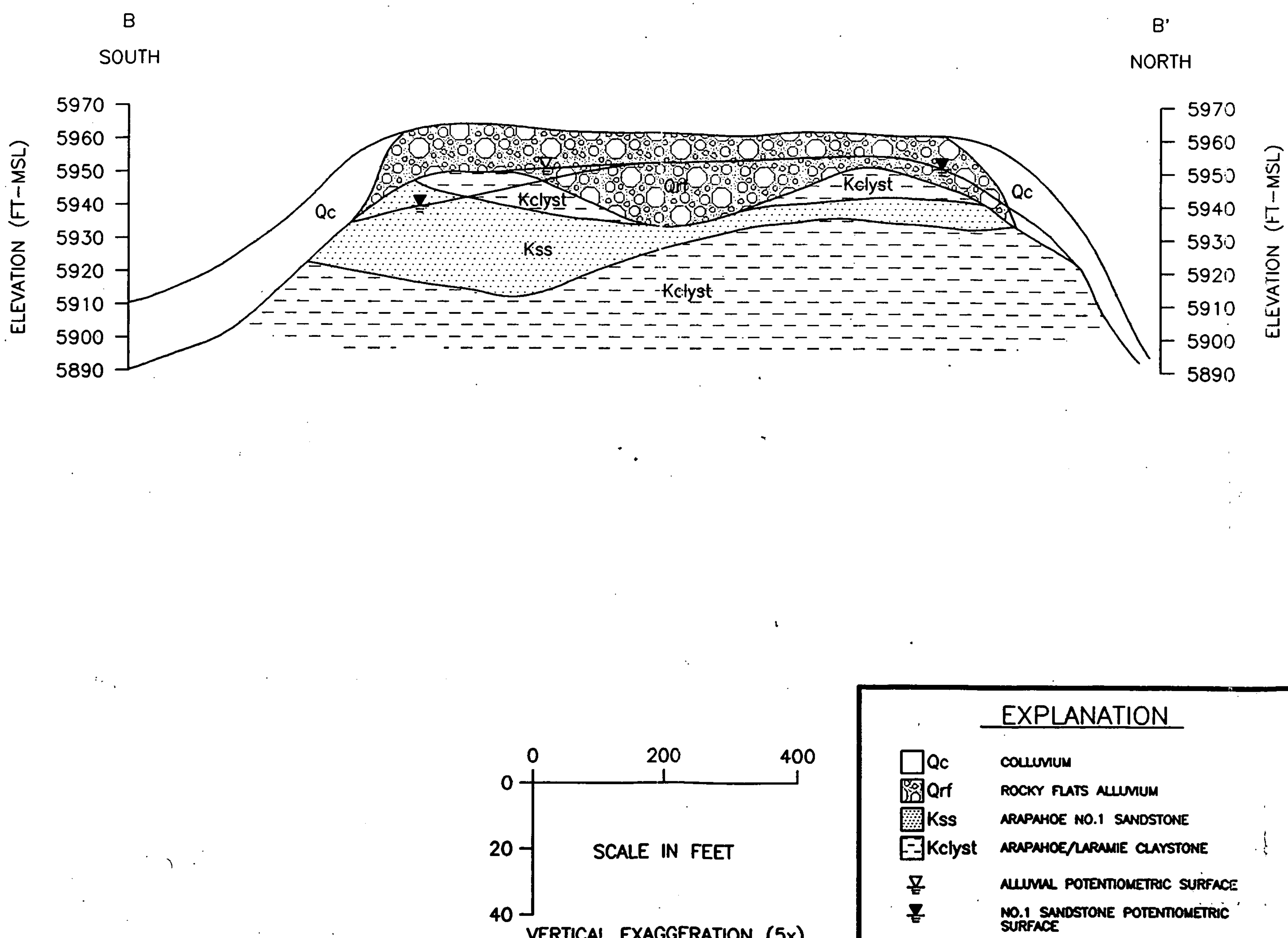
HYDROGEOLOGIC
CROSS SECTION A–A'

FIGURE 3.1–5 JUNE 1995

OU2FS035 1=1



EXPLANATION

- Qc COLLUVIUM
- Qrf ROCKY FLATS ALLUVIUM
- Kss ARAPAHOE NO.1 SANDSTONE
- Kclyst ARAPAHOE/LARAMIE CLAYSTONE
- ALLUVIAL POTENTIOMETRIC SURFACE
- NO.1 SANDSTONE POTENTIOMETRIC SURFACE

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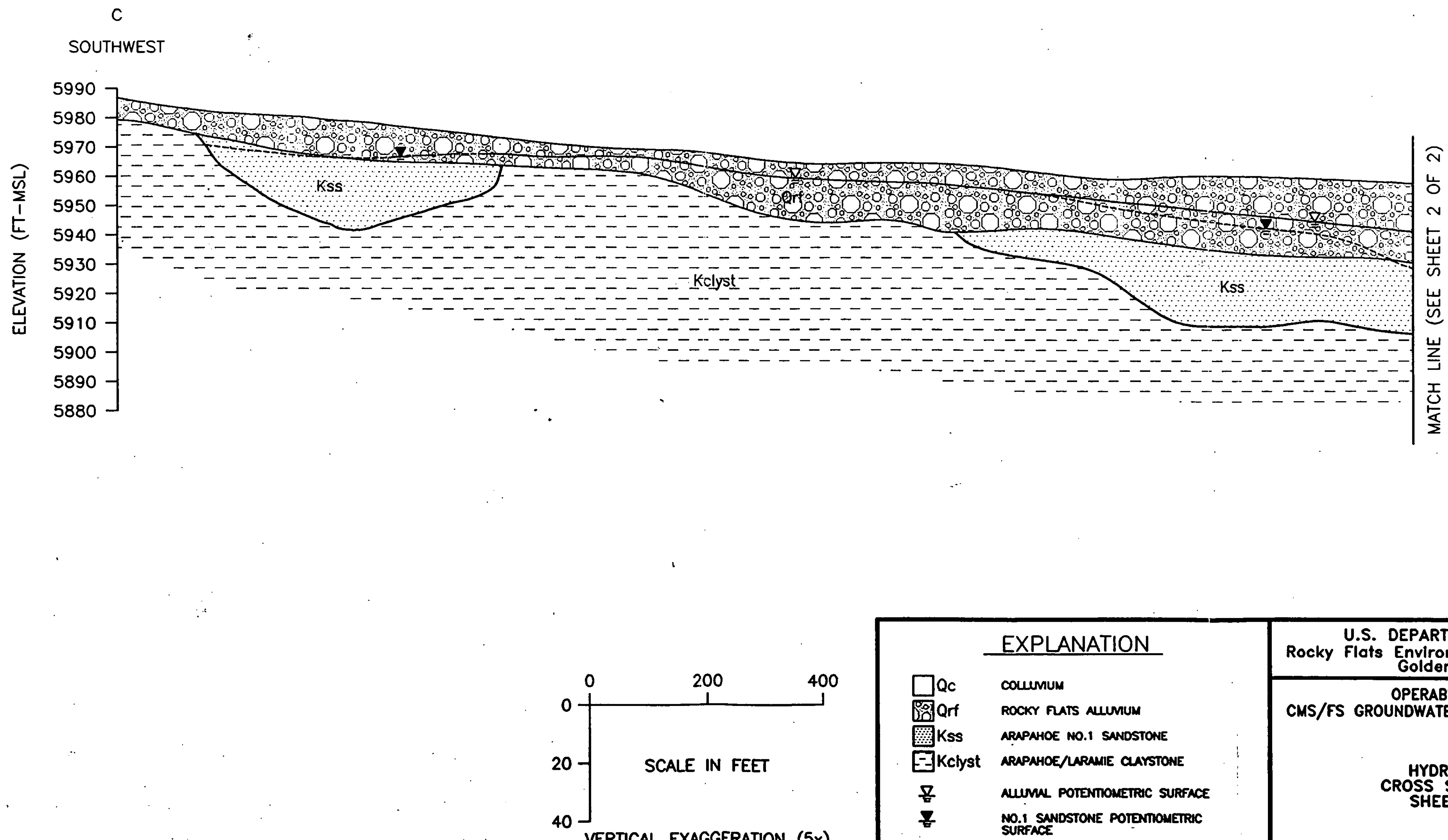
HYDROGEOLOGIC CROSS SECTION B-B'

FIGURE 3.1-6 JUNE 1995

OU2FS036 1=1

36



EXPLANATION

Qc	COLLUVIUM
Qrf	ROCKY FLATS ALLUVIUM
Kss	ARAPAHOE NO.1 SANDSTONE
Kclyst	ARAPAHOE/LARAMIE CLAYSTONE
∇	ALLUVIAL POTENTIOMETRIC SURFACE
▼	NO.1 SANDSTONE POTENTIOMETRIC SURFACE

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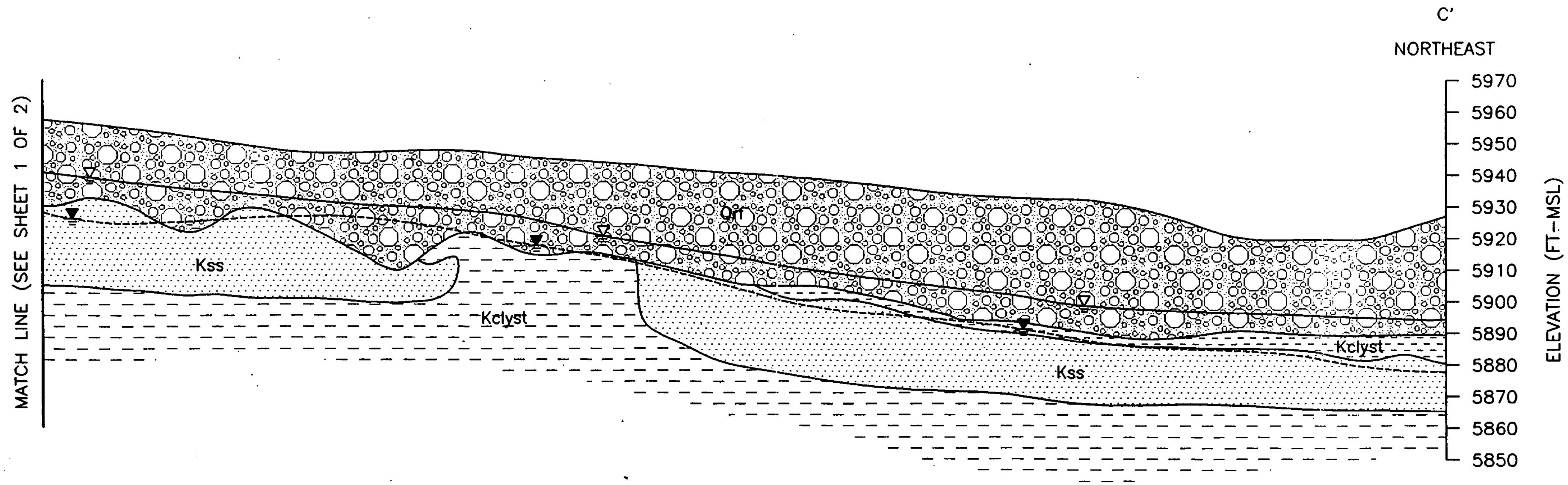
HYDROGEOLOGIC
CROSS SECTION C–C'
SHEET 1 OF 2

FIGURE 3.1–7

JUNE 1995

OU2FS037 1=1

37



0 200 400

0 20 40

SCALE IN FEET

VERTICAL EXAGGERATION (5x)

EXPLANATION

Qc	COLLUVIUM
Qrf	ROCKY FLATS ALLUVIUM
Kss	ARAPAHOE NO.1 SANDSTONE
Kclyst	ARAPAHOE/LARAMIE CLAYSTONE
▽	ALLUVIAL POTENTIOMETRIC SURFACE
▼	NO.1 SANDSTONE POTENTIOMETRIC SURFACE

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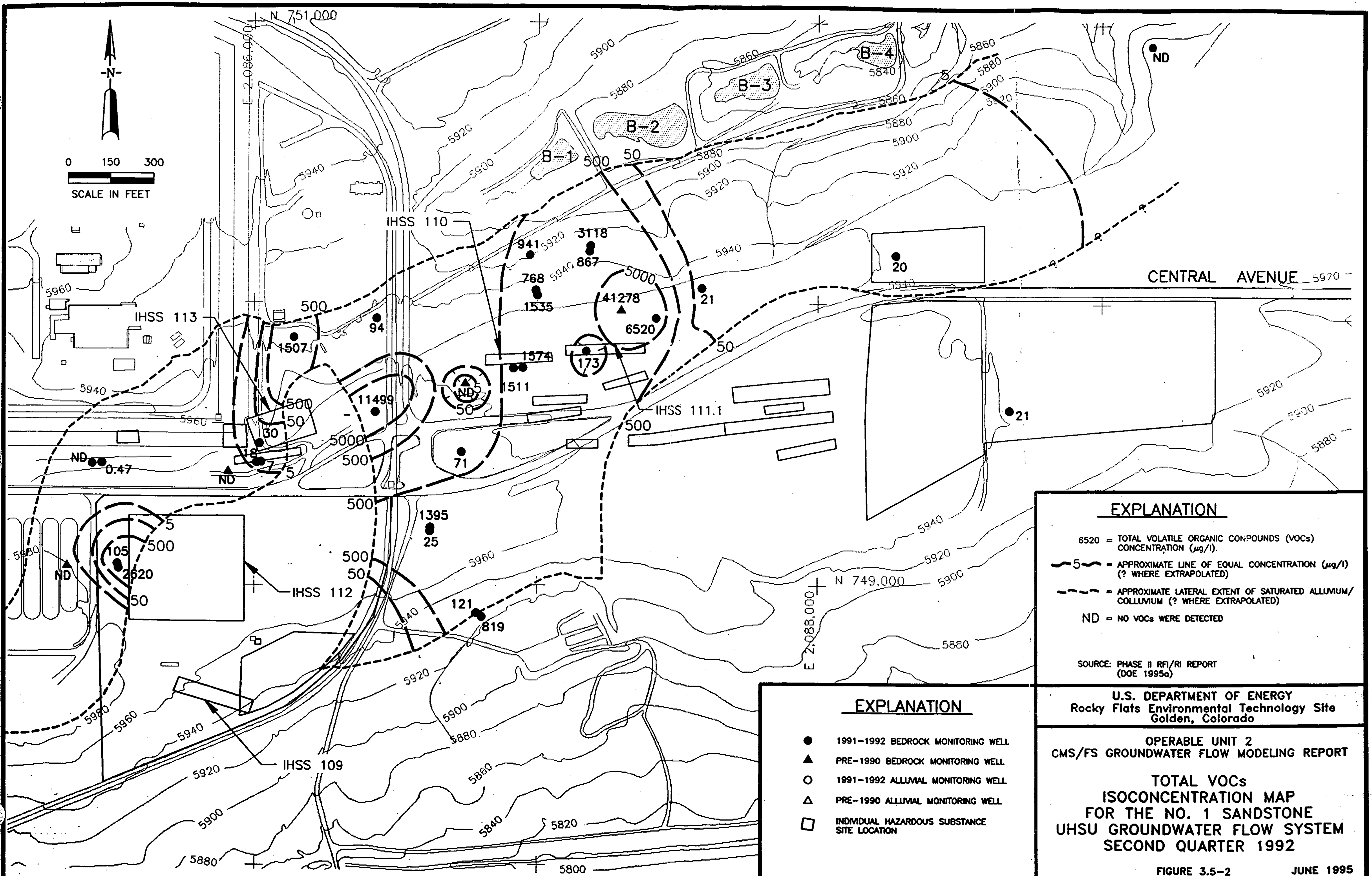
HYDROGEOLOGIC
CROSS SECTION C–C'
SHEET 2 OF 2

FIGURE 3.1–7 JUNE 1995

OU2FS038 1-1

38



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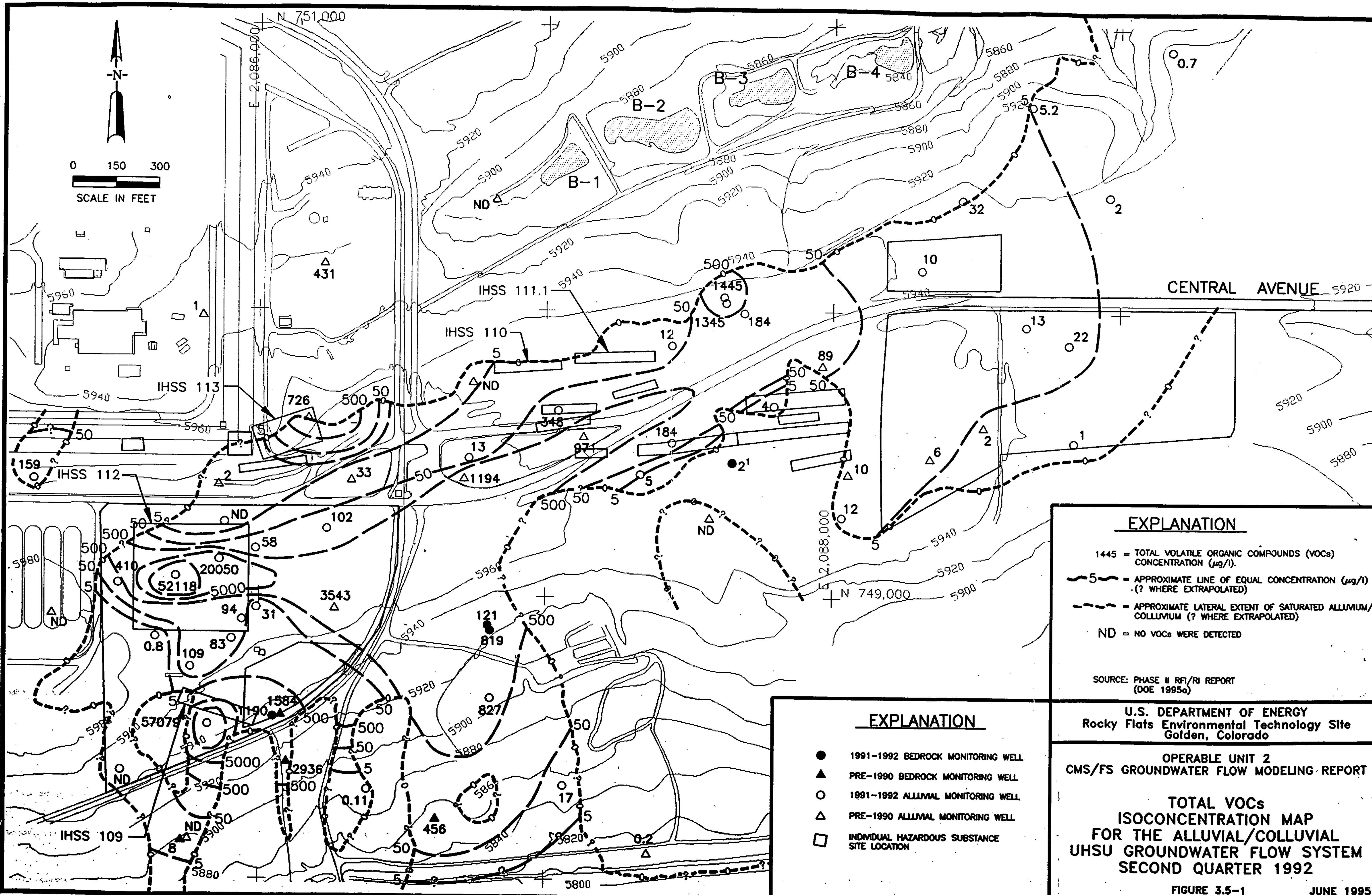
TOTAL VOCs
ISOCONCENTRATION MAP
FOR THE NO. 1 SANDSTONE
UHSU GROUNDWATER FLOW SYSTEM
SECOND QUARTER 1992

FIGURE 3.5–2 JUNE 1995

42



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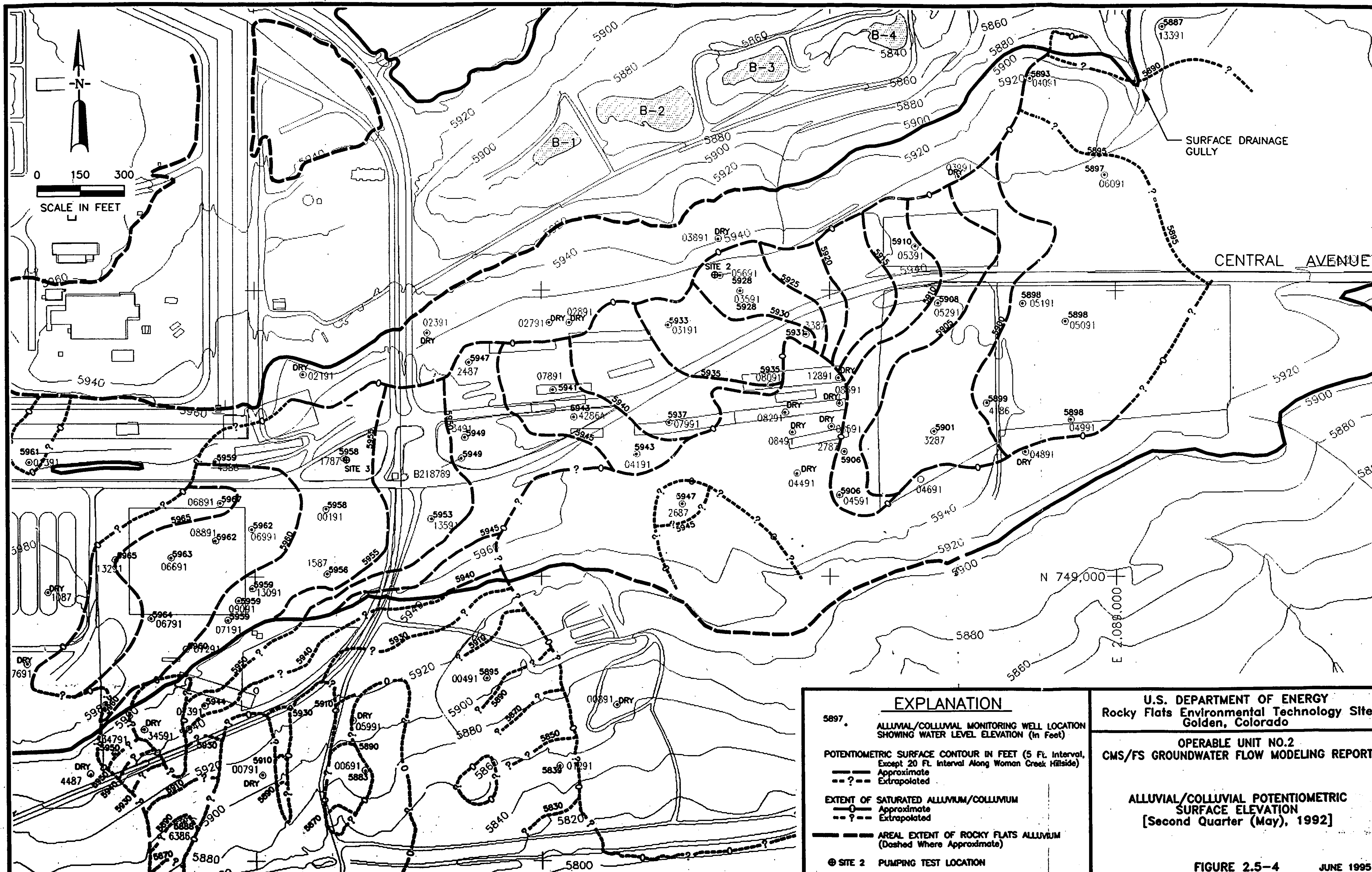
TOTAL VOCs ISOCONCENTRATION MAP FOR THE ALLUVIAL/COLLUVIAL UHSU GROUNDWATER FLOW SYSTEM SECOND QUARTER 1992

FIGURE 3.5-1 JUNE 1995



EXPLANATION

5897 • ALLUVIAL/COLLUVIAL MONITORING WELL LOCATION SHOWING WATER LEVEL ELEVATION (In Feet)

POTENTIOMETRIC SURFACE CONTOUR IN FEET (5 Ft. Interval, Except 20 Ft. Interval Along Woman Creek Hillside)
- Approximate
- Extrapolated

EXTENT OF SATURATED ALLUVIUM/COLLUVIUM
- Approximate
- Extrapolated

AREAL EXTENT OF ROCKY FLATS ALLUVIUM (Dashed Where Approximate)

⊕ SITE 2 PUMPING TEST LOCATION

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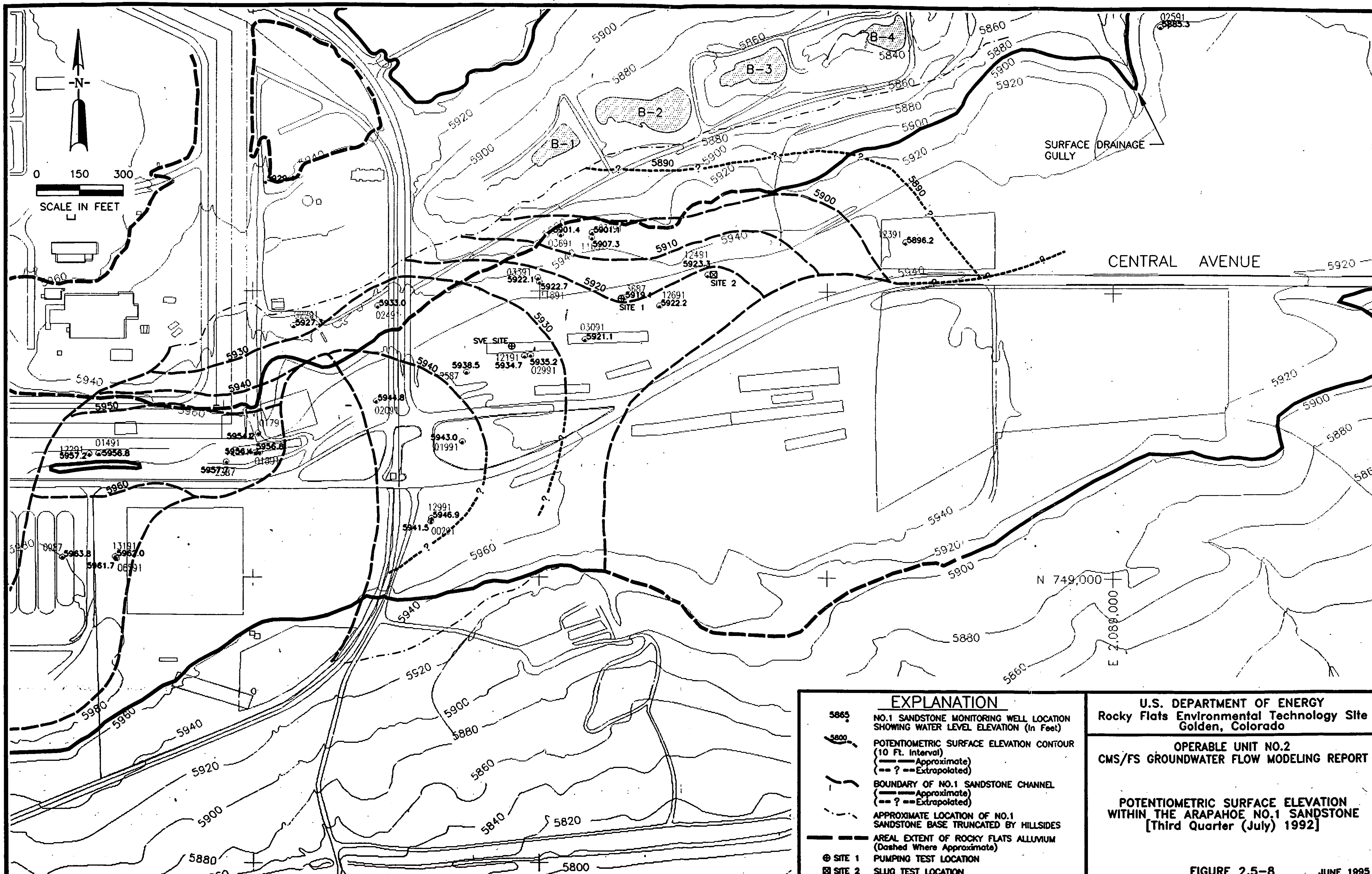
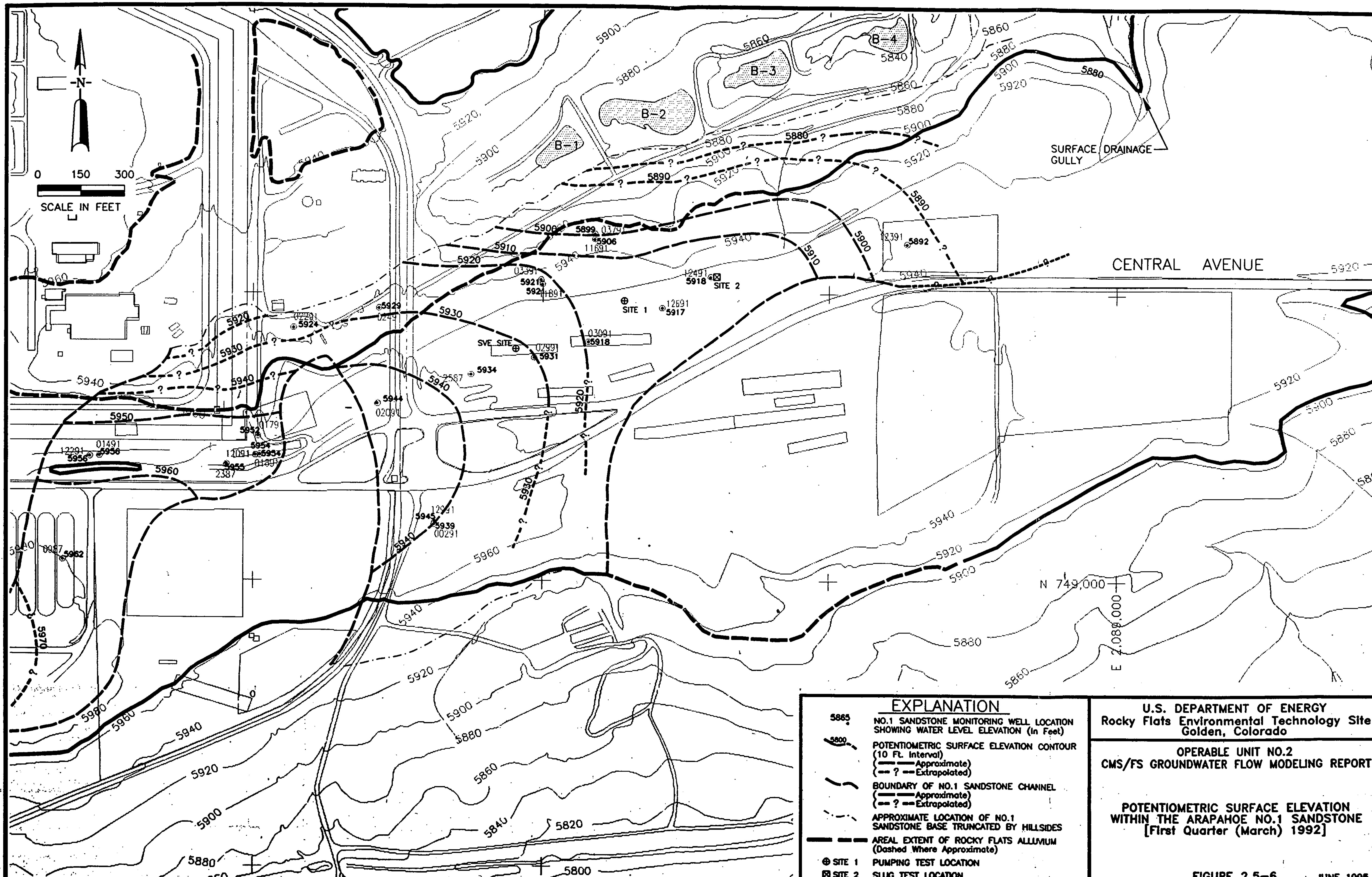
ALLUVIAL/COLLUVIAL POTENTIOMETRIC SURFACE ELEVATION
[Second Quarter (May), 1992]

FIGURE 2.5-4 JUNE 1995

OU2FS001 1=300



OU2FS011 1=300



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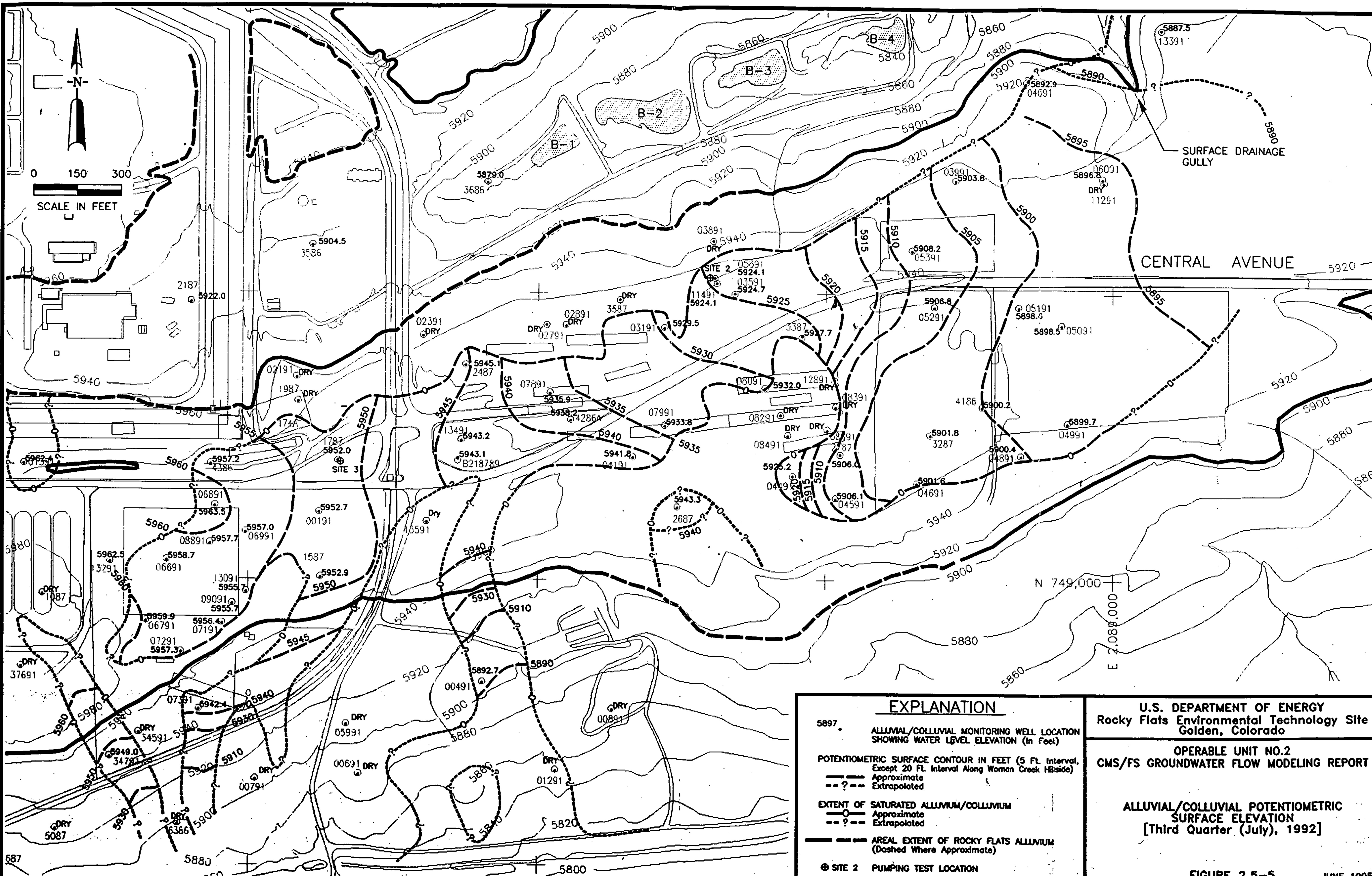
POTENTIOMETRIC SURFACE ELEVATION WITHIN THE ARAPAHOE NO.1 SANDSTONE [First Quarter (March) 1992]

FIGURE 2.5-6 JUNE 1995

OU2FS007 1=300



EXPLANATION

5897 • ALLUVIAL/COLLUVIAL MONITORING WELL LOCATION SHOWING WATER LEVEL ELEVATION (In Feet)

POTENTIOMETRIC SURFACE CONTOUR IN FEET (5 Ft. Interval, Except 20 Ft. Interval Along Woman Creek Hillside)
- Approximate
- Extrapolated

EXTENT OF SATURATED ALLUVIUM/COLLUVIUM
- Approximate
- Extrapolated

AREAL EXTENT OF ROCKY FLATS ALLUVIUM (Dashed Where Approximate)

⊕ SITE 2 PUMPING TEST LOCATION

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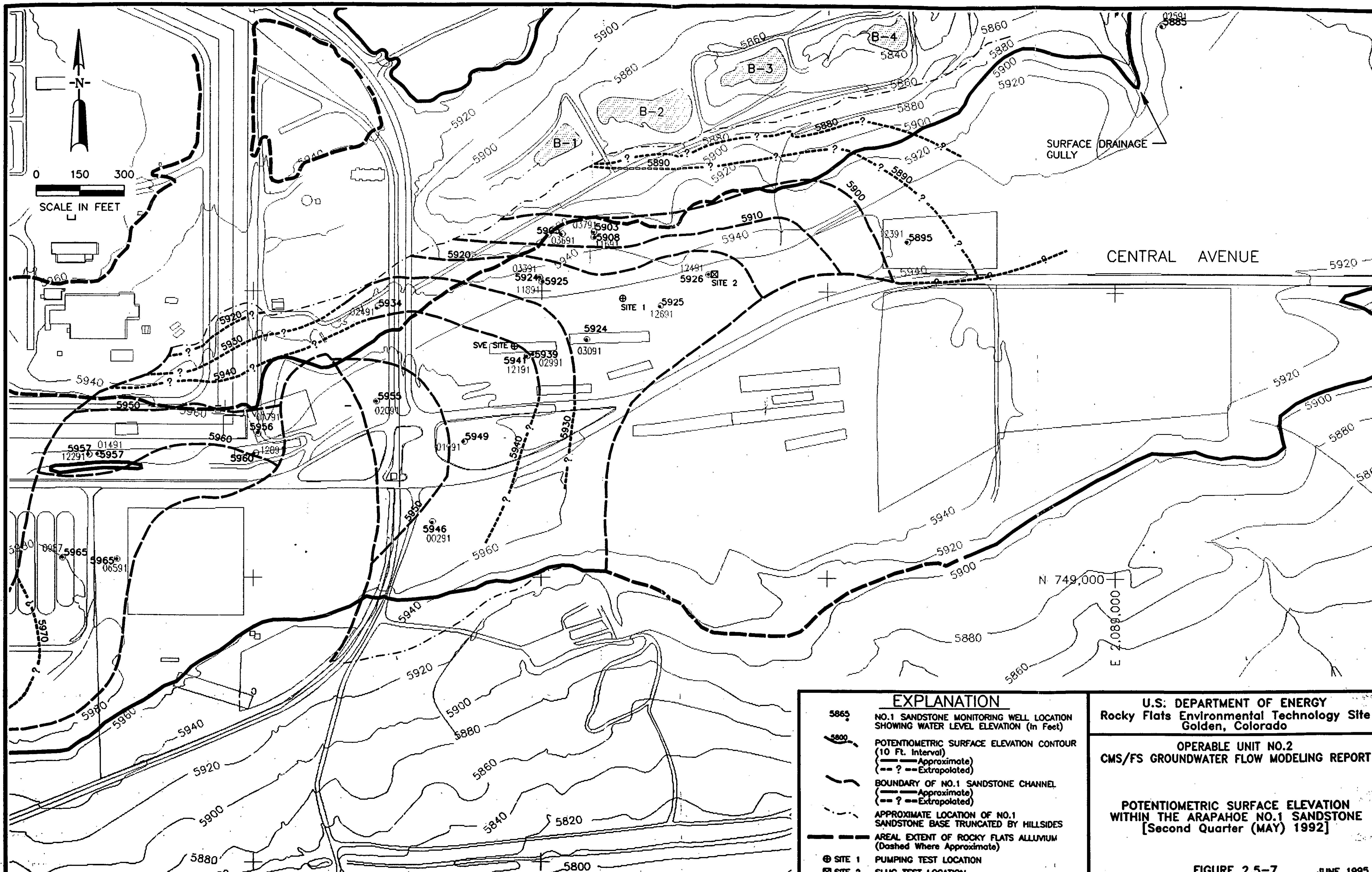
ALLUVIAL/COLLUVIAL POTENTIOMETRIC SURFACE ELEVATION
[Third Quarter (July), 1992]

FIGURE 2.5-5

JUNE 1995

0U2FS009 1=300



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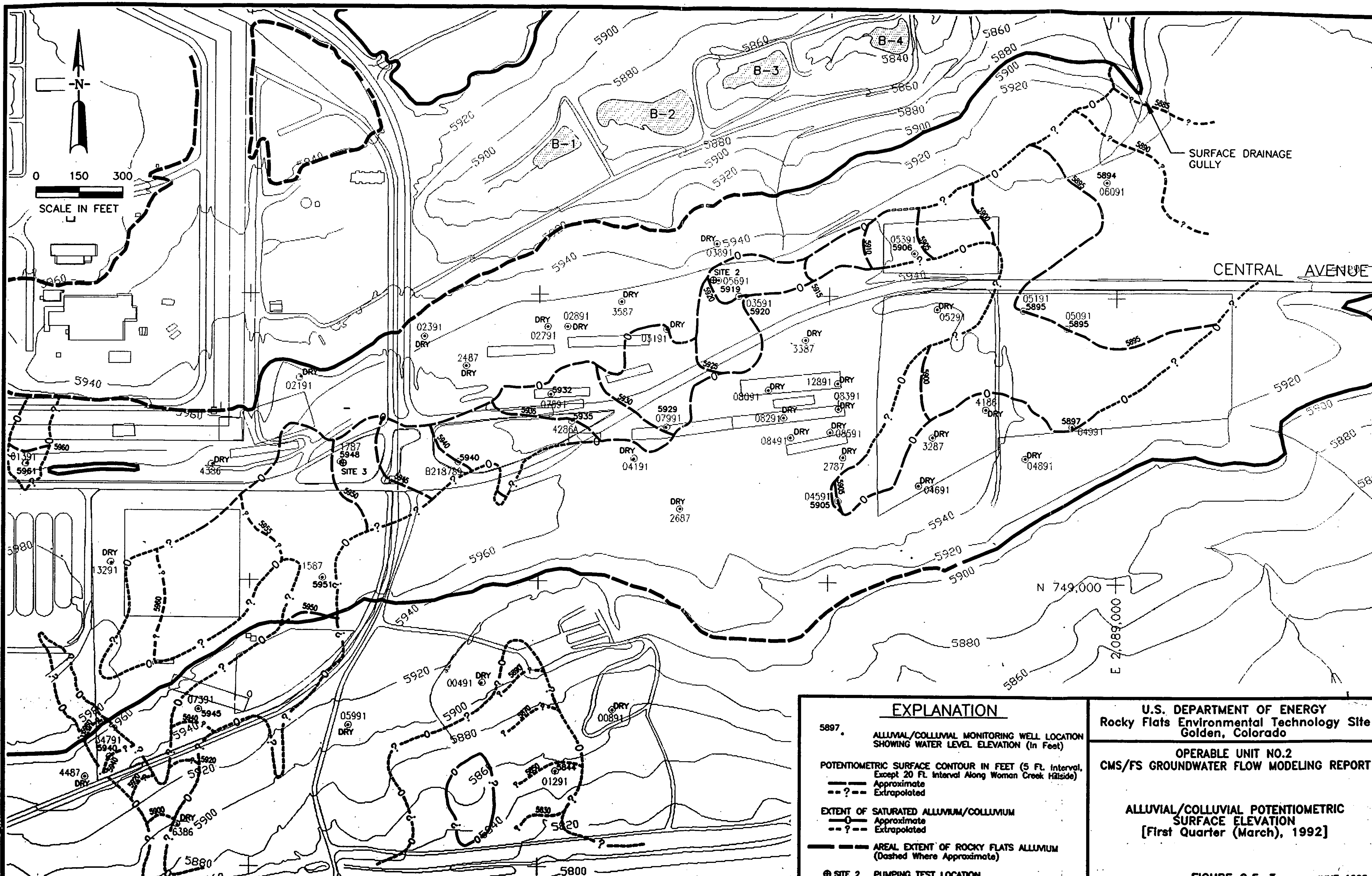
POTENTIOMETRIC SURFACE ELEVATION WITHIN THE ARAPAHOE NO.1 SANDSTONE [Second Quarter (MAY) 1992]

FIGURE 2.5-7

JUNE 1995

OU2FS003 1=300



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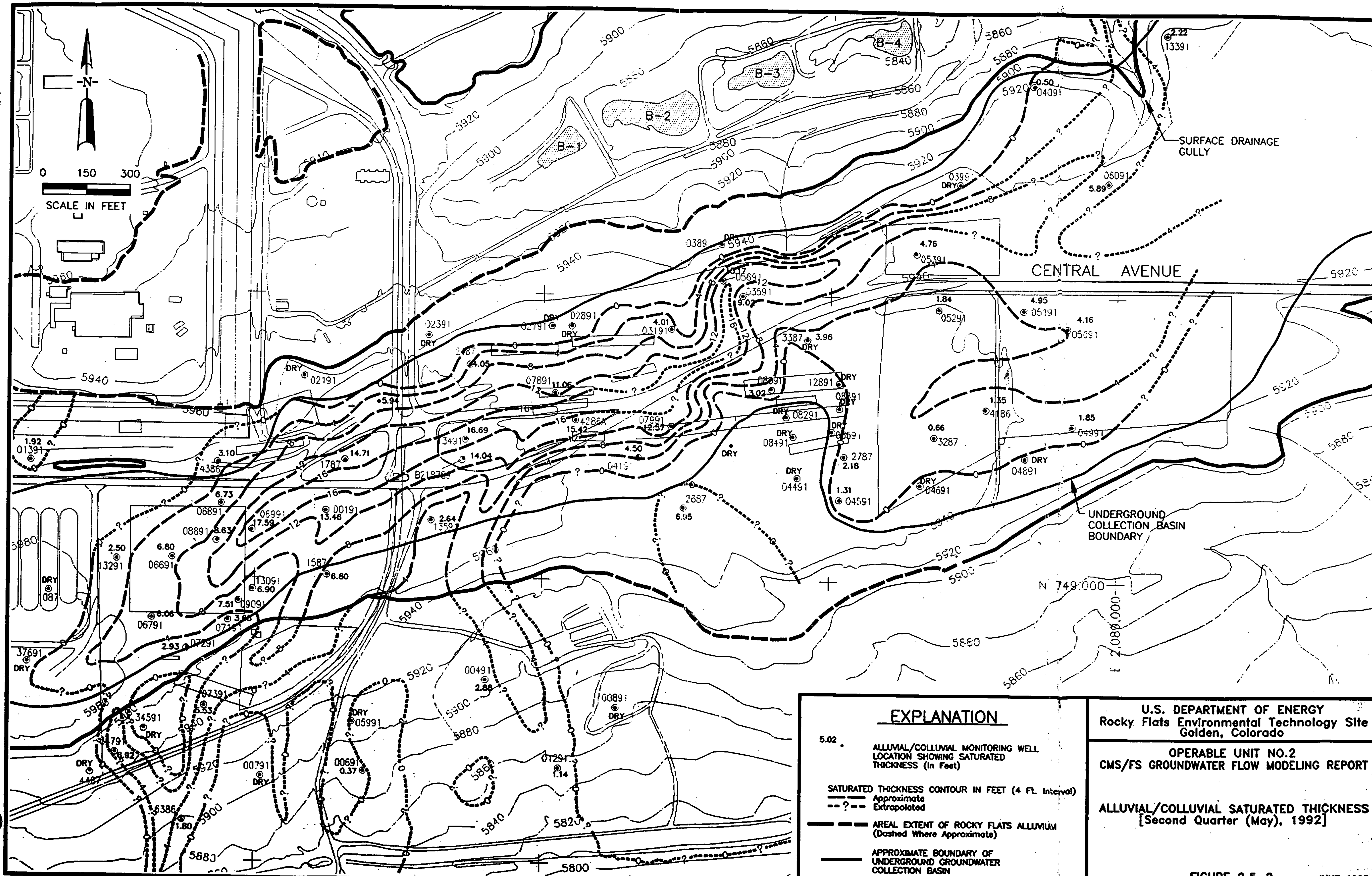
ALLUVIAL/COLLUVIAL POTENTIOMETRIC SURFACE ELEVATION
[First Quarter (March), 1992]

FIGURE 2.5-3

JUNE 1995

OU2FS005 1=300



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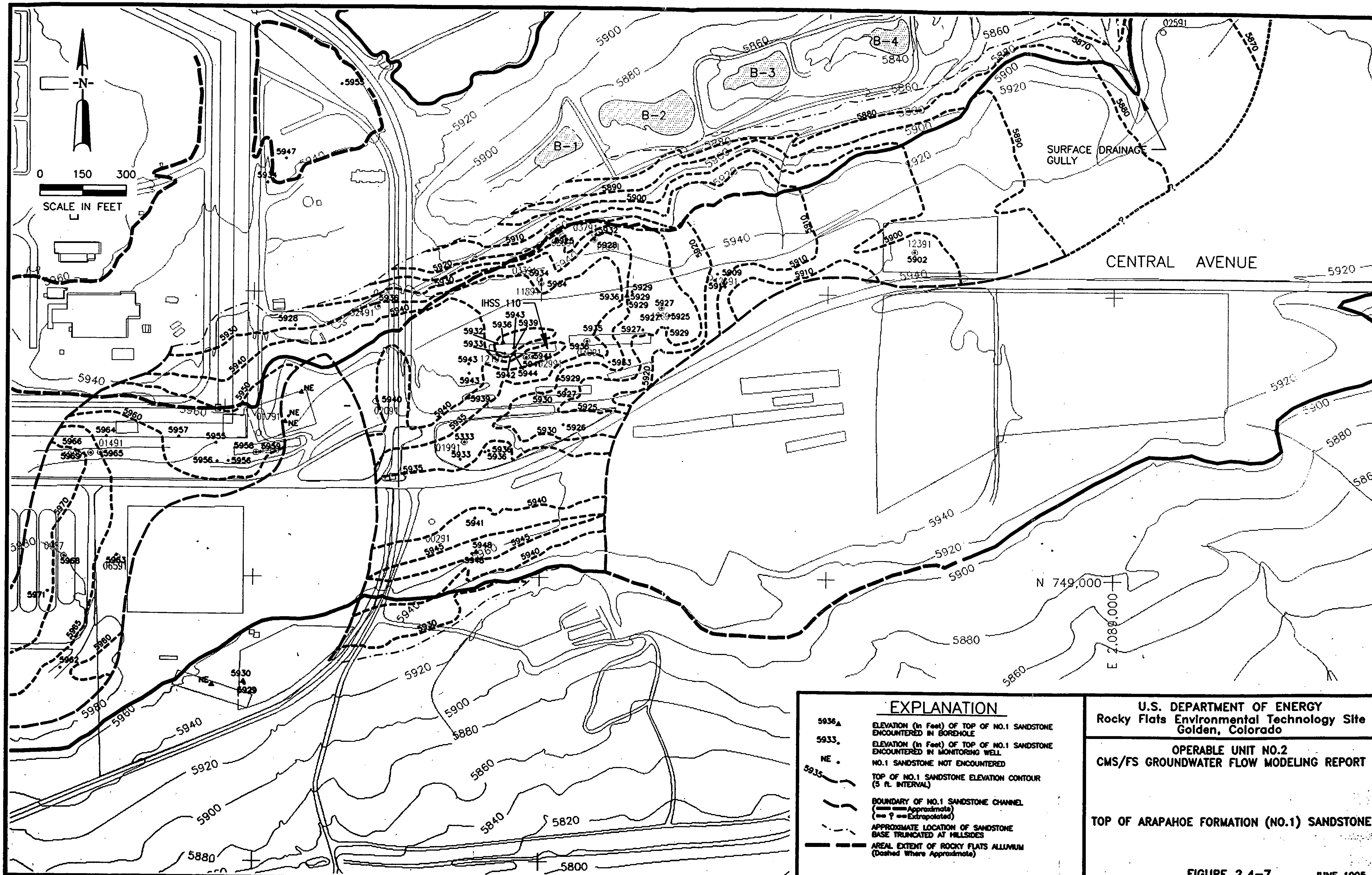
ALLUVIAL/COLLUVIAL SATURATED THICKNESS
[Second Quarter (May), 1992]

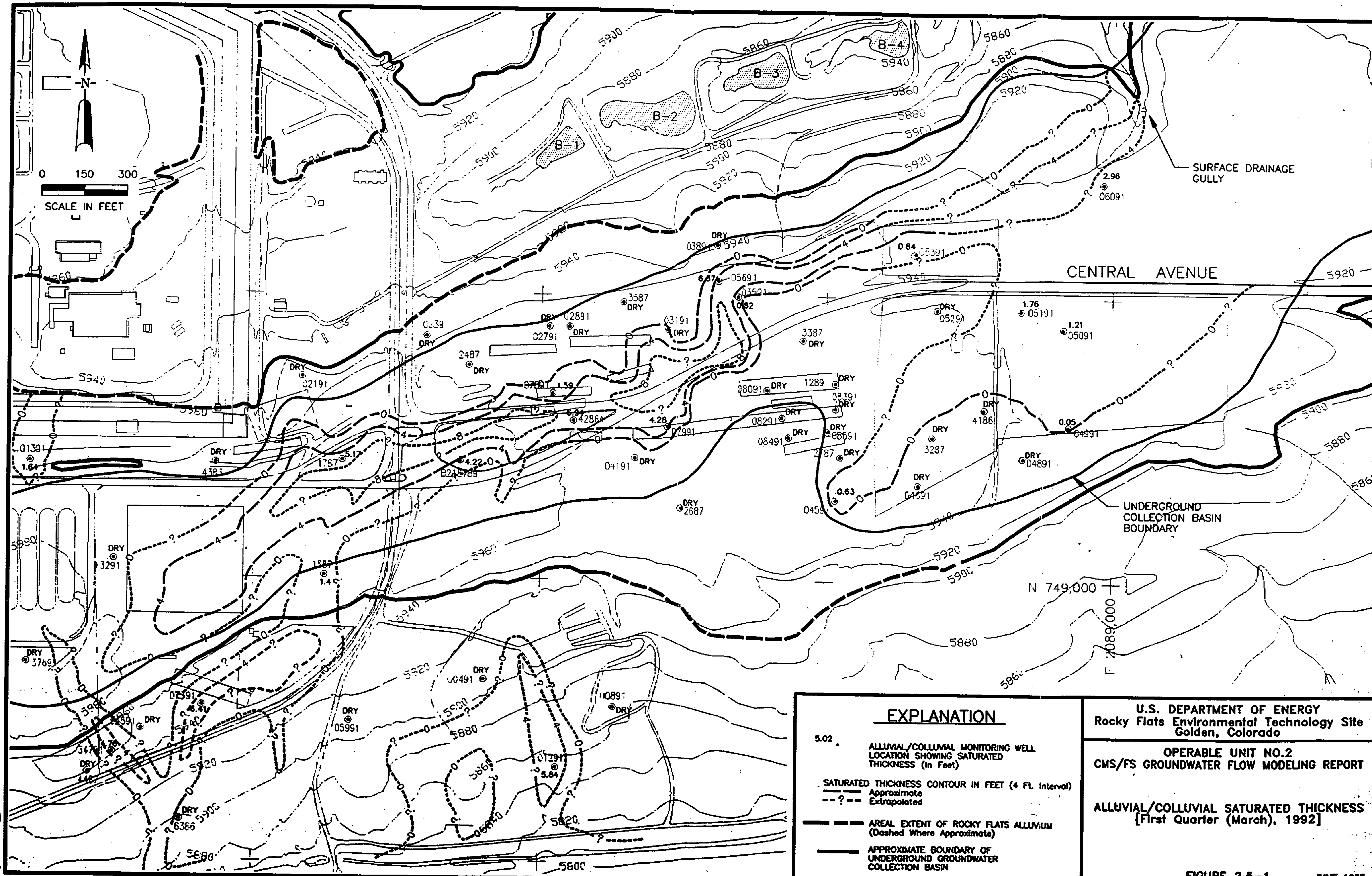
FIGURE 2.5-2

JUNE 1995

OU2FS35 1=300



OU2FS017 1=300



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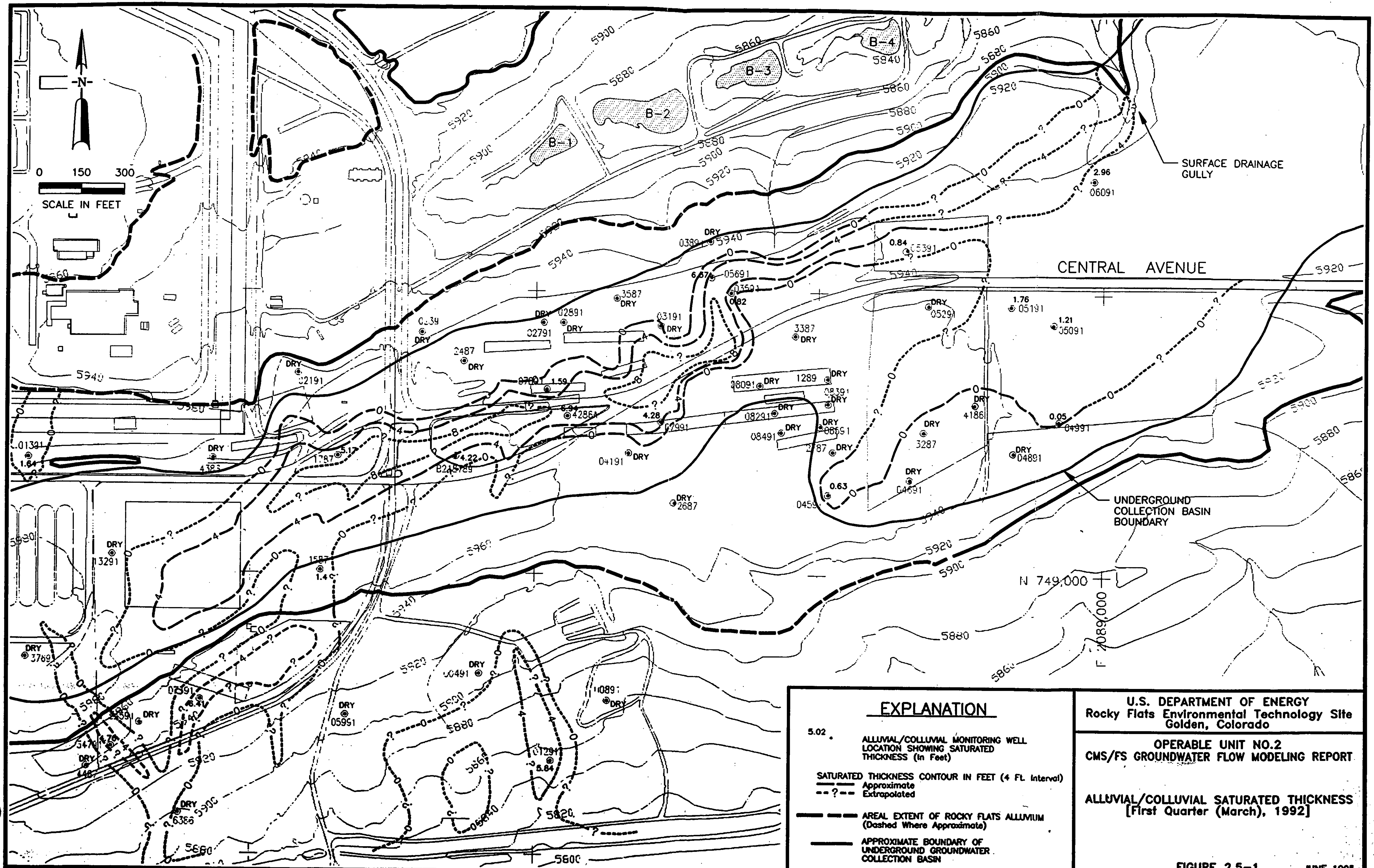
ALLUVIAL/COLLUVIAL SATURATED THICKNESS
[First Quarter (March), 1992]

FIGURE 2.5-1 JUNE 1995

OU2FS36 1=300



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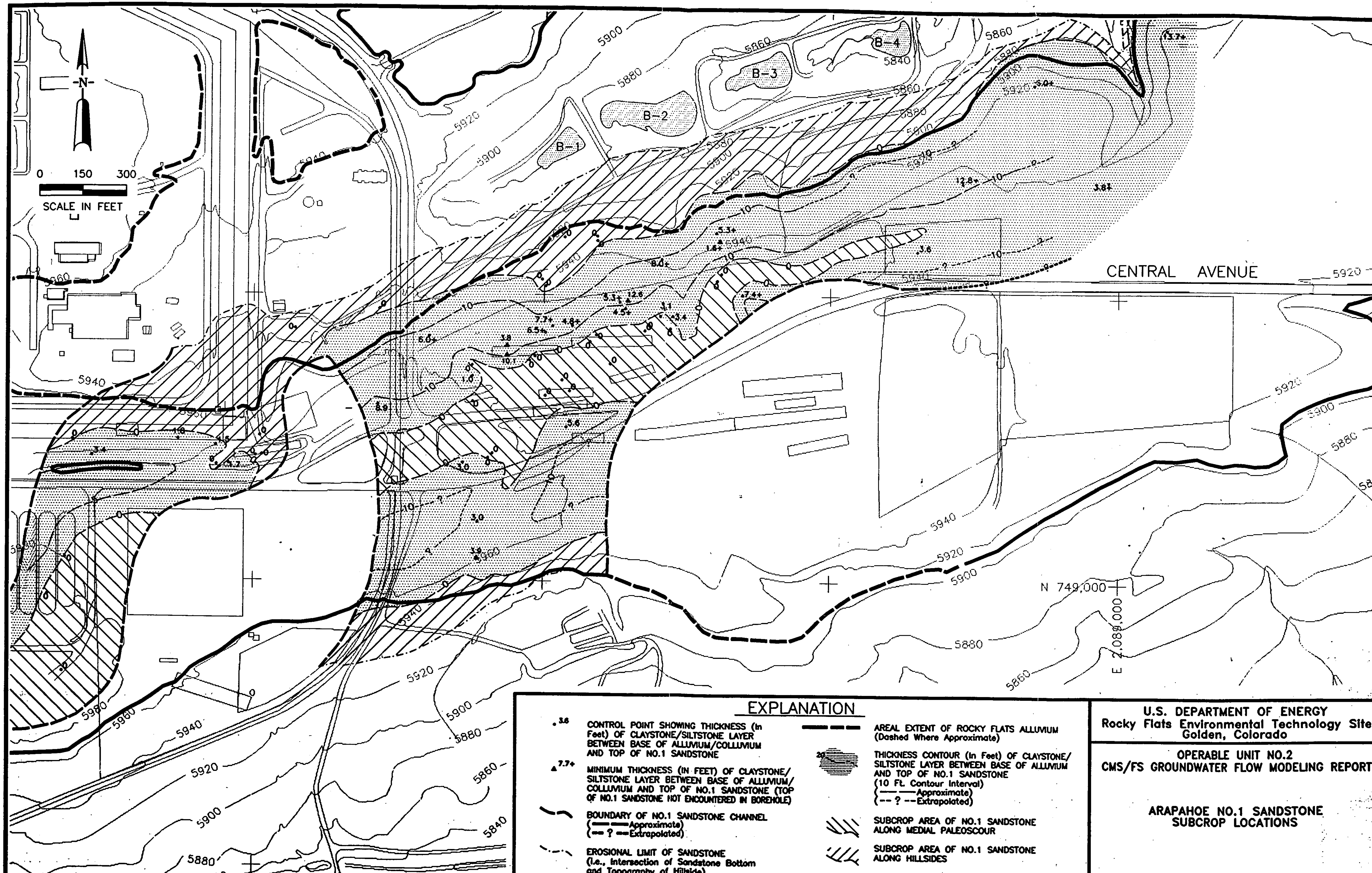
ALLUVIAL/COLLUVIAL SATURATED THICKNESS
[First Quarter (March), 1992]

FIGURE 2.5-1 JUNE 1995

OU2FS36 1=300



EXPLANATION

- 3.6 CONTROL POINT SHOWING THICKNESS (In Feet) OF CLAYSTONE/SILTSTONE LAYER BETWEEN BASE OF ALLUVIUM/COLLUVIUM AND TOP OF NO.1 SANDSTONE
- 7.7+ MINIMUM THICKNESS (IN FEET) OF CLAYSTONE/SILTSTONE LAYER BETWEEN BASE OF ALLUVIUM/COLLUVIUM AND TOP OF NO.1 SANDSTONE (TOP OF NO.1 SANDSTONE NOT ENCOUNTERED IN BOREHOLE)
- BOUNDARY OF NO.1 SANDSTONE CHANNEL (——— Approximate) (-- ? -- Extrapolated)
- EROSIONAL LIMIT OF SANDSTONE (i.e., Intersection of Sandstone Bottom and Topography of Hillside)
- AREAL EXTENT OF ROCKY FLATS ALLUVIUM (Dashed Where Approximate)
- 20 THICKNESS CONTOUR (In Feet) OF CLAYSTONE/SILTSTONE LAYER BETWEEN BASE OF ALLUVIUM AND TOP OF NO.1 SANDSTONE (10 Ft. Contour Interval) (——— Approximate) (-- ? -- Extrapolated)
- SUBCROP AREA OF NO.1 SANDSTONE ALONG MEDIAL PALEOSCOUR
- SUBCROP AREA OF NO.1 SANDSTONE ALONG HILLSIDES

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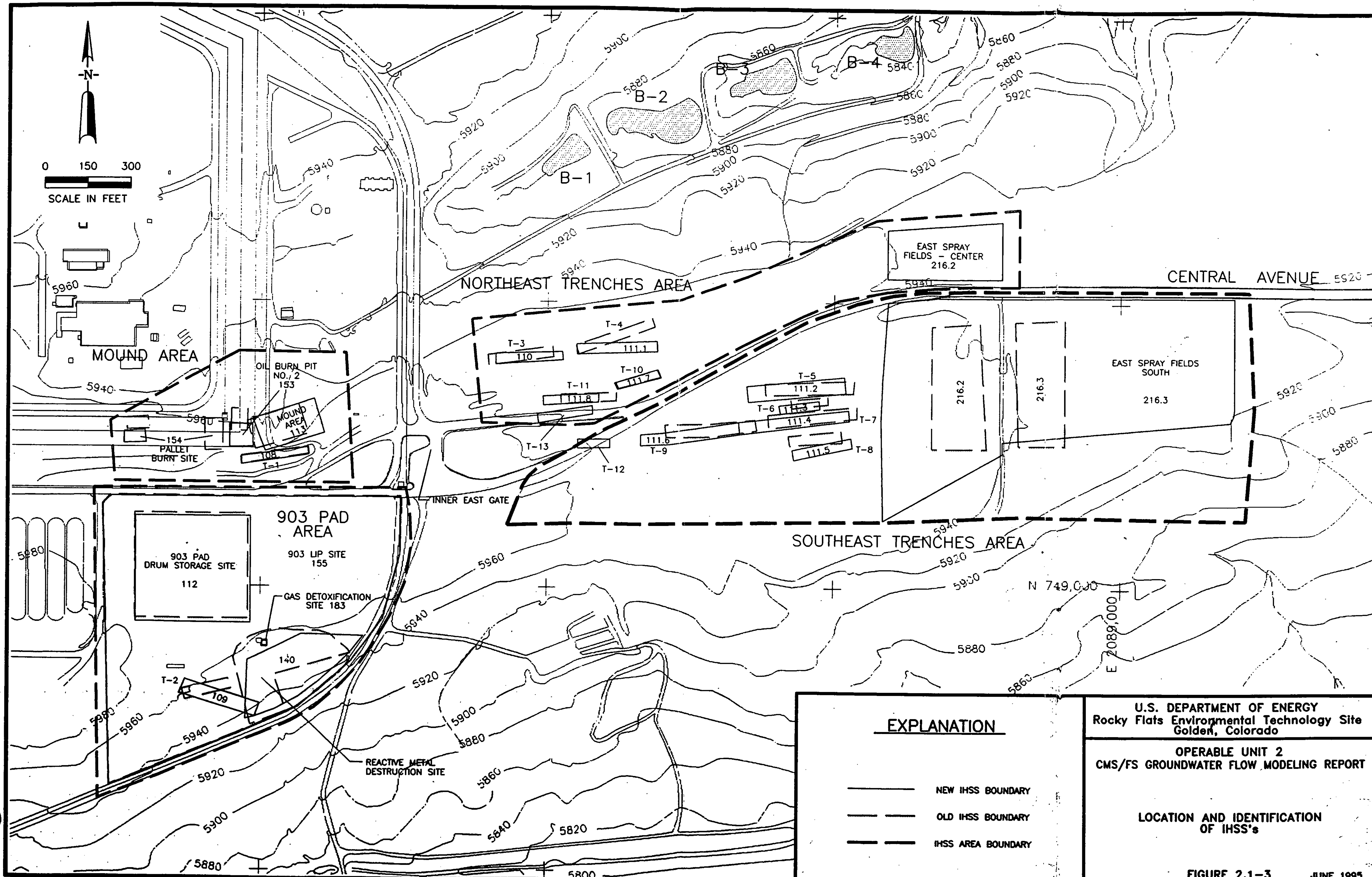
ARAPAHOE NO.1 SANDSTONE SUBCROP LOCATIONS

FIGURE 2.4-6 JUNE 1995

OU2FS021 1=300

54



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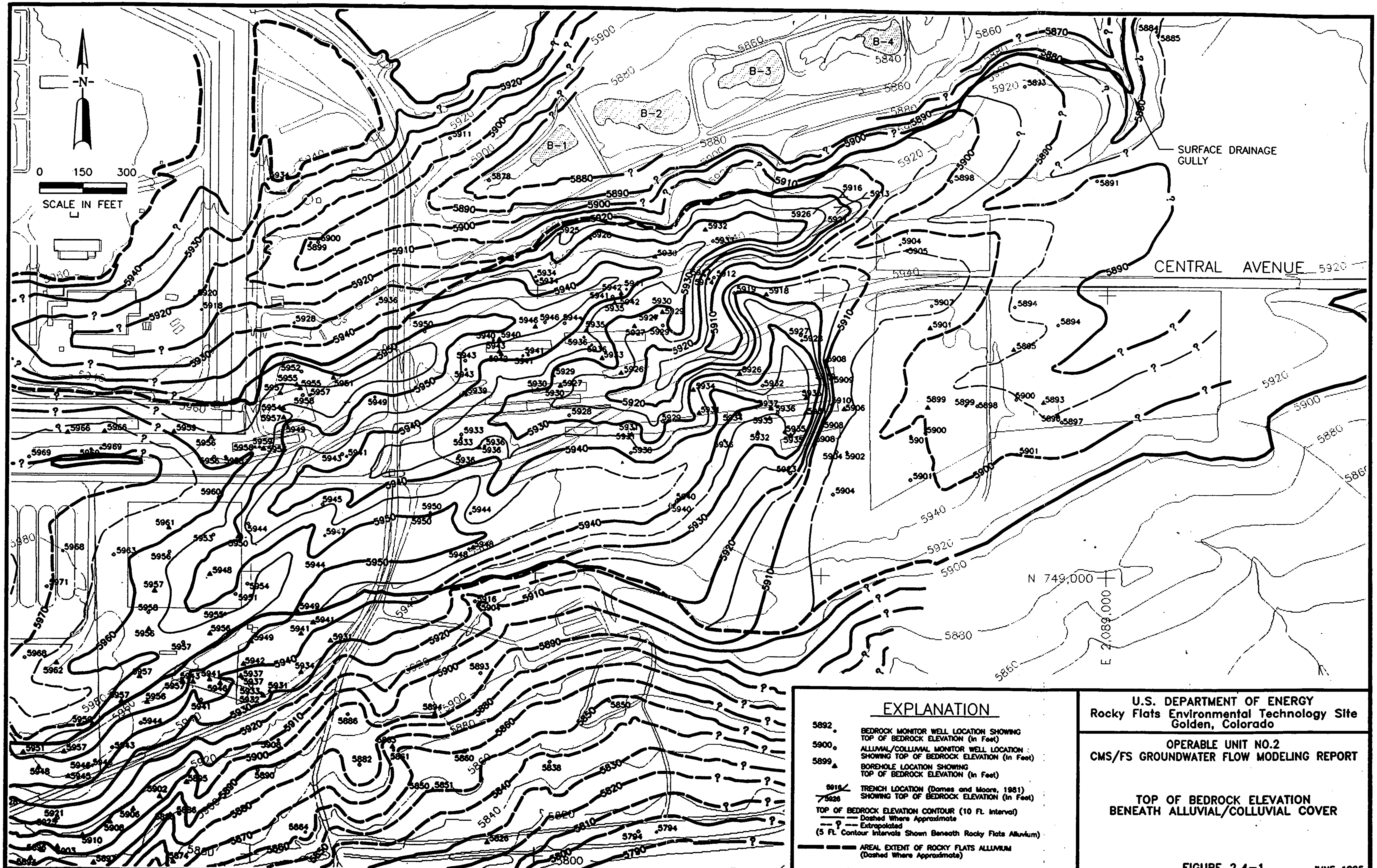
LOCATION AND IDENTIFICATION OF IHSS's

FIGURE 2.1-3 JUNE 1995

OU2FS37 1=300



EXPLANATION

5892 • BEDROCK MONITOR WELL LOCATION SHOWING TOP OF BEDROCK ELEVATION (In Feet)

5900 ○ ALLUVIAL/COLLUVIAL MONITOR WELL LOCATION SHOWING TOP OF BEDROCK ELEVATION (In Feet)

5899 ▲ BOREHOLE LOCATION SHOWING TOP OF BEDROCK ELEVATION (In Feet)

5916/5926 TRENCH LOCATION (Dames and Moore, 1981) SHOWING TOP OF BEDROCK ELEVATION (In Feet)

TOP OF BEDROCK ELEVATION CONTOUR (10 Ft. Interval)
— — Dashed Where Approximate
— ? — Extrapolated
(5 Ft. Contour Intervals Shown Beneath Rocky Flats Alluvium)

AREAL EXTENT OF ROCKY FLATS ALLUVIUM (Dashed Where Approximate)

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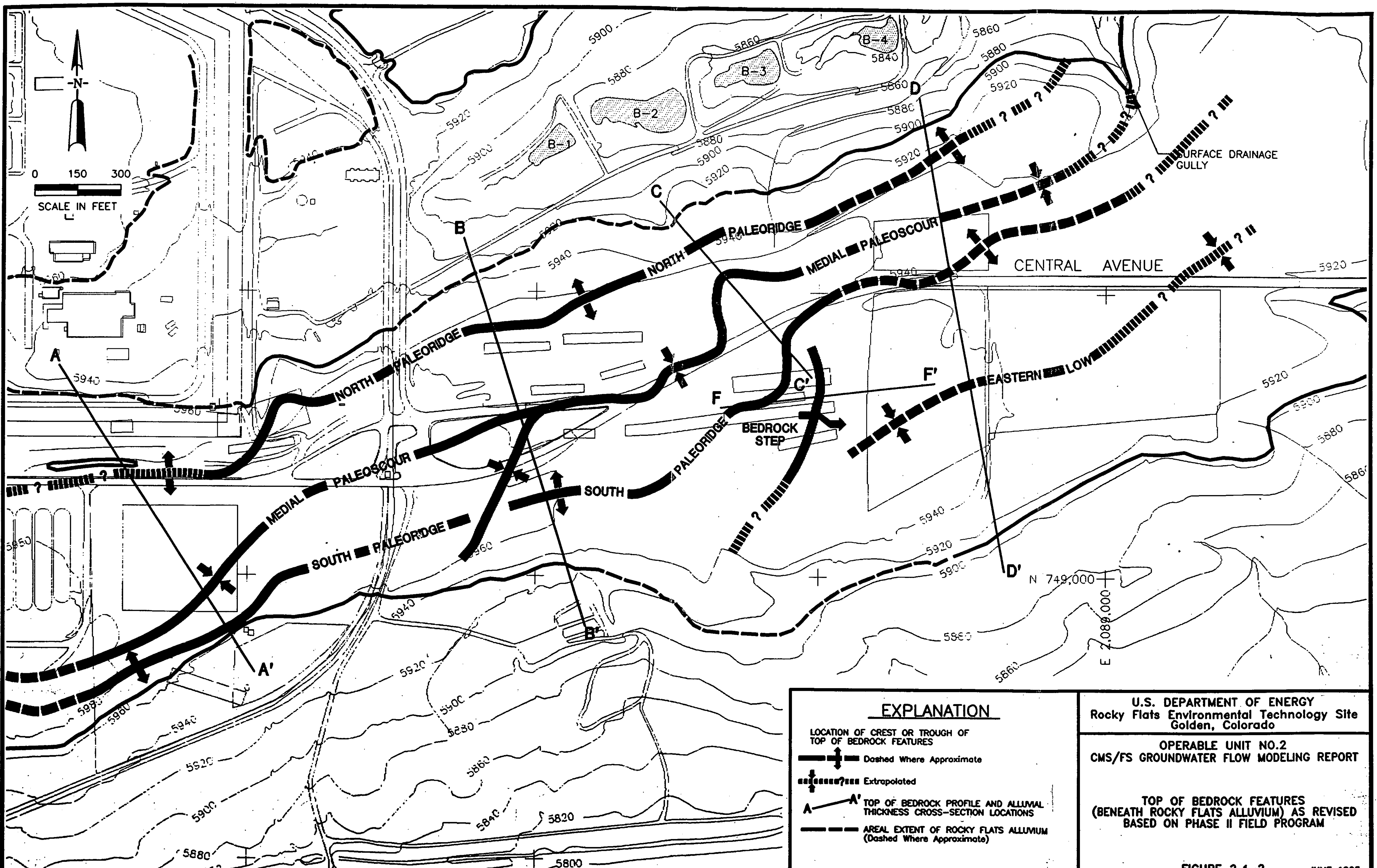
TOP OF BEDROCK ELEVATION
BENEATH ALLUVIAL/COLLUVIAL COVER

FIGURE 2.4-1 JUNE 1995

OU2FS015 1=300

58



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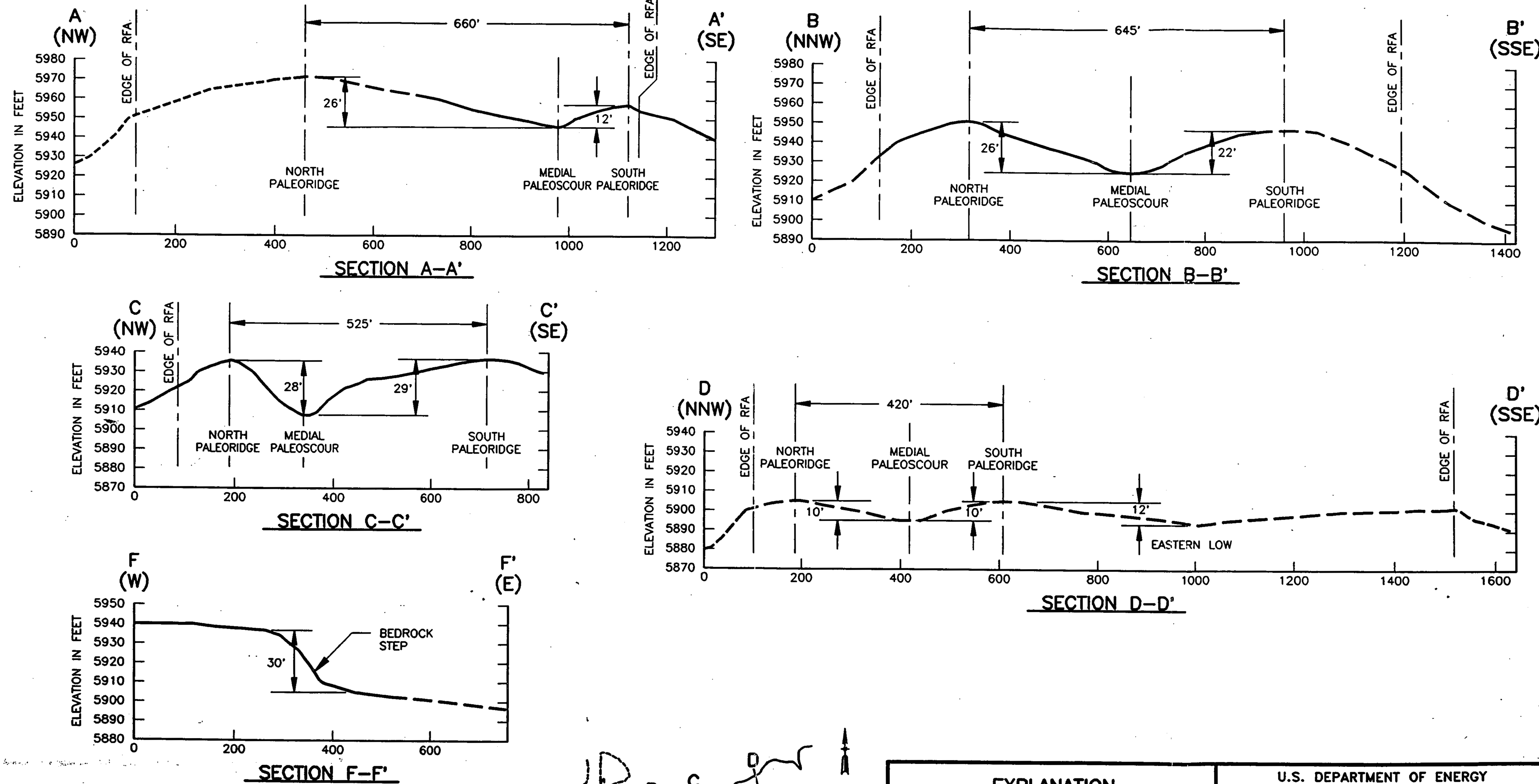
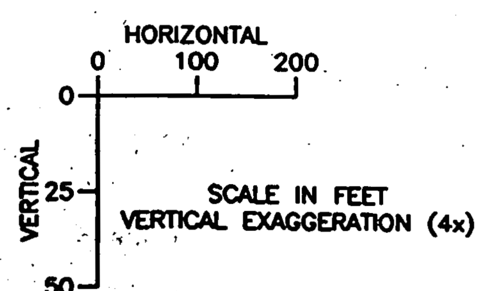
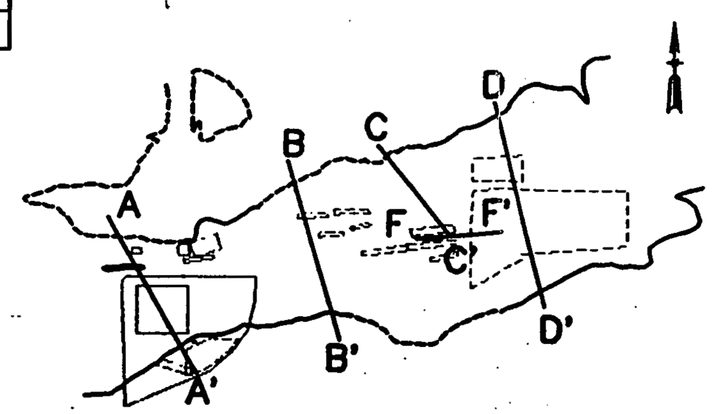
TOP OF BEDROCK FEATURES
(BENEATH ROCKY FLATS ALLUVIUM) AS REVISED
BASED ON PHASE II FIELD PROGRAM

FIGURE 2.4-2 JUNE 1995

OU2FS32 1=300







CROSS-SECTION LOCATION MAP

EXPLANATION

TOP OF BEDROCK SURFACE
— — Dashed Where Approximate
- - - Extrapolated

12' APPROXIMATE RELIEF FROM RIDGE CREST TO SCOUR TROUGH

RFA ROCKY FLATS ALLUVIUM

NOTE:
PROFILES CONSTRUCTED FROM CONTOUR MAP OF TOP OF BEDROCK SURFACE (FIG. 3.5–5)

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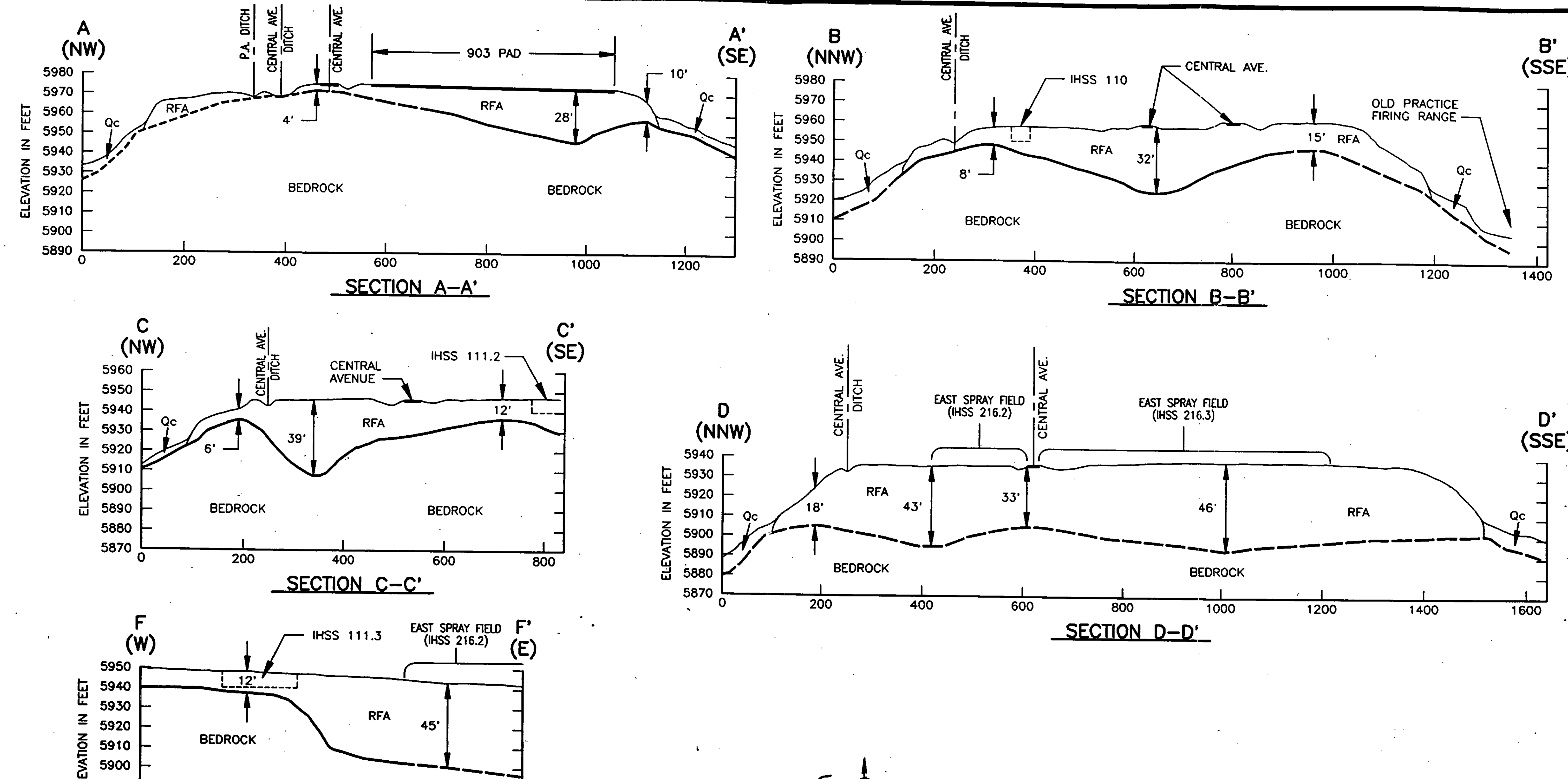
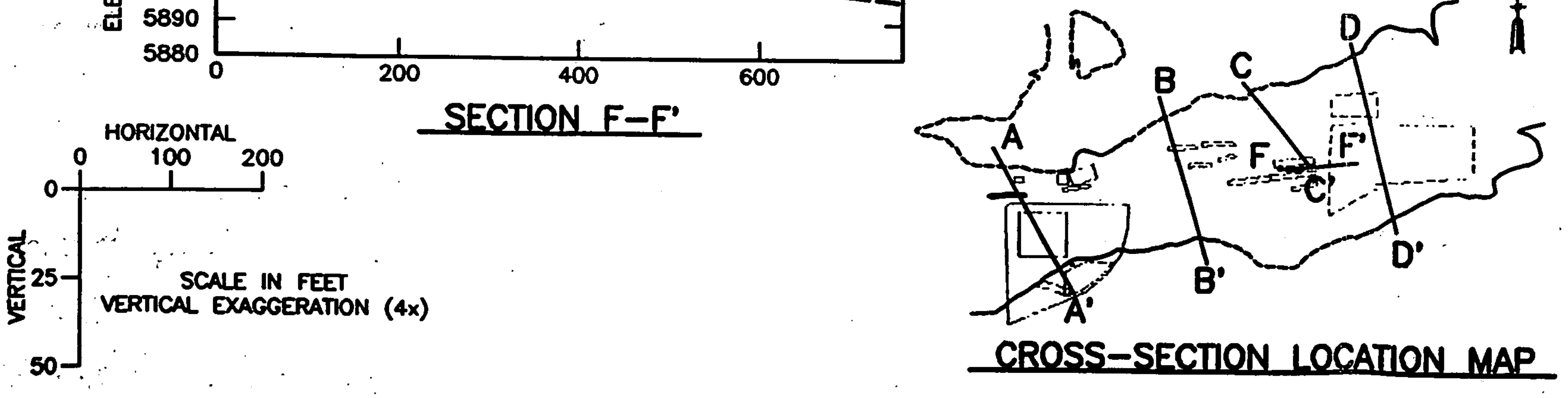
TOP OF BEDROCK PROFILES
SHOWING MAJOR FEATURES
BENEATH ROCKY FLATS ALLUVIUM

FIGURE 2.4–3 JUNE 1995

OU2FS33 1=200





EXPLANATION

TOP OF BEDROCK SURFACE
Dashed Where Approximate
Extrapolated

20' APPROXIMATE THICKNESS OF ROCKY FLATS ALLUVIUM

RFA ROCKY FLATS ALLUVIUM

Qc COLLUVIUM

NOTE:
CROSS-SECTIONS CONSTRUCTED FROM CONTOUR MAP OF TOP OF BEDROCK SURFACE (FIG. 3.5-5) AND TOTPGRAPHIC BASE MAP.

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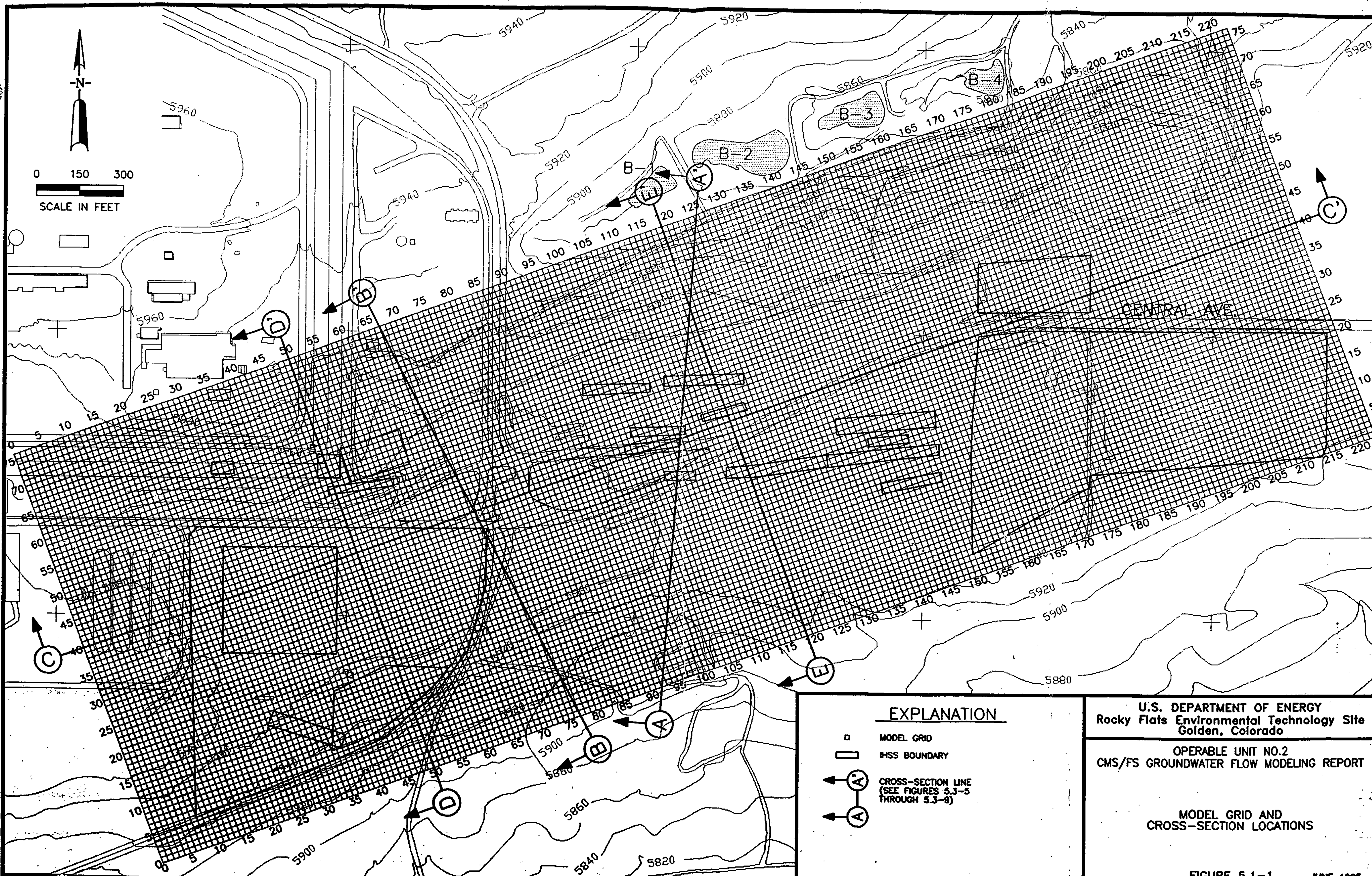
CROSS SECTIONS SHOWING THICKNESS OF ROCKY FLATS ALLUVIUM

FIGURE 2.4-4

JUNE 1995

OU2FS34 1=200



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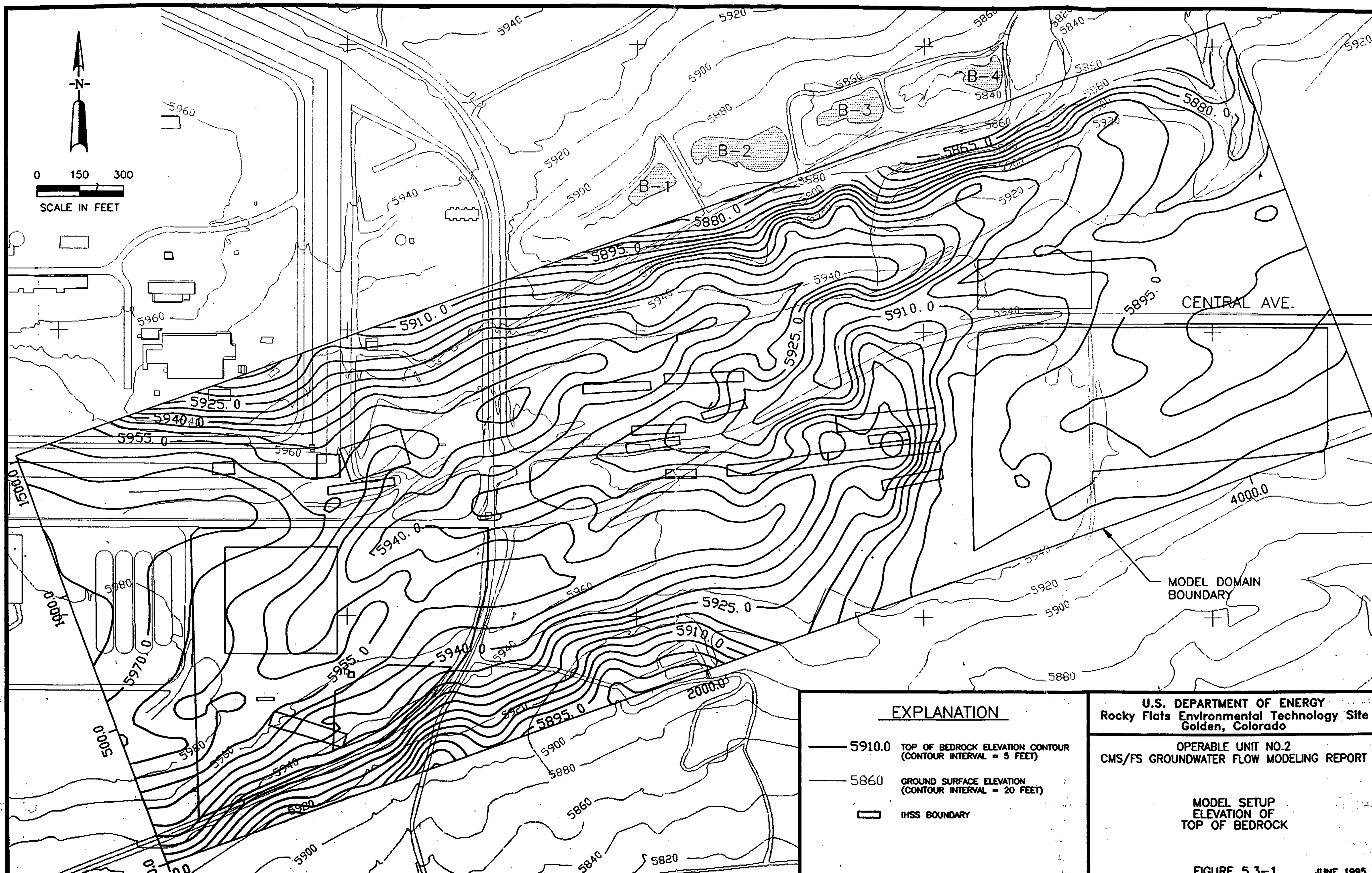
MODEL GRID AND
CROSS-SECTION LOCATIONS

FIGURE 5.1-1 JUNE 1995

OU2FS034 1=300



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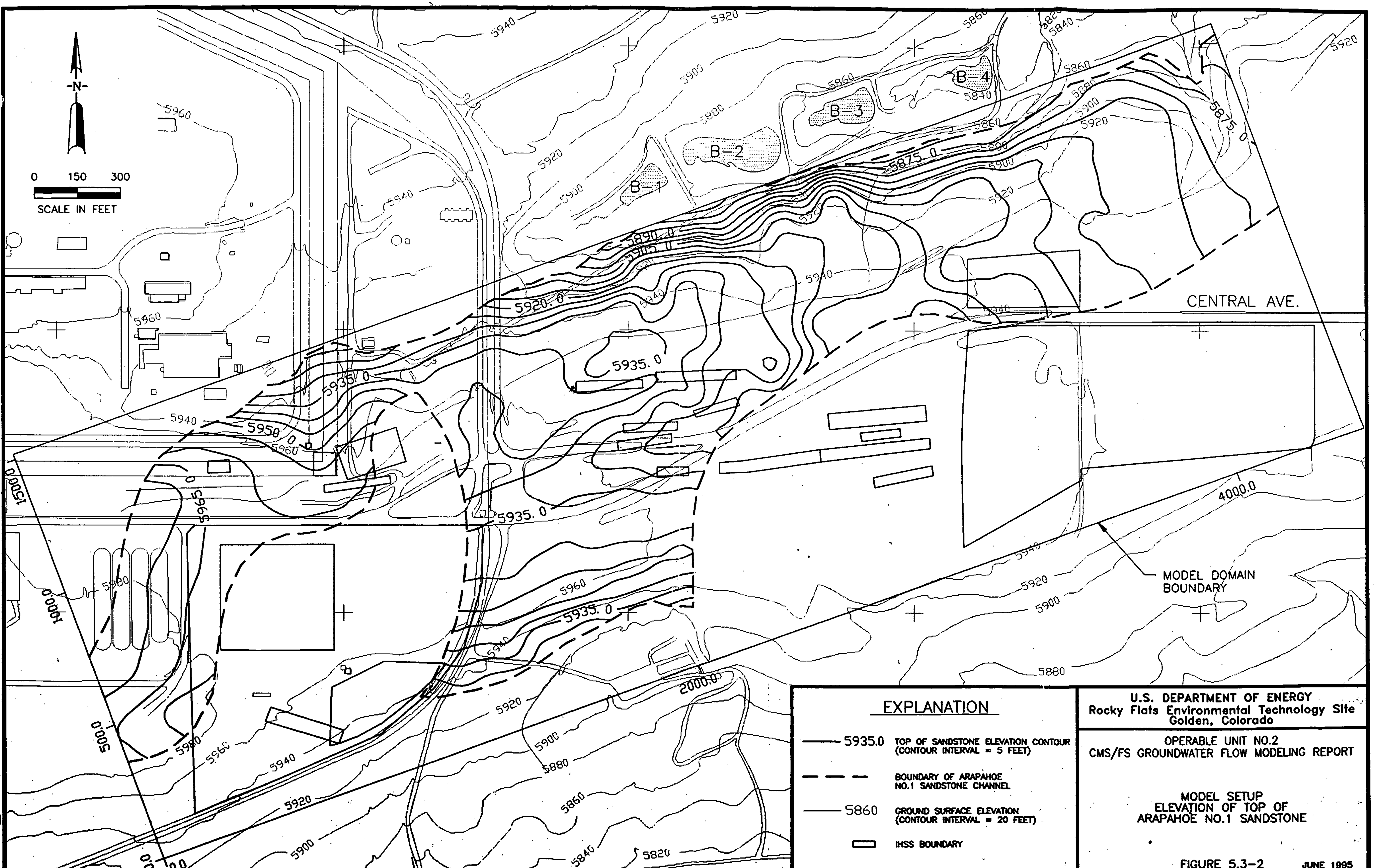
MODEL SETUP
ELEVATION OF
TOP OF BEDROCK

FIGURE 5.3-1 JUNE 1995

OU2FS016 1=300

13



EXPLANATION

- 5935.0 — TOP OF SANDSTONE ELEVATION CONTOUR (CONTOUR INTERVAL = 5 FEET)
- BOUNDARY OF ARAPAHOE NO.1 SANDSTONE CHANNEL
- 5860 — GROUND SURFACE ELEVATION (CONTOUR INTERVAL = 20 FEET)
- IHSS BOUNDARY

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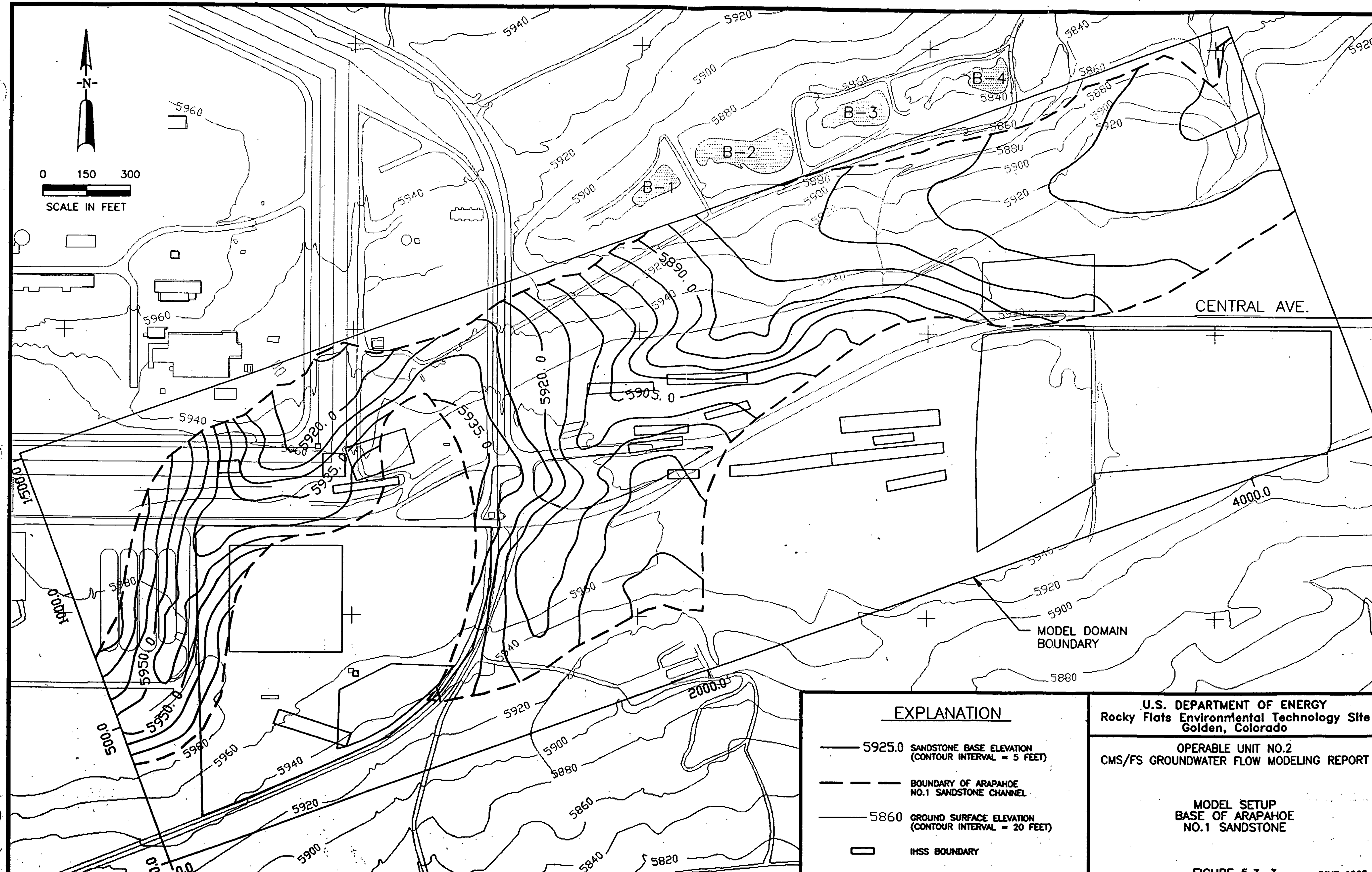
MODEL SETUP
ELEVATION OF TOP OF
ARAPAHOE NO.1 SANDSTONE

FIGURE 5.3-2 JUNE 1995

OU2FS018 1=300

24



EXPLANATION

5925.0 SANDSTONE BASE ELEVATION (CONTOUR INTERVAL = 5 FEET)

BOUNDARY OF ARAPAHOE NO.1 SANDSTONE CHANNEL

5860 GROUND SURFACE ELEVATION (CONTOUR INTERVAL = 20 FEET)

IHSS BOUNDARY

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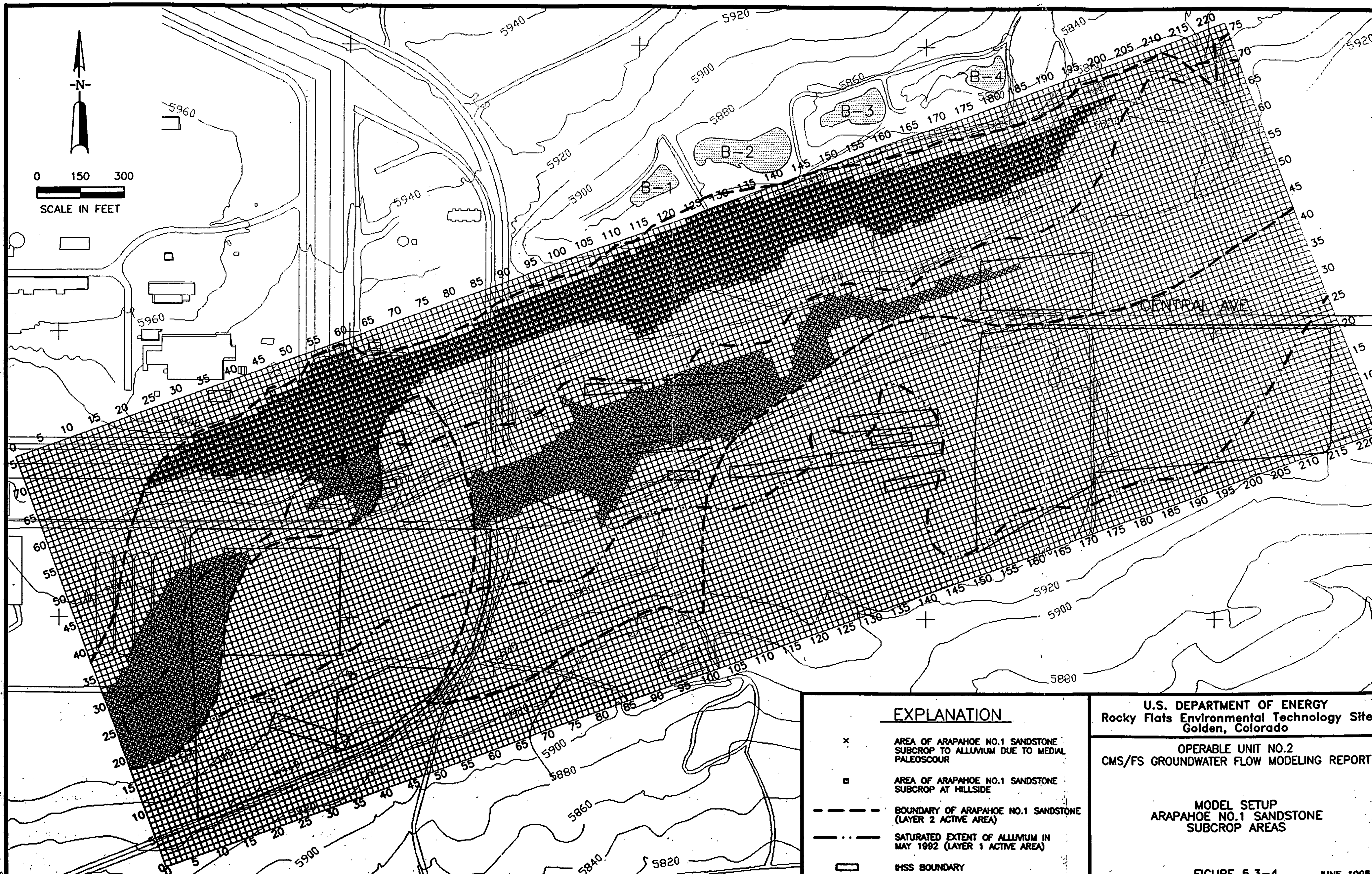
MODEL SETUP
BASE OF ARAPAHOE
NO.1 SANDSTONE

FIGURE 5.3-3 JUNE 1995

OU2FS028 1=300

75



EXPLANATION

× AREA OF ARAPAHOE NO.1 SANDSTONE SUBCROP TO ALLUVIUM DUE TO MEDIAL PALEOSCOUR

AREA OF ARAPAHOE NO.1 SANDSTONE SUBCROP AT HILLSIDE

BOUNDARY OF ARAPAHOE NO.1 SANDSTONE (LAYER 2 ACTIVE AREA)

SATURATED EXTENT OF ALLUVIUM IN MAY 1992 (LAYER 1 ACTIVE AREA)

IHSS BOUNDARY

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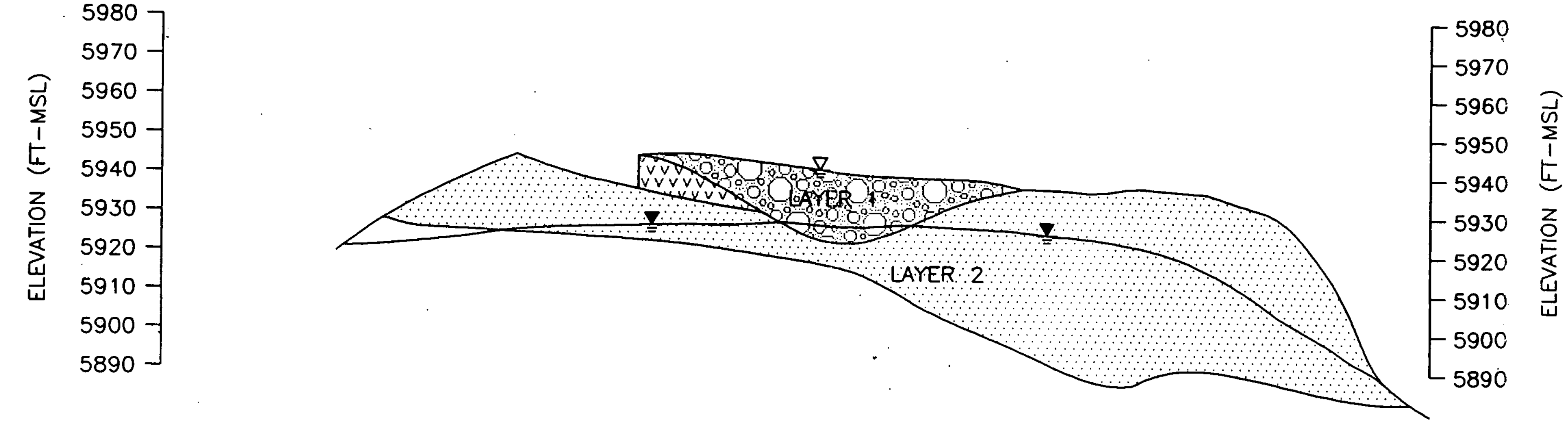
MODEL SETUP
ARAPAHOE NO.1 SANDSTONE
SUBCROP AREAS

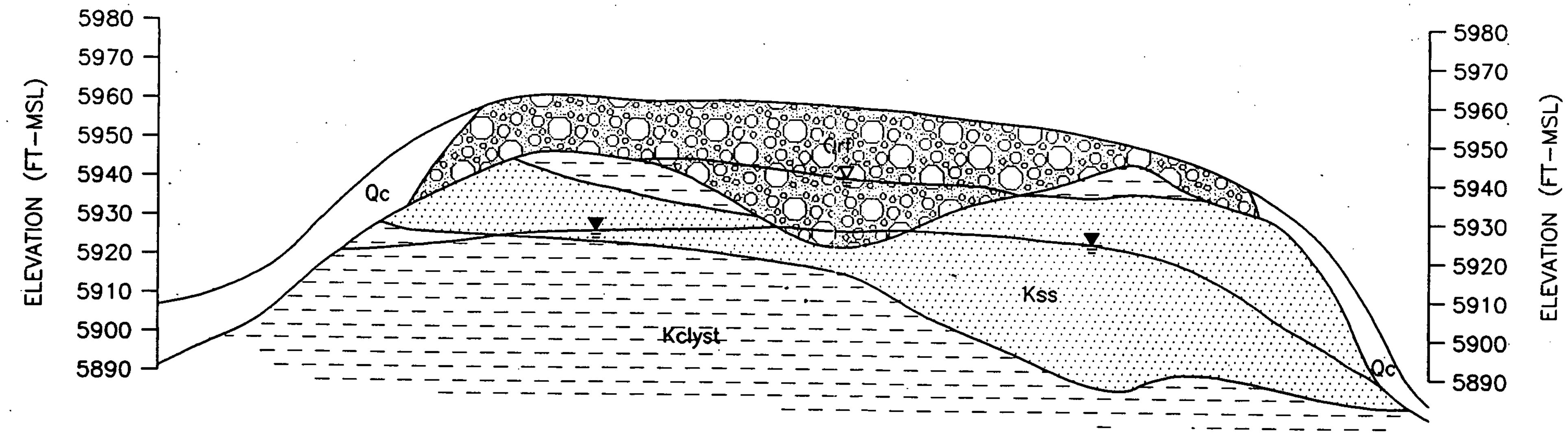
FIGURE 5.3-4 JUNE 1995

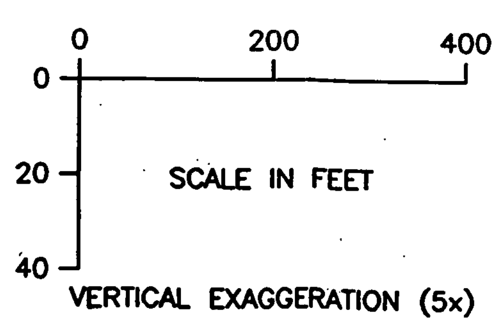
OU2FS022 1=300

MODELED LAYERS



HYDROGEOLOGIC CROSS-SECTION





EXPLANATION

- Qc — COLLUVIUM
- Qrf — ROCKY FLATS ALLUVIUM
- Kss — ARAPAHOE NO.1 SANDSTONE
- Kclyst — ARAPAHOE/LARAMIE CLAYSTONE
- CLAYSTONE SIMULATED USING VERTICAL CONDUCTANCE
- ALLUVIAL POTENTIOMETRIC SURFACE
- NO.1 SANDSTONE POTENTIOMETRIC SURFACE

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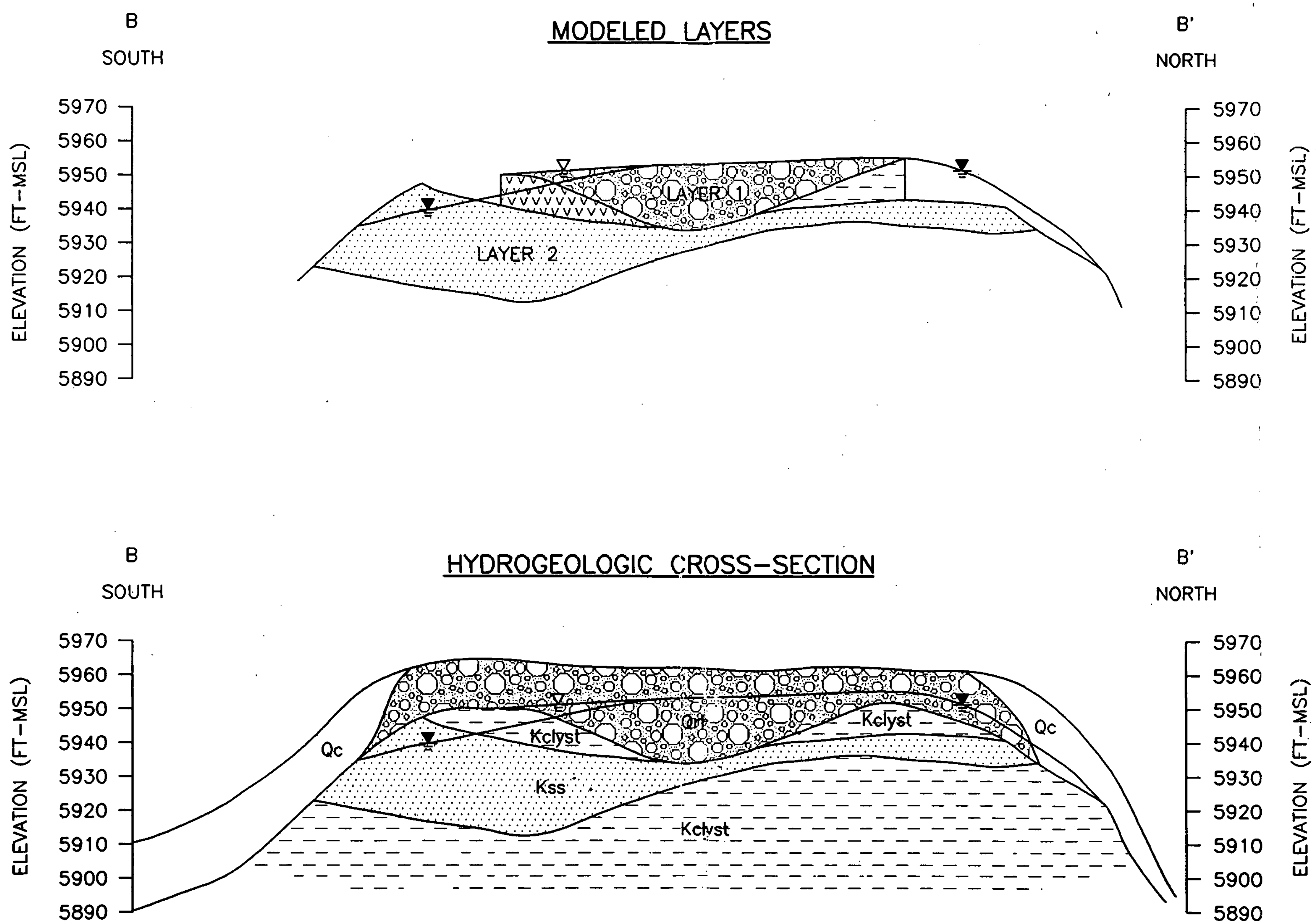
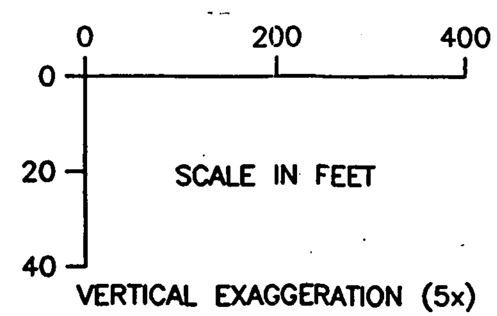
MODEL SETUP
CROSS SECTION A–A'

FIGURE 5.3–5 JUNE 1995

SEC–A 1=1





EXPLANATION

Qc	COLLUVIUM
Qrf	ROCKY FLATS ALLUVIUM
Kss	ARAPAHOE NO.1 SANDSTONE
Kclyst	ARAPAHOE/LARAMIE CLAYSTONE
	CLAYSTONE SIMULATED USING VERTICAL CONDUCTANCE
	ALLUVIAL POTENTIOMETRIC SURFACE
	NO.1 SANDSTONE POTENTIOMETRIC SURFACE

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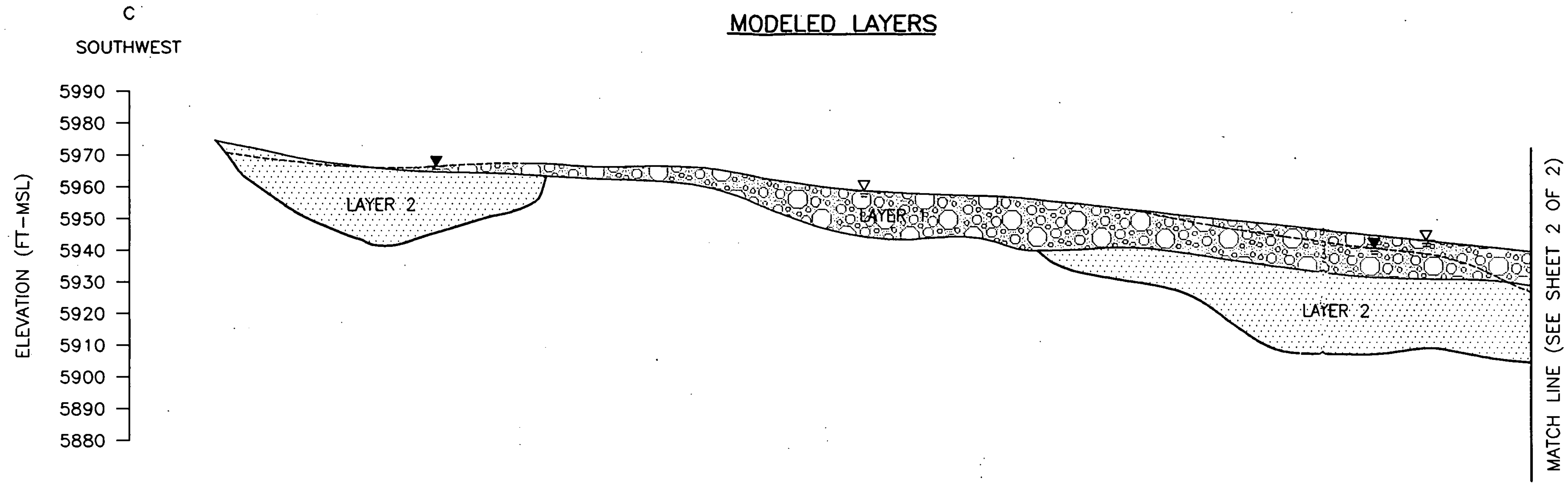
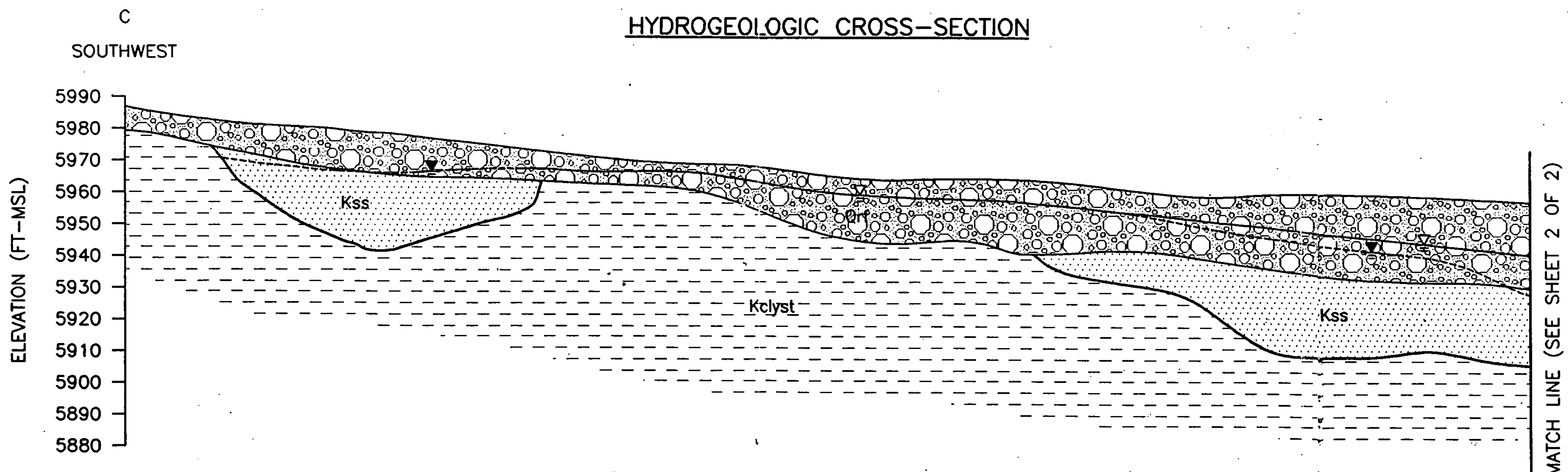
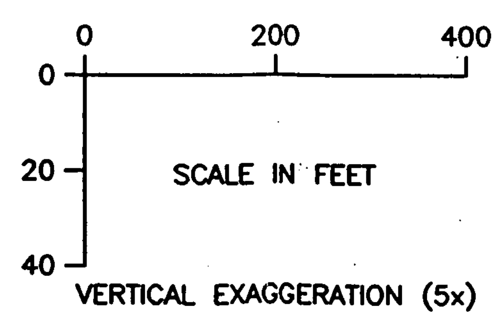
MODEL SETUP
CROSS SECTION B-B'

FIGURE 5.3-6 JUNE 1995

SEC-B 1=1







EXPLANATION

Symbol	Description
Qc	COLLUVIUM
Qrf	ROCKY FLATS ALLUVIUM
Kss	ARAPAHOE NO.1 SANDSTONE
Kclyst	ARAPAHOE/LARAMIE CLAYSTONE
▽	ALLUVIAL POTENTIOMETRIC SURFACE
▼	NO.1 SANDSTONE POTENTIOMETRIC SURFACE

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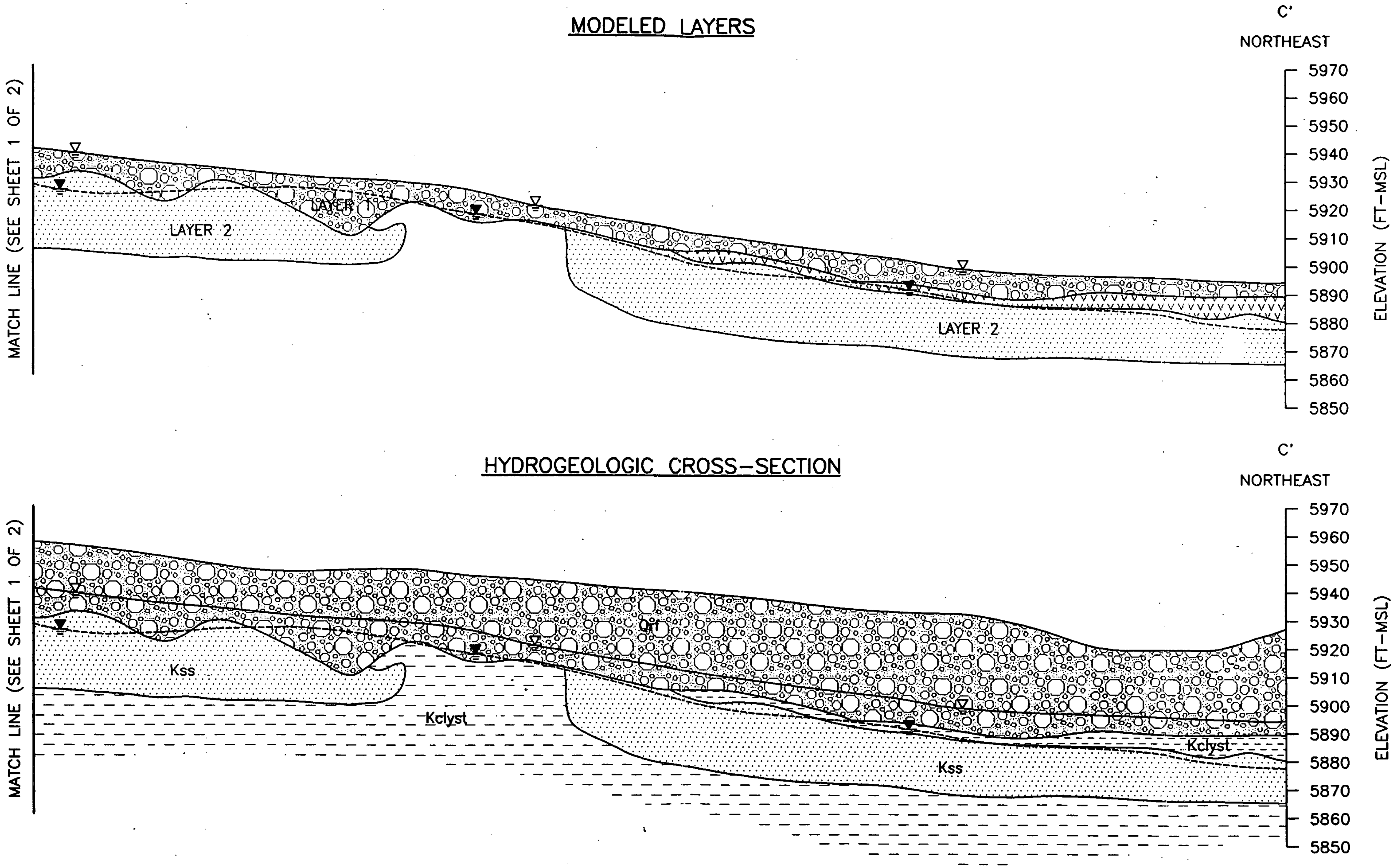
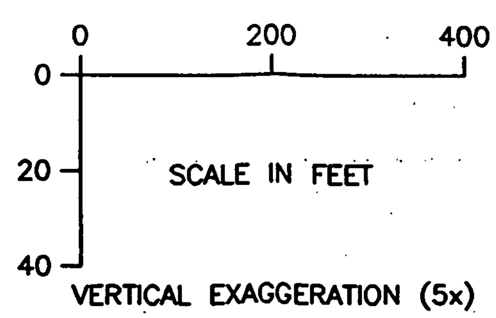
MODEL SETUP
CROSS SECTION C-C'
SHEET 1 OF 2

FIGURE 5.3-7 JUNE 1995

SEC-C1 1=1

79





EXPLANATION

- Qc — COLLUVIUM
- Qrf — ROCKY FLATS ALLUVIUM
- Kss — ARAPAHOE NO.1 SANDSTONE
- Kclyst — ARAPAHOE/LARAMIE CLAYSTONE
- CLAYSTONE SIMULATED USING VERTICAL CONDUCTANCE
- ALLUVIAL POTENTIOMETRIC SURFACE
- NO.1 SANDSTONE POTENTIOMETRIC SURFACE

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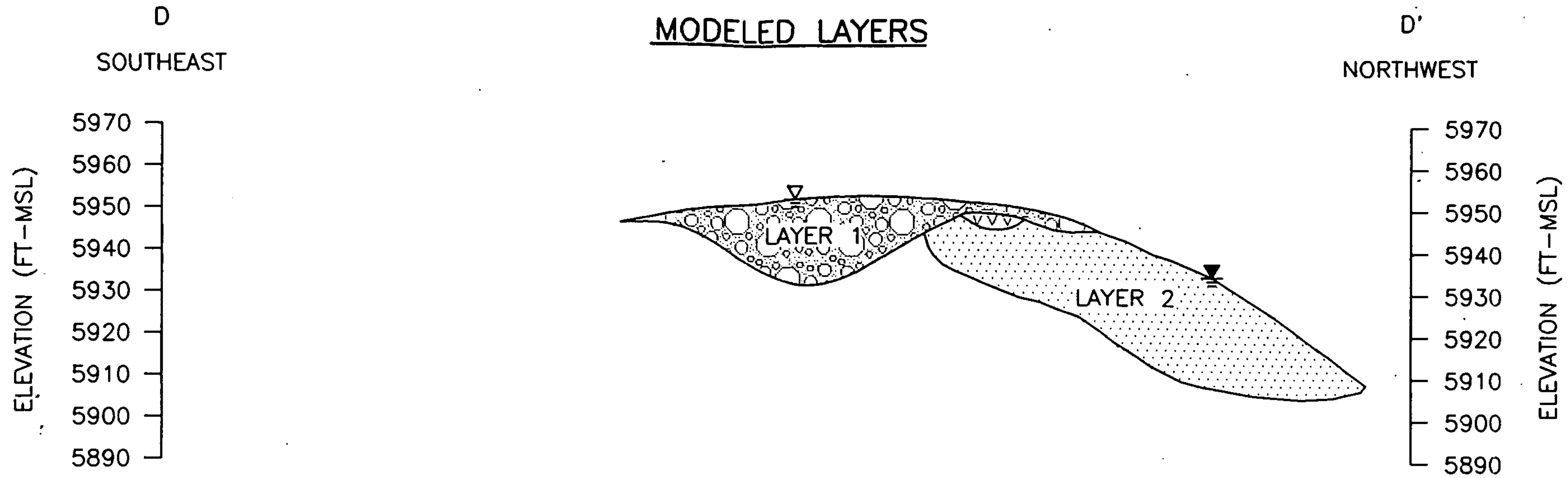
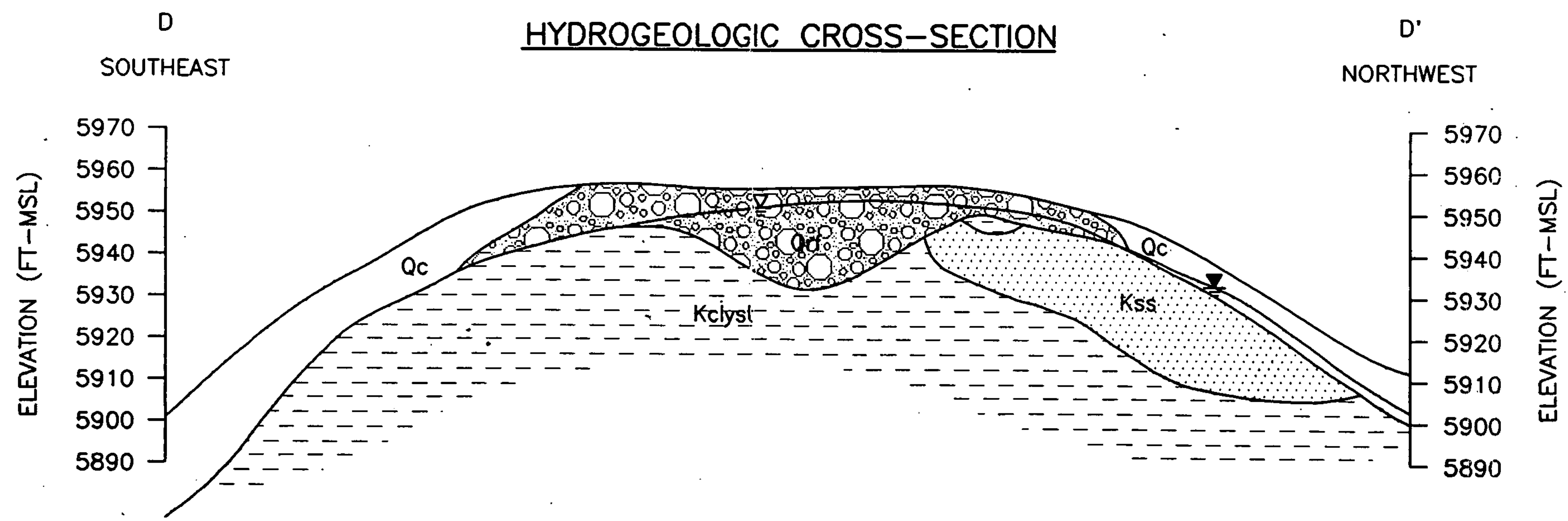
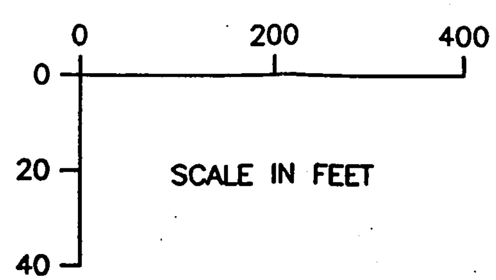
MODEL SETUP
CROSS SECTION C-C'
SHEET 2 OF 2

FIGURE 5.3-7 JUNE 1995

SEC-C2 1=1







VERTICAL EXAGGERATION (5x)

EXPLANATION

- Qc — COLLUVIUM
- Qrf — ROCKY FLATS ALLUVIUM
- Kss — ARAPAHOE NO.1 SANDSTONE
- Kclyst — ARAPAHOE/LARAMIE CLAYSTONE
- CLAYSTONE SIMULATED USING VERTICAL CONDUCTANCE
- ALLUVIAL POTENTIOMETRIC SURFACE
- NO.1 SANDSTONE POTENTIOMETRIC SURFACE

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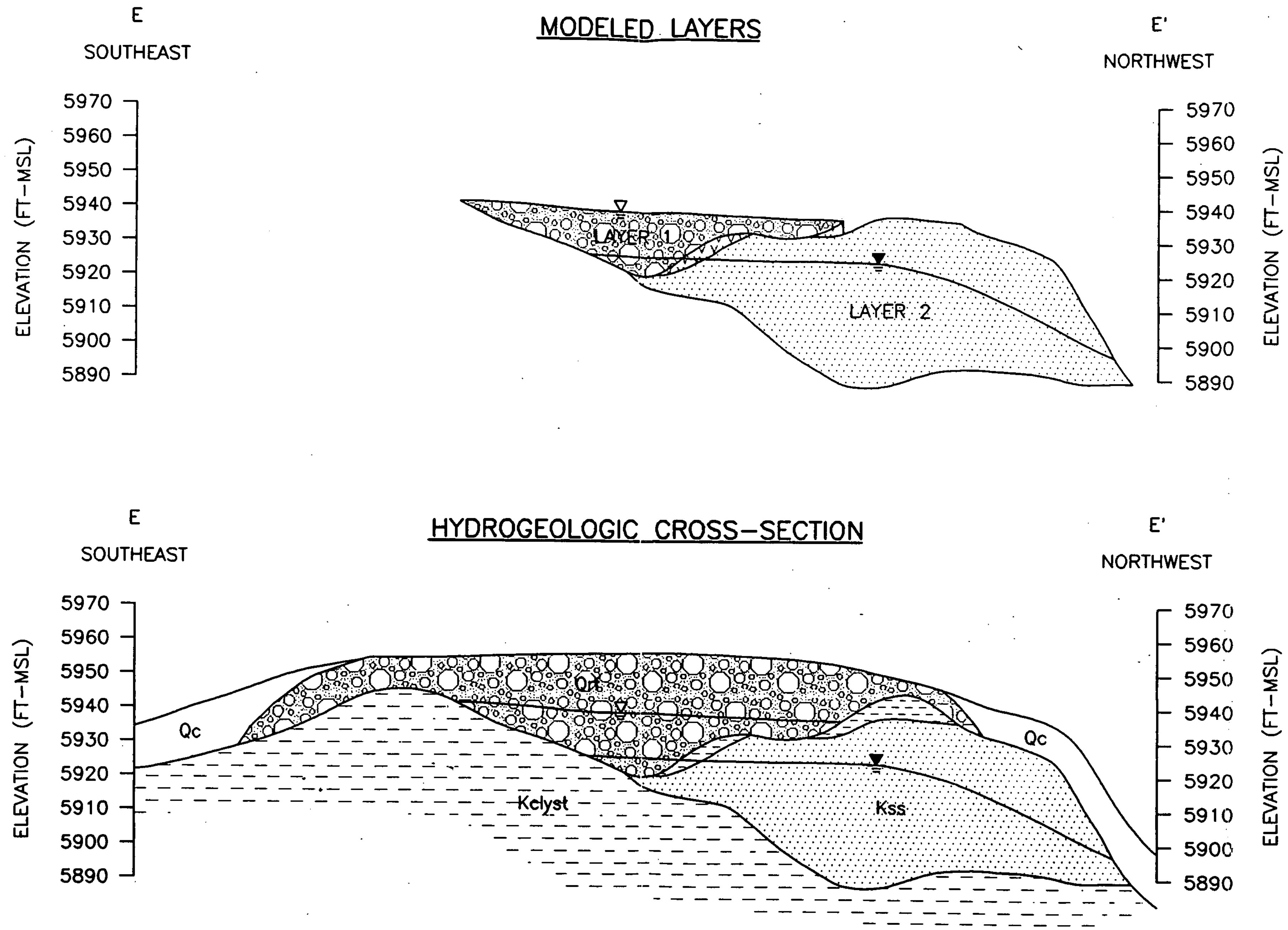
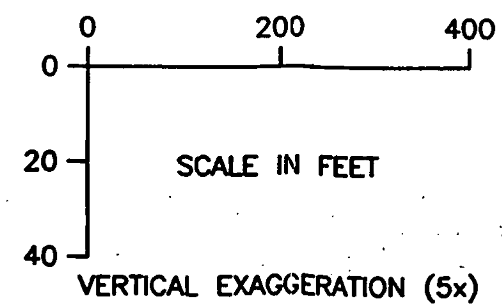
CMS/FS GROUNDWATER FLOW MODELING REPORT

MODEL SETUP
CROSS SECTION D-D'

FIGURE 5.3-8 JUNE 1995

SEC-D 1=1





EXPLANATION

- Qc — COLLUVIUM
- Qrf — ROCKY FLATS ALLUVIUM
- Kss — ARAPAHOE NO.1 SANDSTONE
- Kclyst — ARAPAHOE/LARAMIE CLAYSTONE
- CLAYSTONE SIMULATED USING VERTICAL CONDUCTANCE
- ALLUVIAL POTENTIOMETRIC SURFACE
- NO.1 SANDSTONE POTENTIOMETRIC SURFACE

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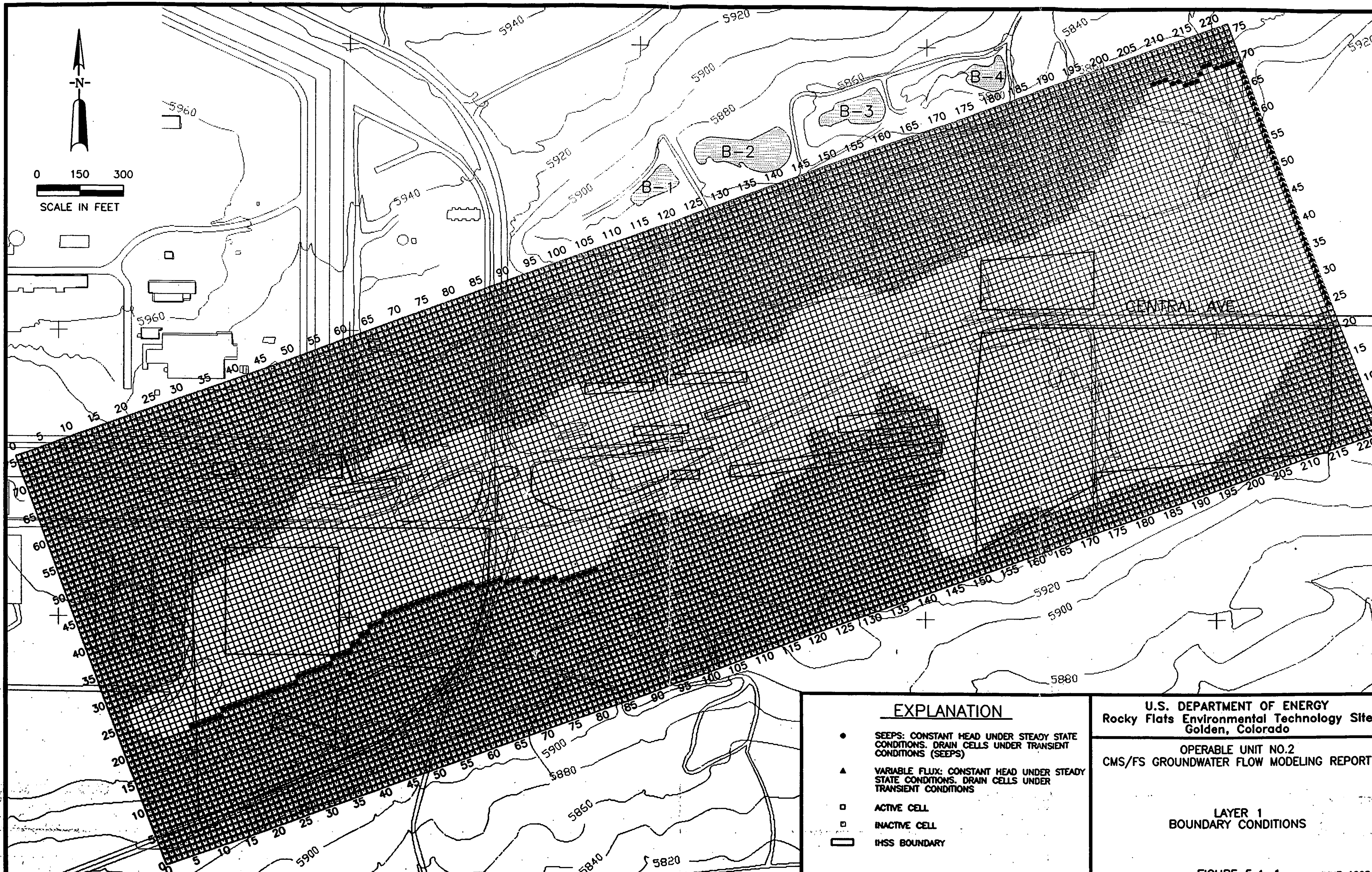
MODEL SETUP
CROSS SECTION E-E'

FIGURE 5.3-9 JUNE 1995

SEC-E 1=1



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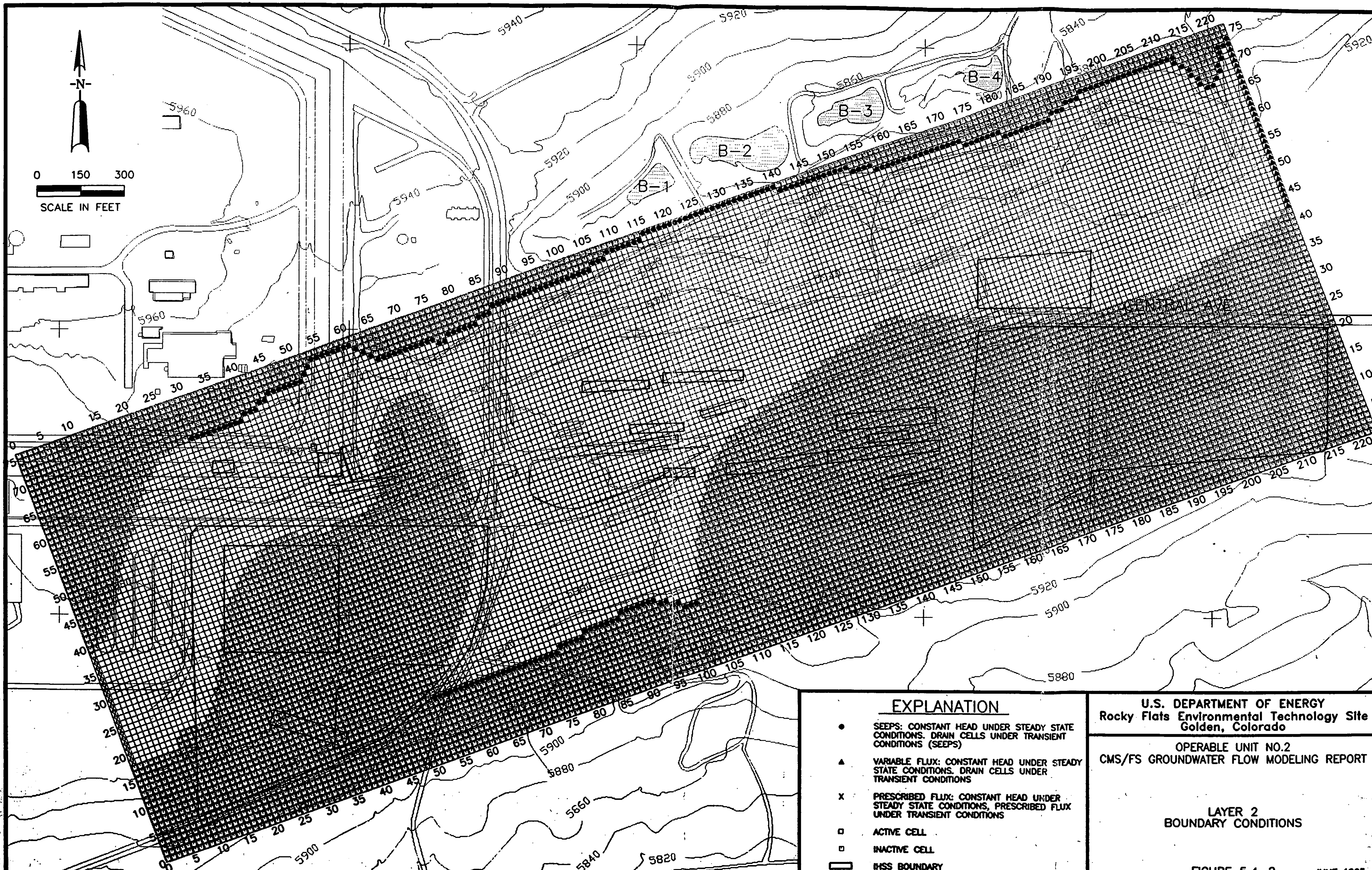
CMS/FS GROUNDWATER FLOW MODELING REPORT

LAYER 1
BOUNDARY CONDITIONS

FIGURE 5.4-1 JUNE 1995

OU2FS024 1=300



EXPLANATION

- ● SEEPS: CONSTANT HEAD UNDER STEADY STATE CONDITIONS. DRAIN CELLS UNDER TRANSIENT CONDITIONS (SEEPS)
- ▲ VARIABLE FLUX: CONSTANT HEAD UNDER STEADY STATE CONDITIONS. DRAIN CELLS UNDER TRANSIENT CONDITIONS
- x PRESCRIBED FLUX: CONSTANT HEAD UNDER STEADY STATE CONDITIONS, PRESCRIBED FLUX UNDER TRANSIENT CONDITIONS
- ▫ ACTIVE CELL
- ▫ INACTIVE CELL
- ▭ IHSS BOUNDARY

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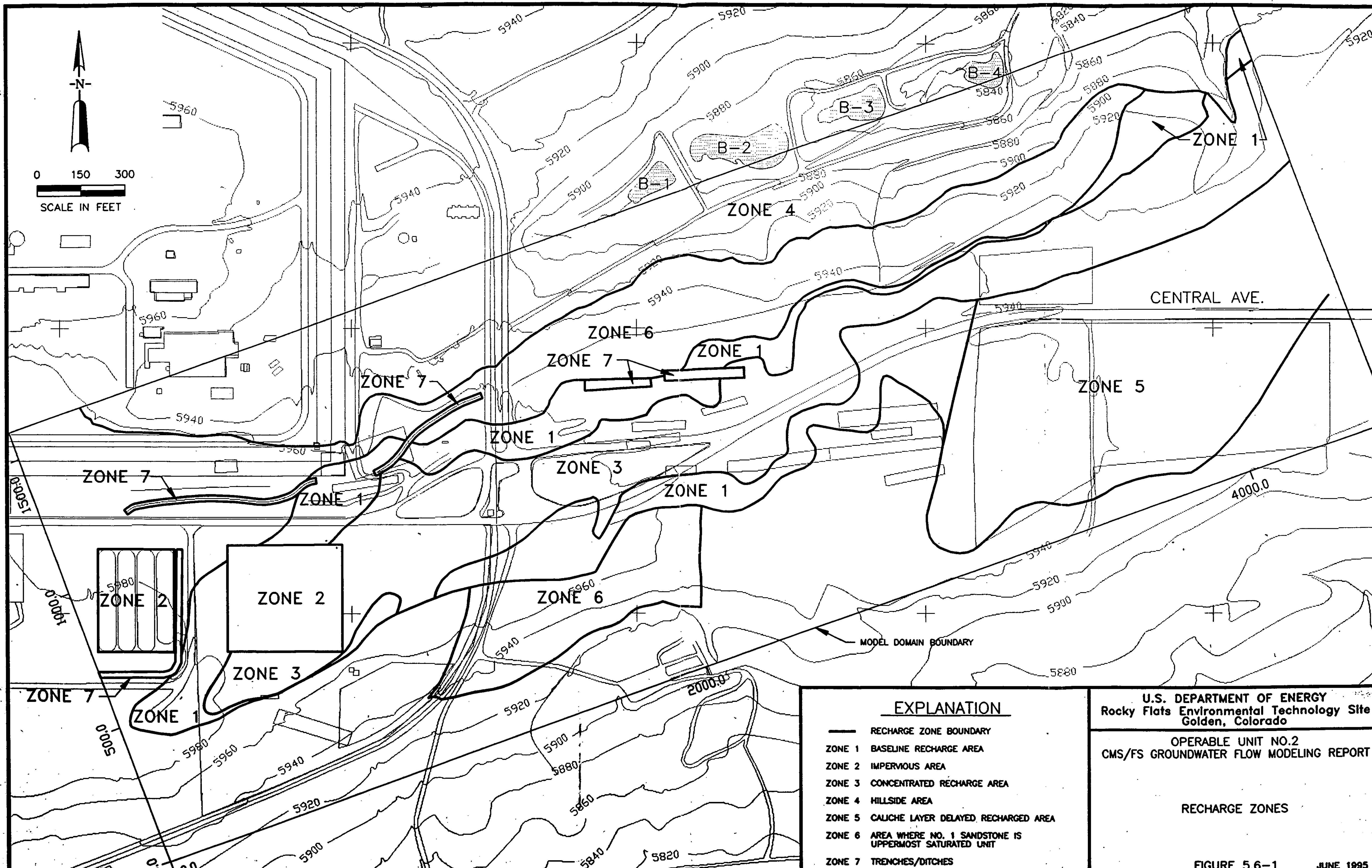
LAYER 2
BOUNDARY CONDITIONS

FIGURE 5.4-2 JUNE 1995

OU2FS025 1=300

84



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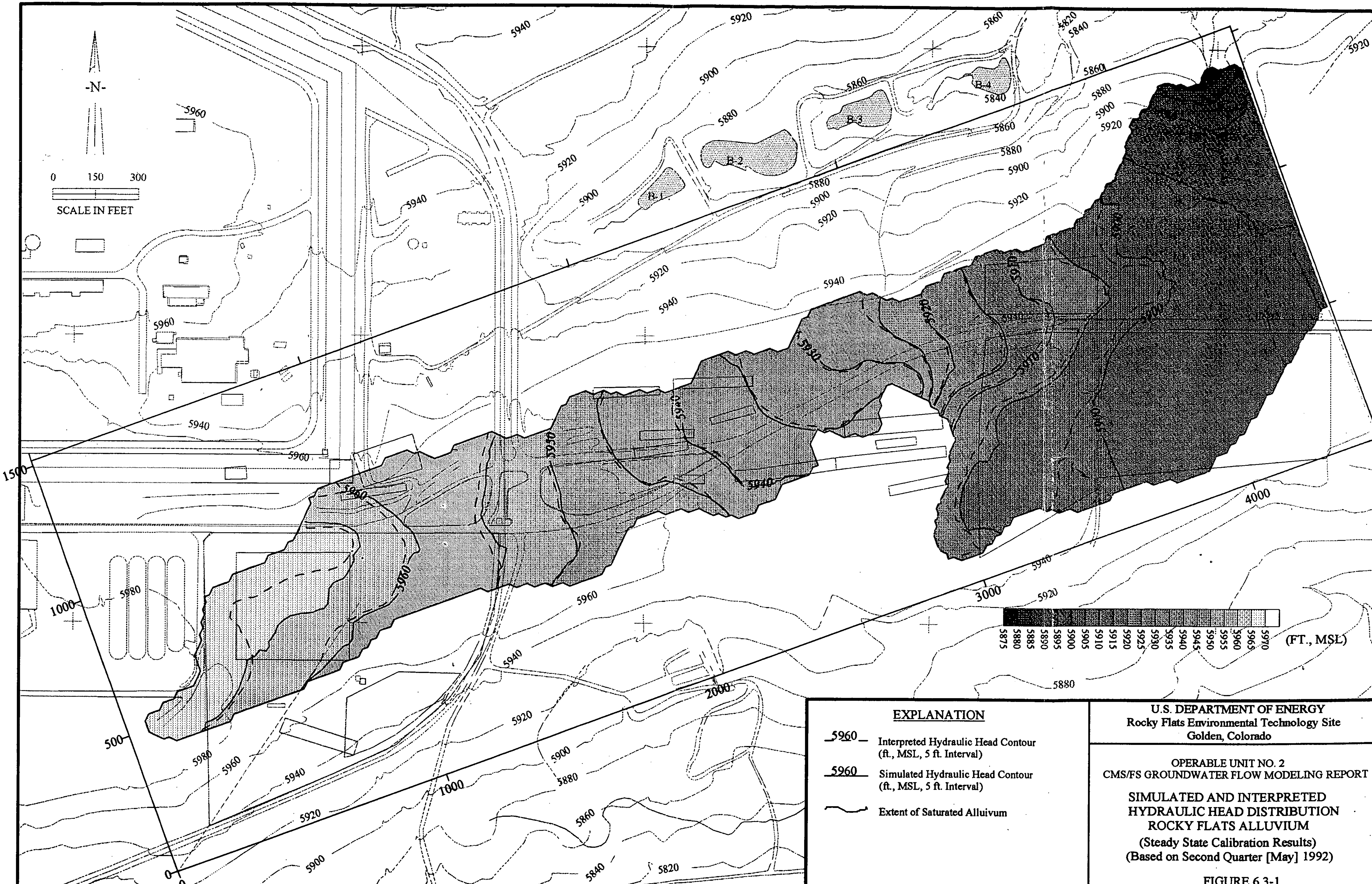
RECHARGE ZONES

FIGURE 5.6-1 JUNE 1995

OU2FS100 1=300



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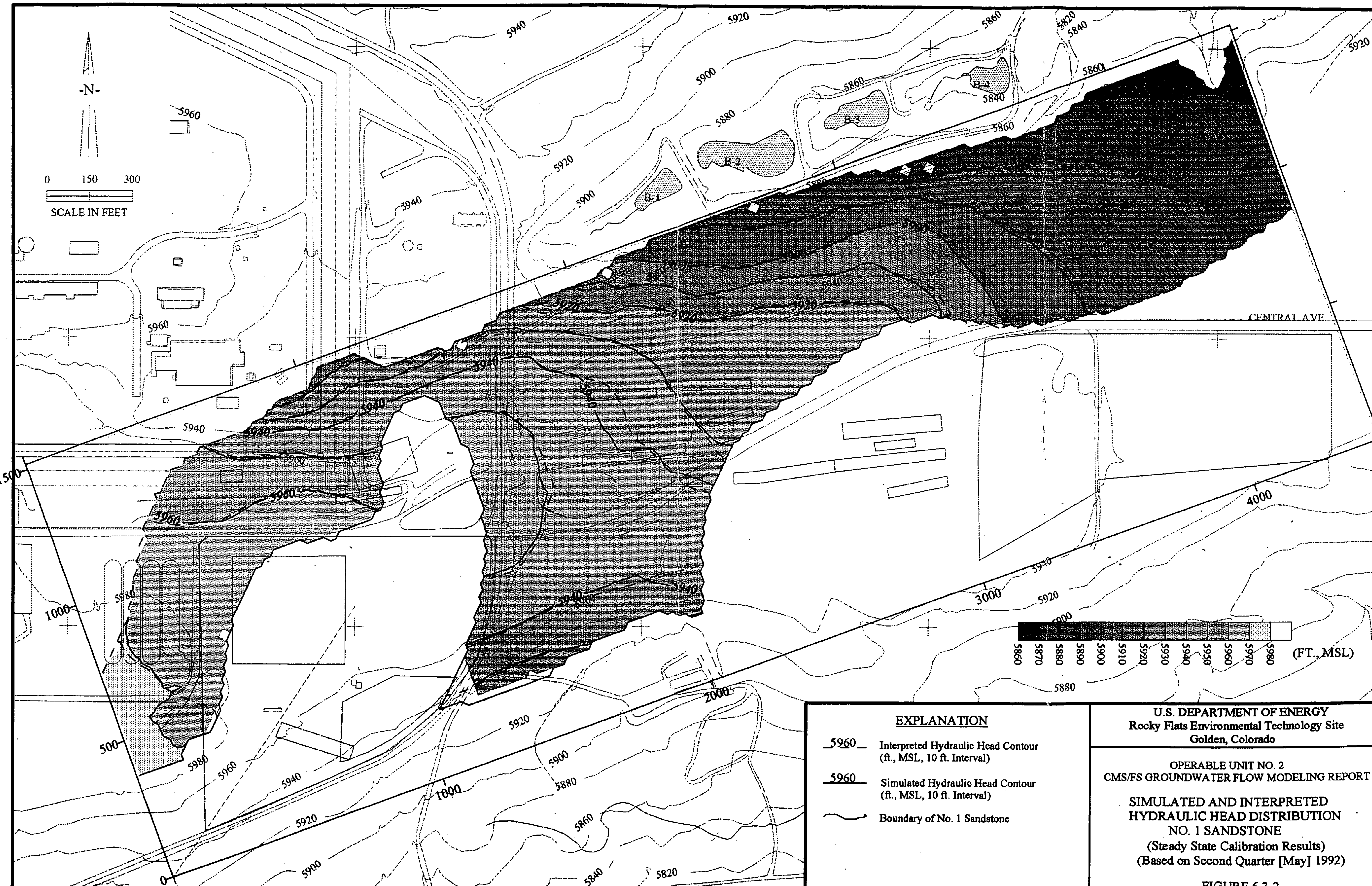
OPERABLE UNIT NO. 2
CMS/FS GROUNDWATER FLOW MODELING REPORT

SIMULATED AND INTERPRETED HYDRAULIC HEAD DISTRIBUTION ROCKY FLATS ALLUVIUM
(Steady State Calibration Results)
(Based on Second Quarter [May] 1992)

FIGURE 6.3-1



EXPLANATION

5960 Interpreted Hydraulic Head Contour (ft., MSL, 10 ft. Interval)

5960 Simulated Hydraulic Head Contour (ft., MSL, 10 ft. Interval)

Boundary of No. 1 Sandstone

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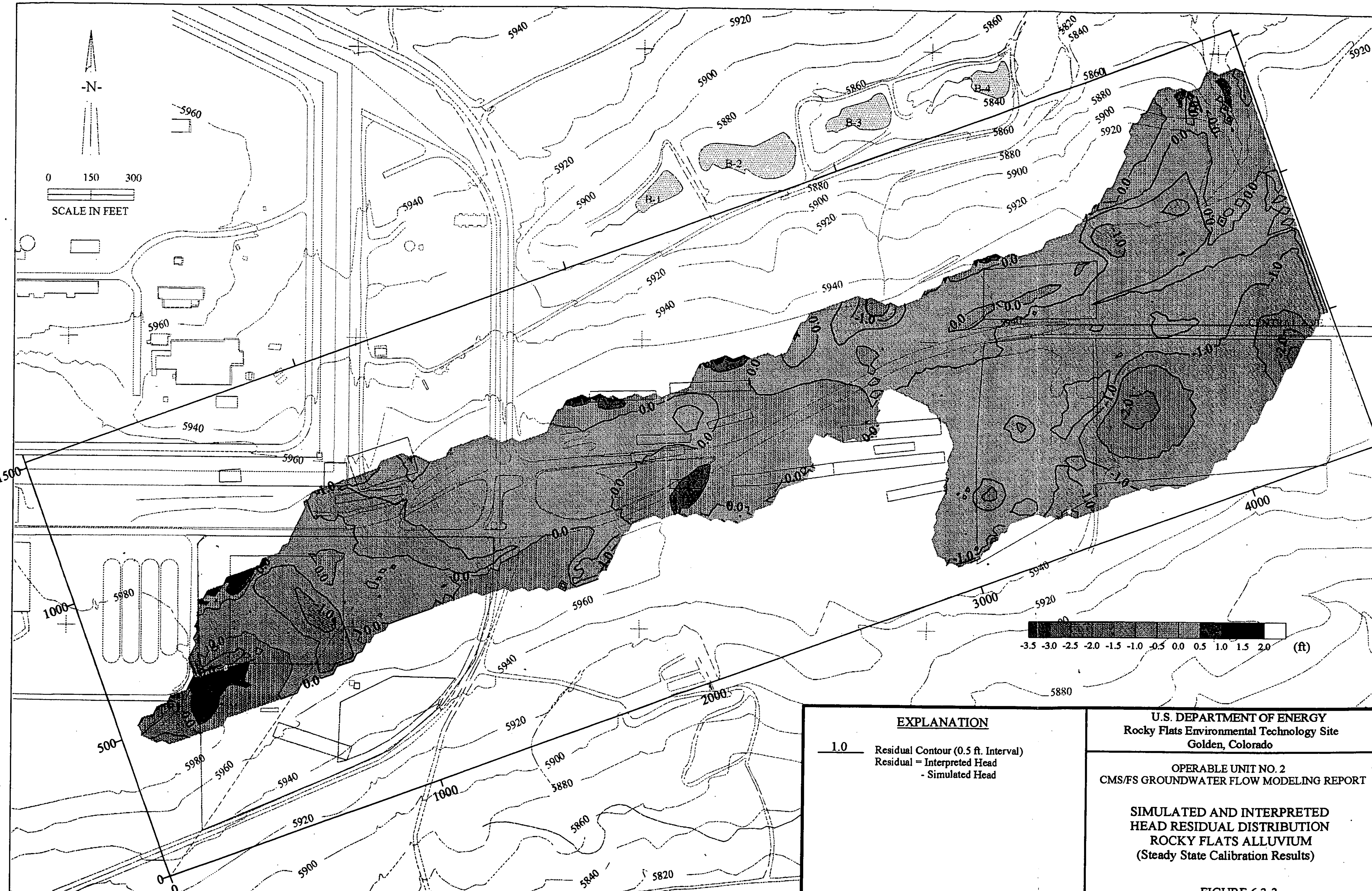
SIMULATED AND INTERPRETED HYDRAULIC HEAD DISTRIBUTION NO. 1 SANDSTONE
(Steady State Calibration Results)
(Based on Second Quarter [May] 1992)

FIGURE 6.3-2

118



EXPLANATION

1.0 Residual Contour (0.5 ft. Interval)
Residual = Interpreted Head - Simulated Head

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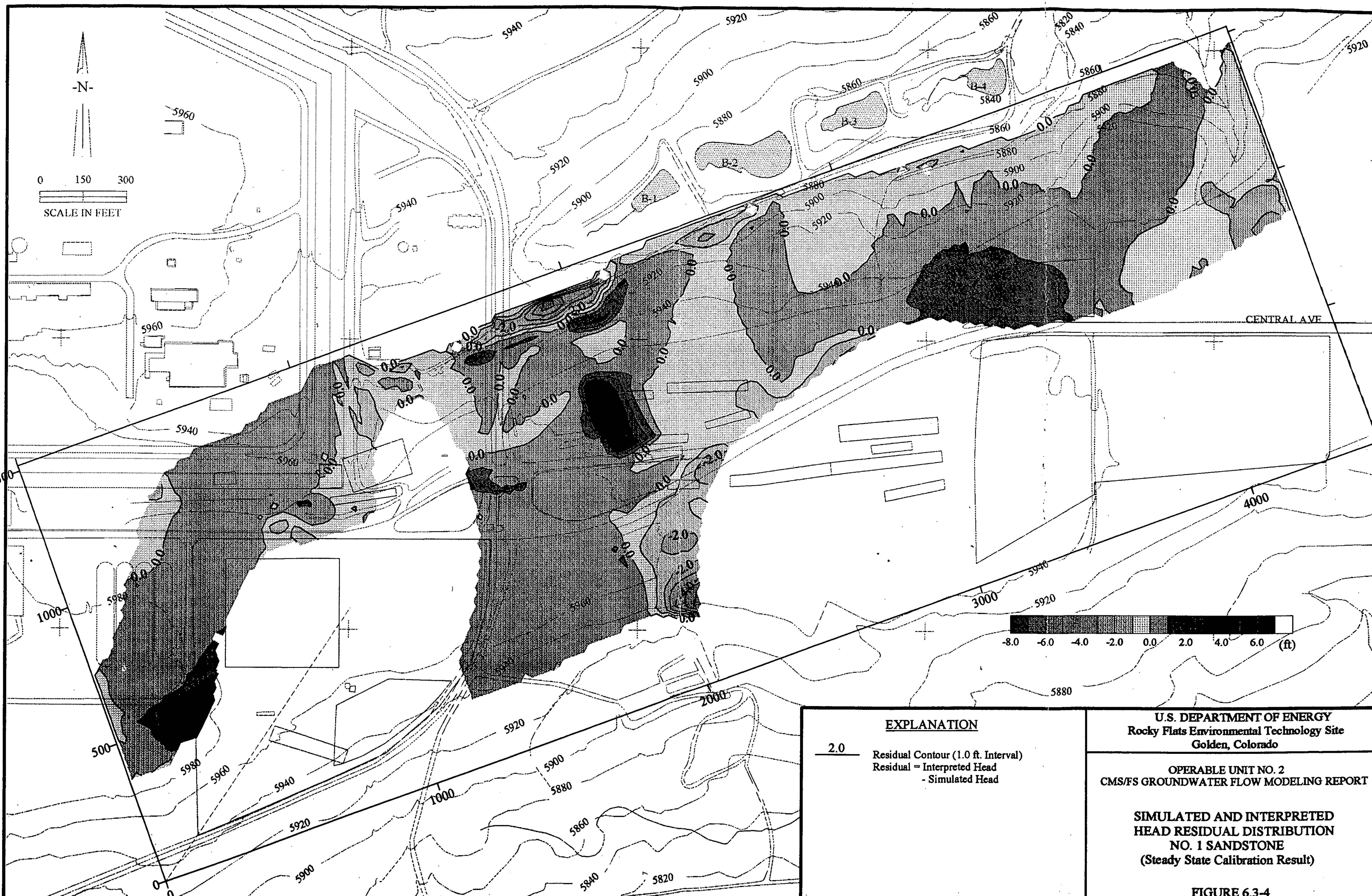
SIMULATED AND INTERPRETED HEAD RESIDUAL DISTRIBUTION ROCKY FLATS ALLUVIUM (Steady State Calibration Results)

FIGURE 6.3-3

119



EXPLANATION

2.0 — Residual Contour (1.0 ft. Interval)
Residual = Interpreted Head - Simulated Head

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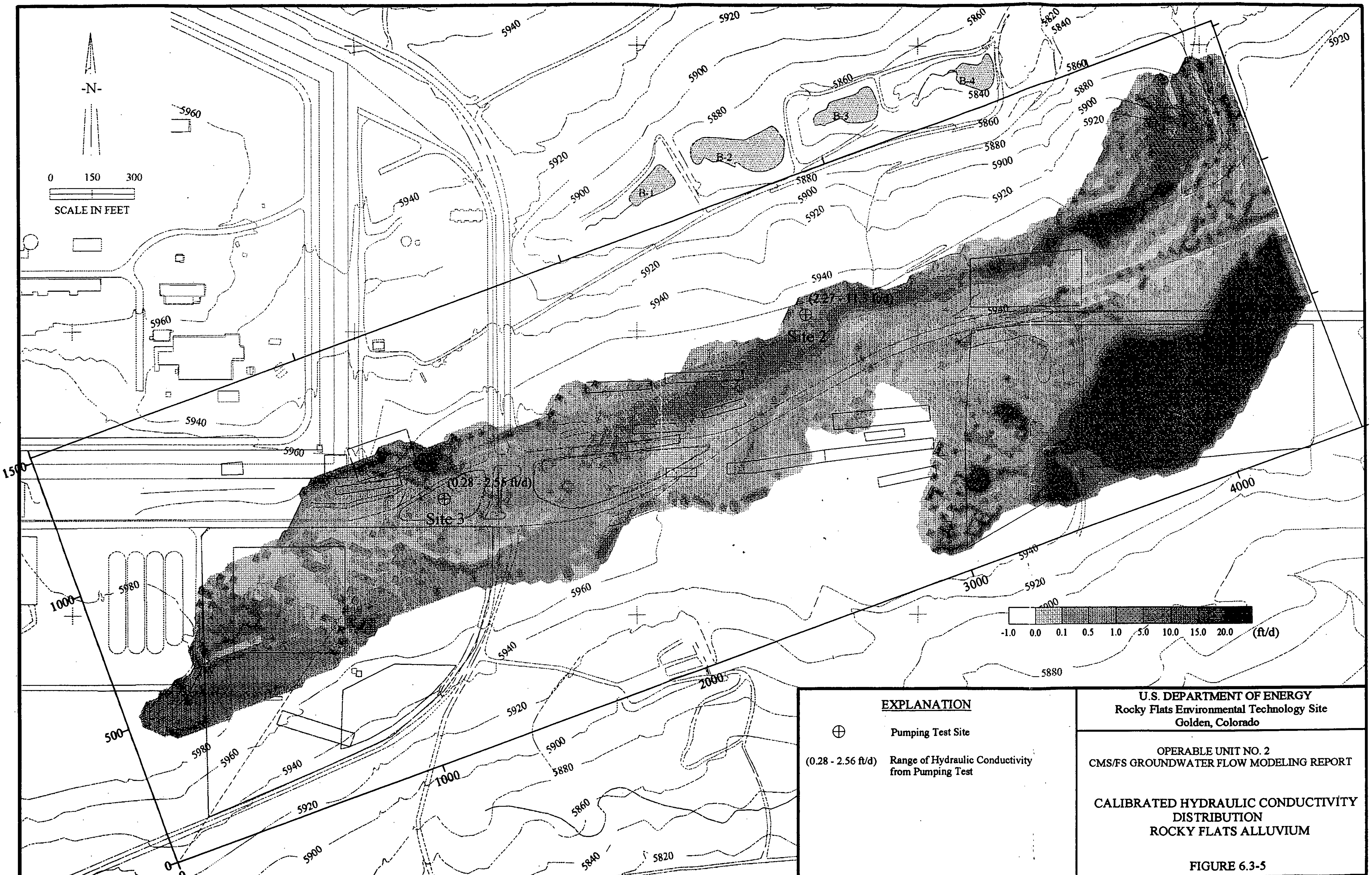
OPERABLE UNIT NO. 2
CMS/FS GROUNDWATER FLOW MODELING REPORT

SIMULATED AND INTERPRETED HEAD RESIDUAL DISTRIBUTION NO. 1 SANDSTONE (Steady State Calibration Result)

FIGURE 6.3-4



EXPLANATION

⊕ Pumping Test Site

(0.28 - 2.56 ft/d) Range of Hydraulic Conductivity from Pumping Test

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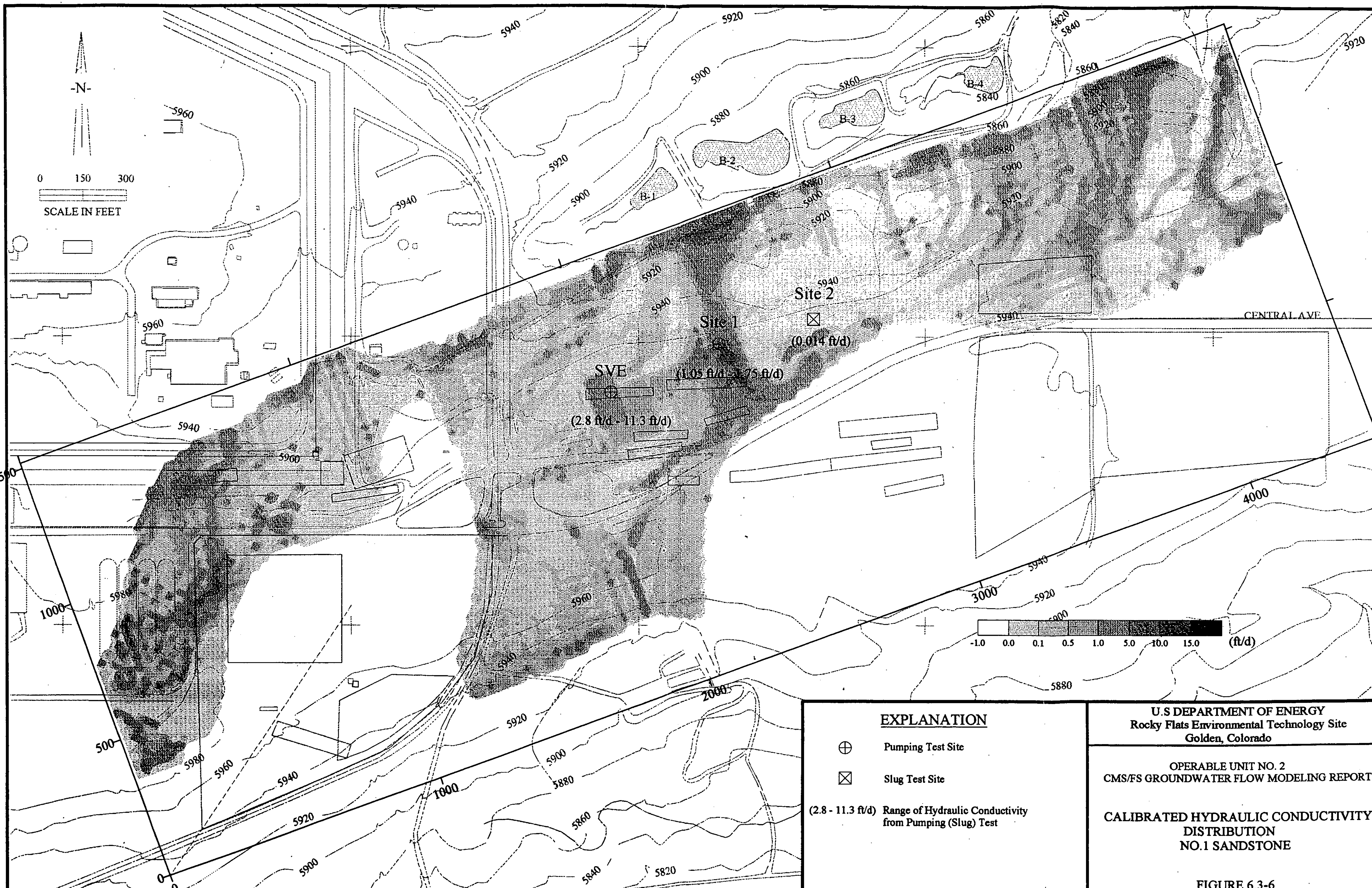
CALIBRATED HYDRAULIC CONDUCTIVITY DISTRIBUTION
ROCKY FLATS ALLUVIUM

FIGURE 6.3-5

121



EXPLANATION

⊕ Pumping Test Site

⊠ Slug Test Site

(2.8 - 11.3 ft/d) Range of Hydraulic Conductivity from Pumping (Slug) Test

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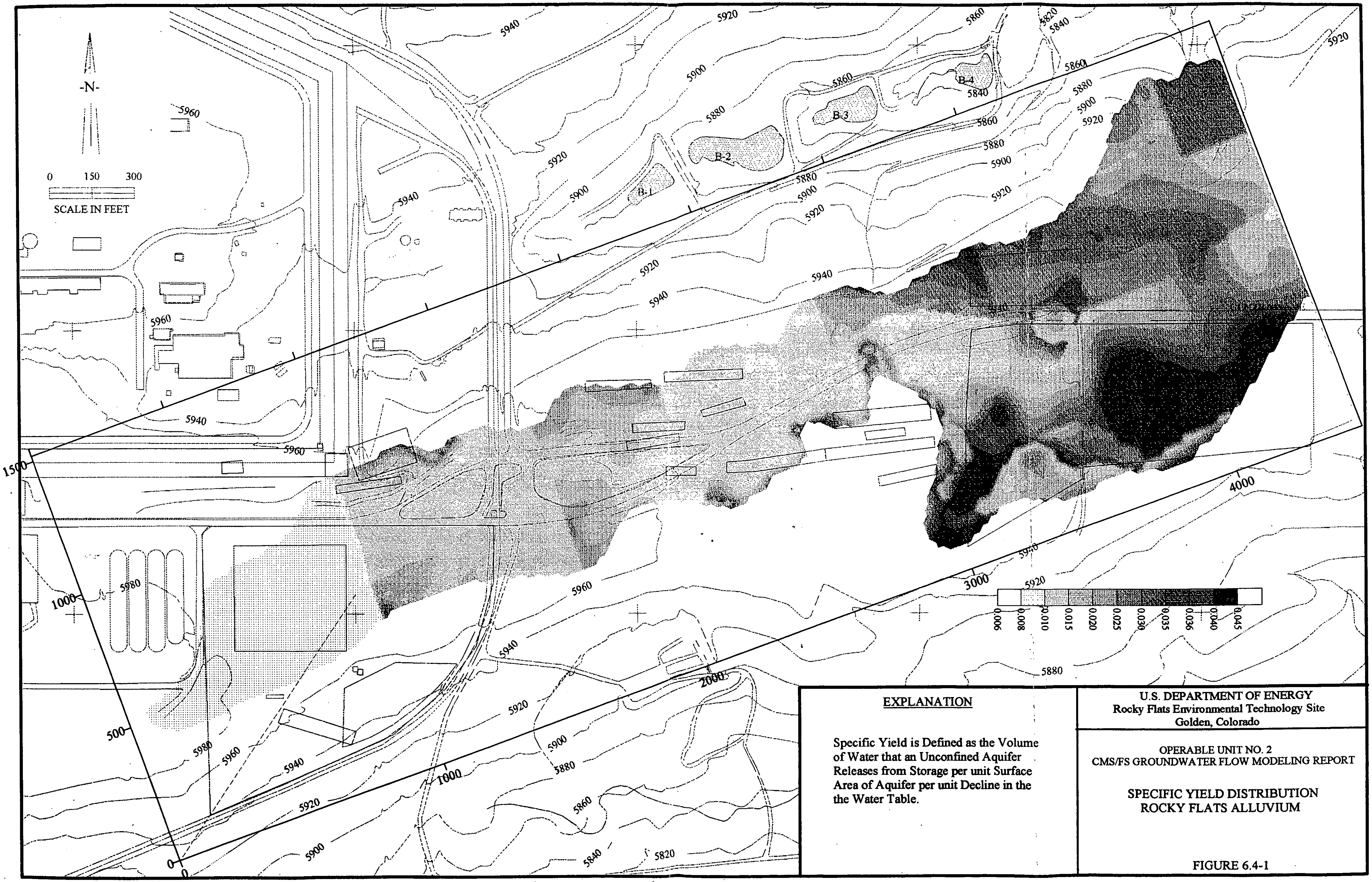
CMS/FS GROUNDWATER FLOW MODELING REPORT

CALIBRATED HYDRAULIC CONDUCTIVITY DISTRIBUTION
NO.1 SANDSTONE

FIGURE 6.3-6



EXPLANATION

Specific Yield is Defined as the Volume of Water that an Unconfined Aquifer Releases from Storage per unit Surface Area of Aquifer per unit Decline in the the Water Table.

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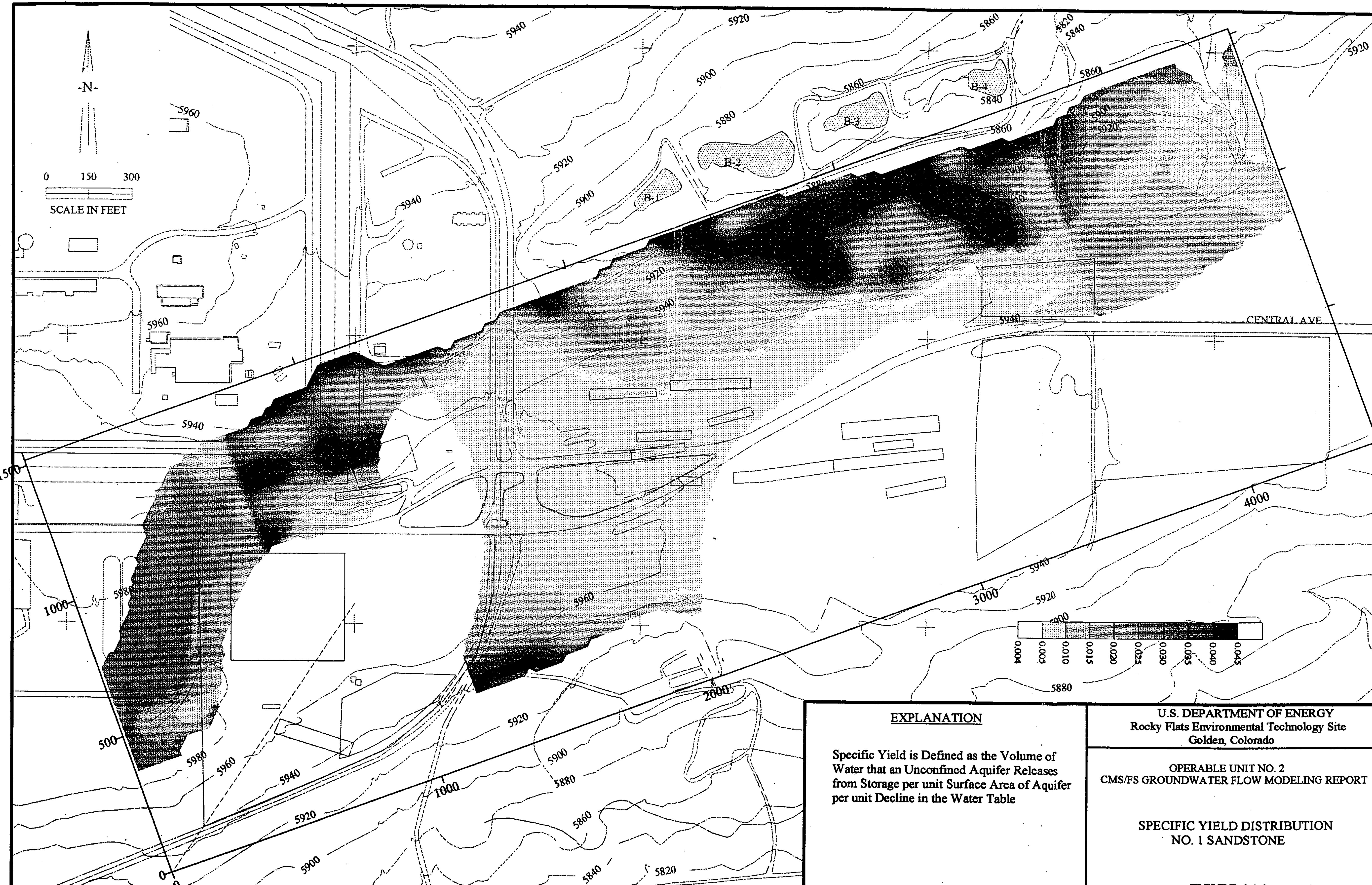
SPECIFIC YIELD DISTRIBUTION
ROCKY FLATS ALLUVIUM

FIGURE 6.4-1

125



EXPLANATION

Specific Yield is Defined as the Volume of Water that an Unconfined Aquifer Releases from Storage per unit Surface Area of Aquifer per unit Decline in the Water Table

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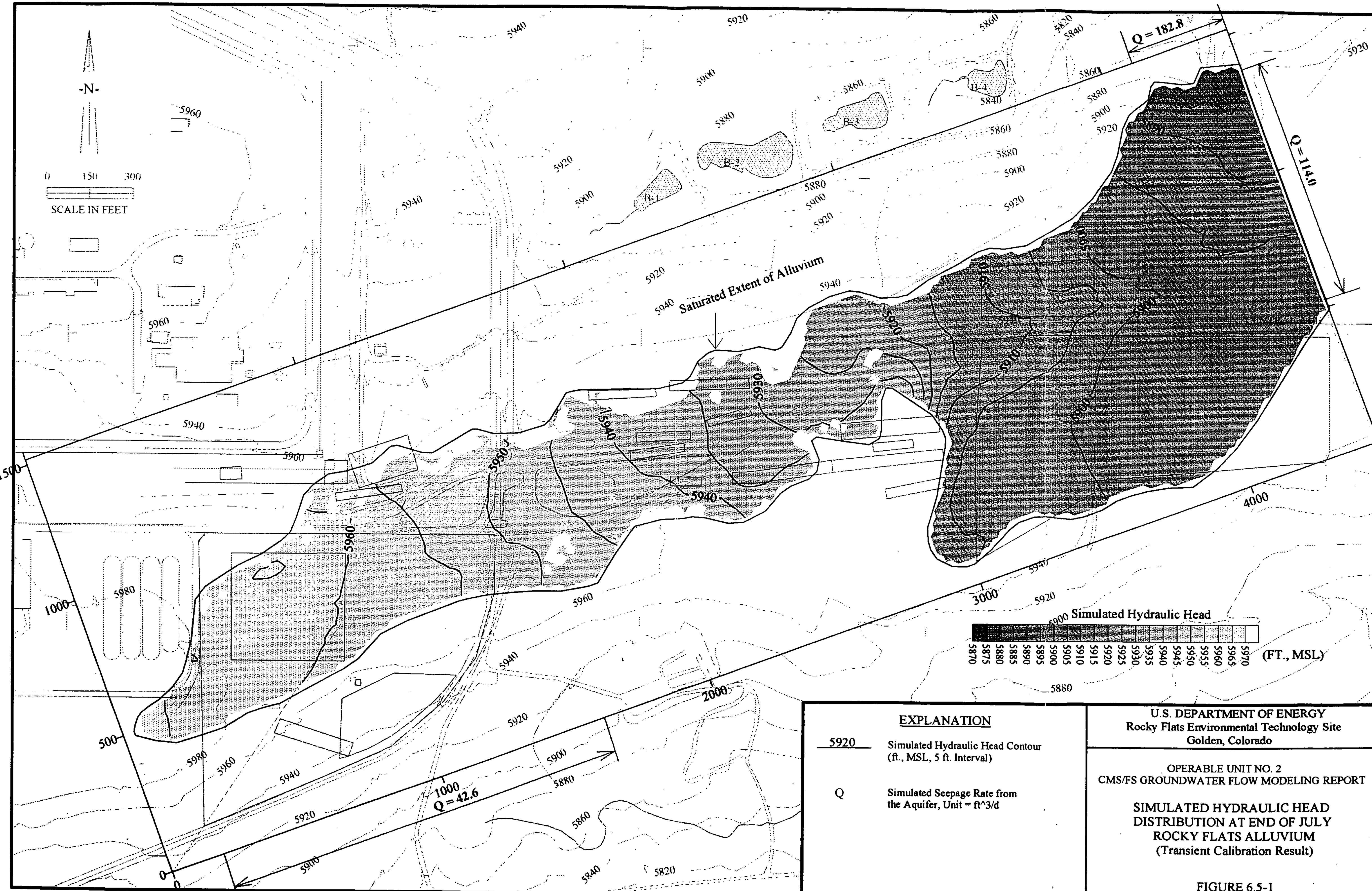
CMS/FS GROUNDWATER FLOW MODELING REPORT

SPECIFIC YIELD DISTRIBUTION
NO. 1 SANDSTONE

FIGURE 6.4-2

126



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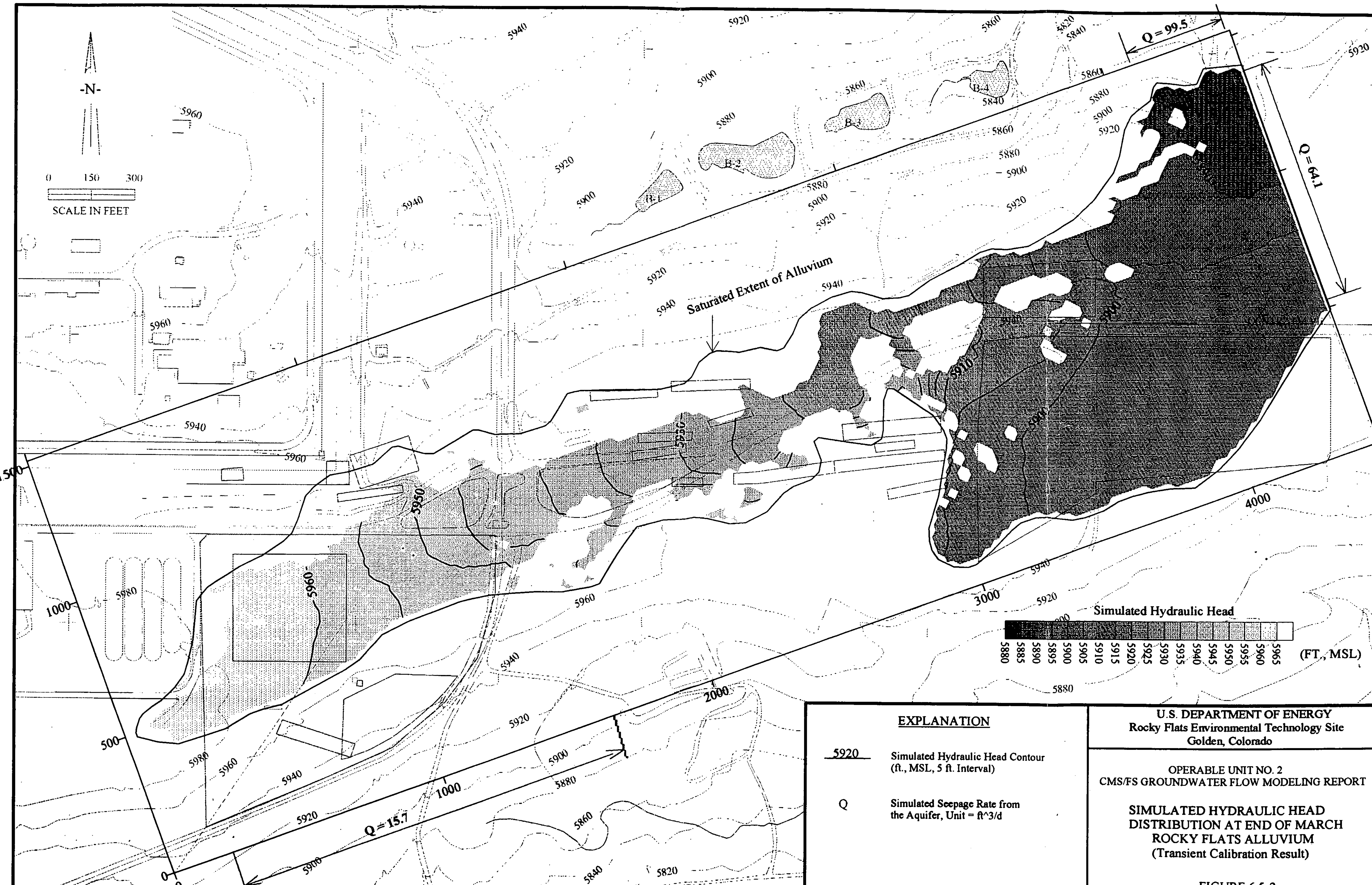
OPERABLE UNIT NO. 2
CMS/FS GROUNDWATER FLOW MODELING REPORT

SIMULATED HYDRAULIC HEAD DISTRIBUTION AT END OF JULY ROCKY FLATS ALLUVIUM (Transient Calibration Result)

FIGURE 6.5-1

127



EXPLANATION

5920	Simulated Hydraulic Head Contour (ft., MSL, 5 ft. Interval)
Q	Simulated Seepage Rate from the Aquifer, Unit = ft^3/d

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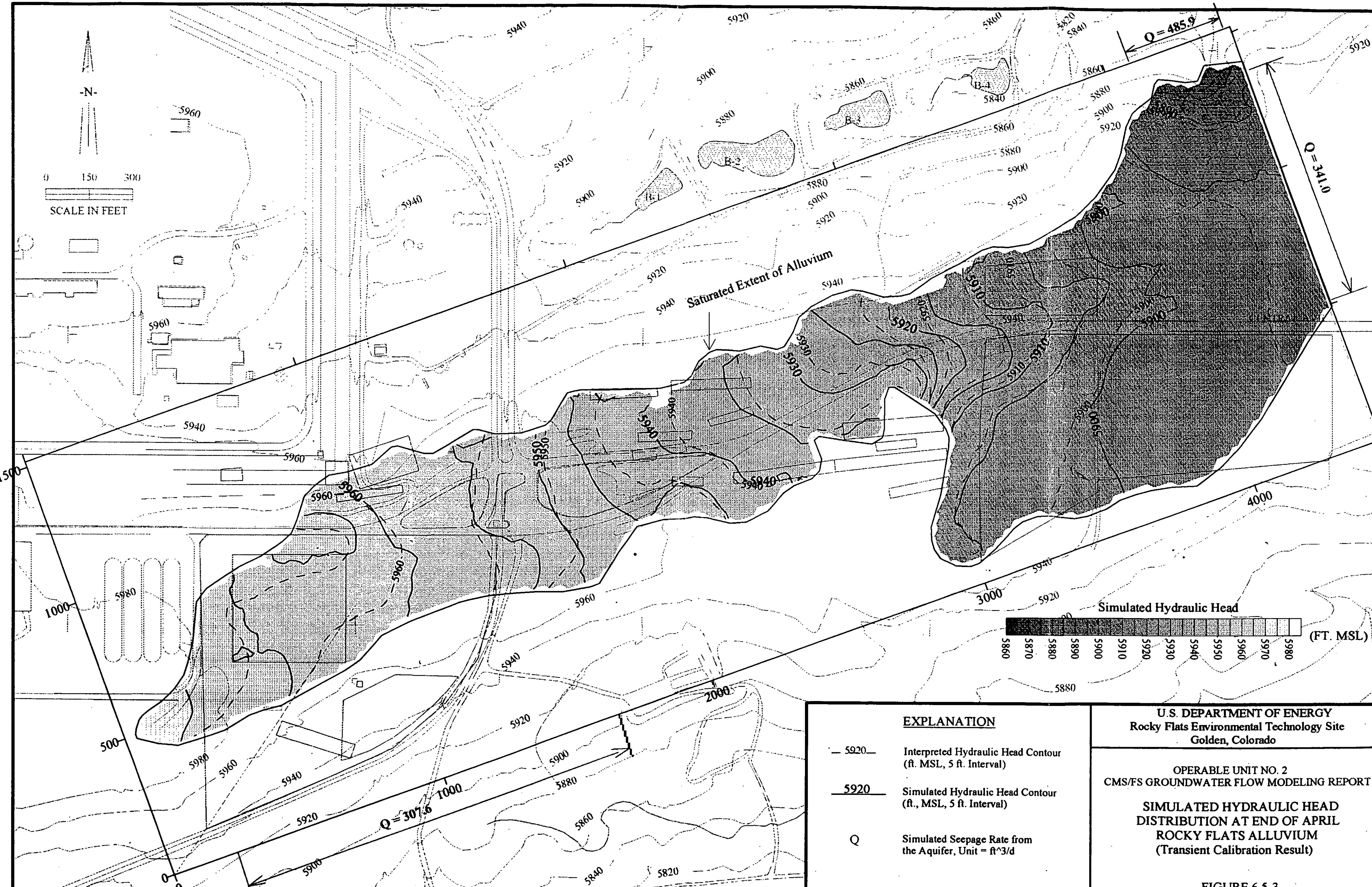
OPERABLE UNIT NO. 2
CMS/FS GROUNDWATER FLOW MODELING REPORT

SIMULATED HYDRAULIC HEAD
DISTRIBUTION AT END OF MARCH
ROCKY FLATS ALLUVIUM
(Transient Calibration Result)

FIGURE 6.5-2

128



-N-
0 150 300
SCALE IN FEET
Saturated Extent of Alluvium
Q = 485.9
Q = 341.0
Q = 307.6
B-1
B-2
B-3
B-4
Simulated Hydraulic Head
5860 5870 5880 5890 5900 5910 5920 5930 5940 5950 5960 5970 5980
(FT. MSL)
EXPLANATION
5920 Interpreted Hydraulic Head Contour (ft. MSL, 5 ft. Interval)
5920 Simulated Hydraulic Head Contour (ft., MSL, 5 ft. Interval)
Q Simulated Seepage Rate from the Aquifer, Unit = ft^3/d
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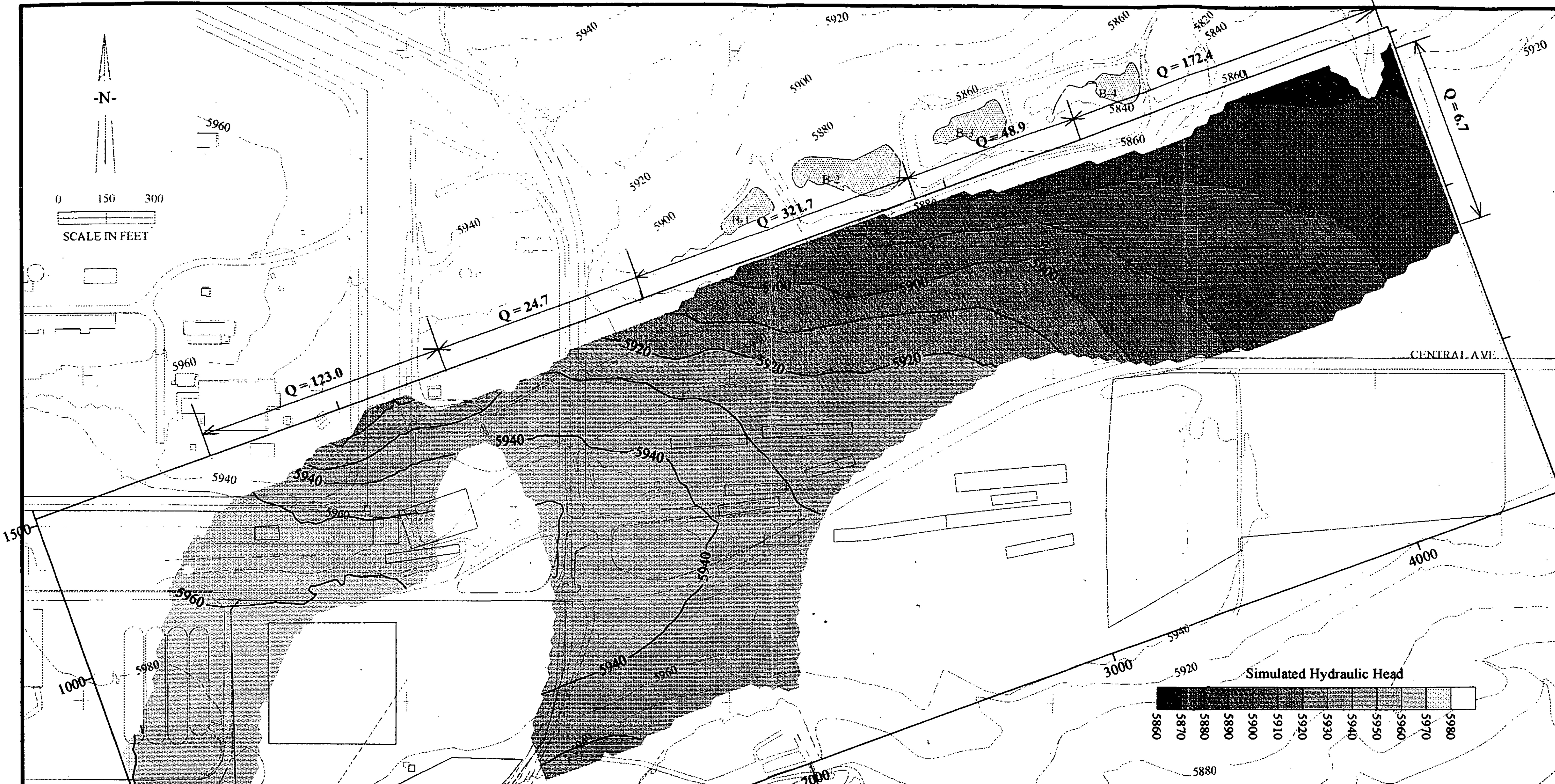
OPERABLE UNIT NO. 2
CMS/FS GROUNDWATER FLOW MODELING REPORT
SIMULATED HYDRAULIC HEAD DISTRIBUTION AT END OF APRIL ROCKY FLATS ALLUVIUM (Transient Calibration Result)
FIGURE 6.5-3

129



EXPLANATION

5910 — Simulated Hydraulic Head Contour (ft., MSL, 10 ft. Interval)

Q — Simulated Seepage Rate from the Aquifer, Unit = ft^3/d

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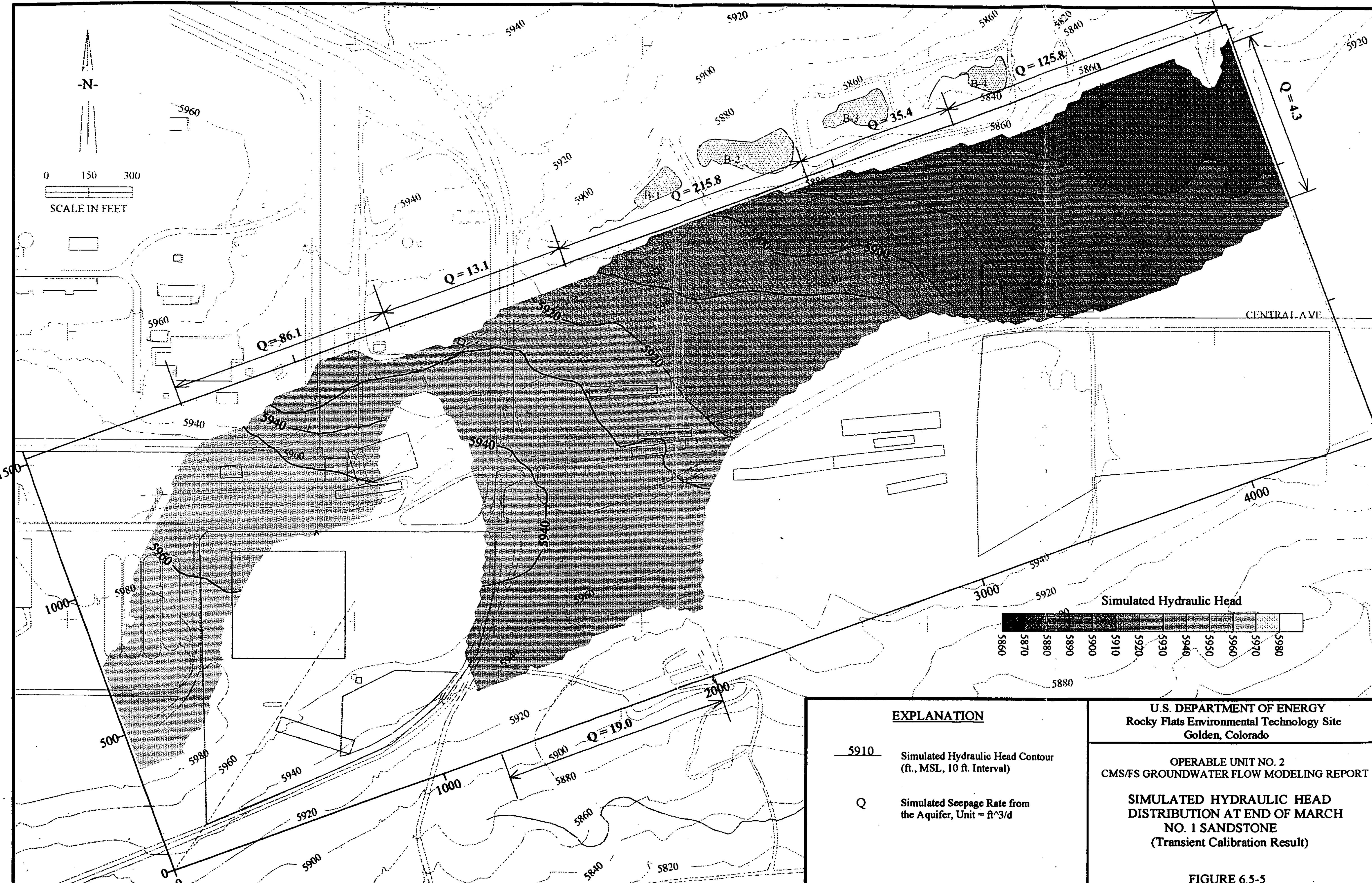
OPERABLE UNIT NO. 2
CMS/FS GROUNDWATER FLOW MODELING REPORT

SIMULATED HYDRAULIC HEAD DISTRIBUTION AT END OF JULY
NO. 1 SANDSTONE
(Transient Calibration Result)

FIGURE 6.5-4

130



EXPLANATION

5910 Simulated Hydraulic Head Contour (ft., MSL, 10 ft. Interval)

Q Simulated Seepage Rate from the Aquifer, Unit = ft^3/d

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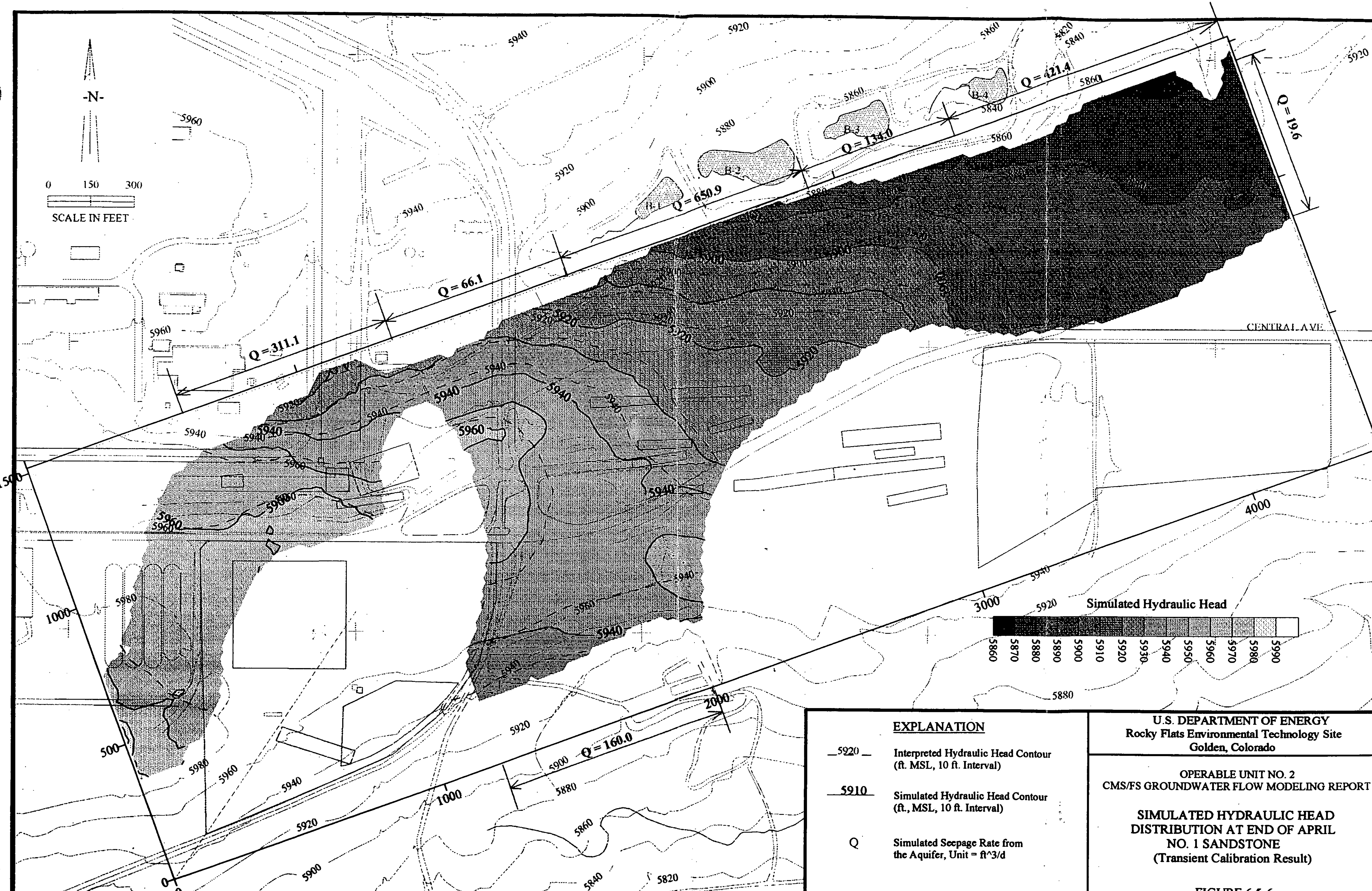
OPERABLE UNIT NO. 2
CMS/FS GROUNDWATER FLOW MODELING REPORT

SIMULATED HYDRAULIC HEAD DISTRIBUTION AT END OF MARCH NO. 1 SANDSTONE
(Transient Calibration Result)

FIGURE 6.5-5



EXPLANATION

5920 — Interpreted Hydraulic Head Contour (ft. MSL, 10 ft. Interval)

5910 — Simulated Hydraulic Head Contour (ft., MSL, 10 ft. Interval)

Q — Simulated Seepage Rate from the Aquifer, Unit = ft^3/d

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OPERABLE UNIT NO. 2
CMS/FS GROUNDWATER FLOW MODELING REPORT

SIMULATED HYDRAULIC HEAD DISTRIBUTION AT END OF APRIL NO. 1 SANDSTONE (Transient Calibration Result)

FIGURE 6.5-6

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