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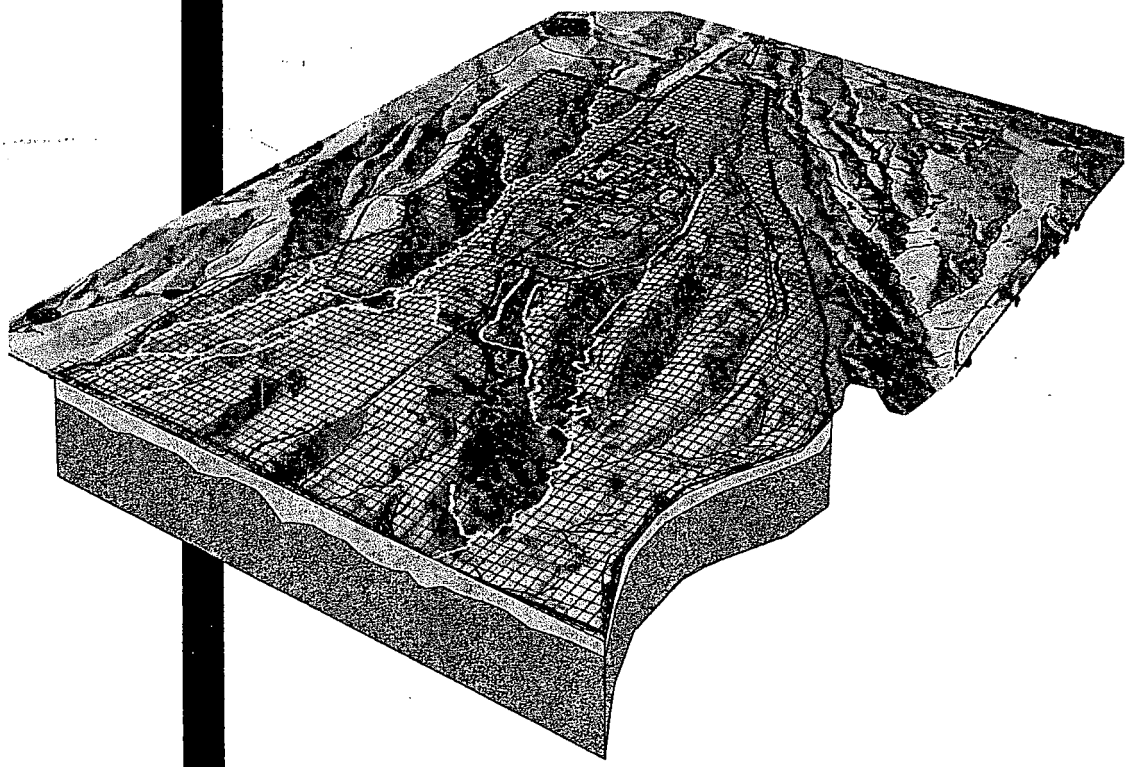
SITE-WIDE WATER BALANCE MODEL REPORT FOR THE ROCKY FLATS ENVIRONMENTAL TECHNOLOGY SITE



Environmental Media Management
Rocky Flats Environmental Technology Site

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EXECUTIVE SUMMARY

Introduction

The Rocky Flats Environmental Technology Site (RFETS or Site) is being closed and converted from a nuclear weapons component production facility into a National Wildlife Refuge. Anticipated closure activities will involve reconfiguring portions of the existing Site. These modifications will impact the current Site surface and subsurface hydrology.

A comprehensive approach, incorporating mechanisms that govern the current RFETS hydrology, was required to understand and predict the potential hydrologic changes caused by anticipated closure activities. The hydrologic system is strongly influenced by surface-groundwater interactions due to the Site's semi-arid climate. The hydrologic system is complicated by man-made modifications within the Industrial Area that impact both surface and subsurface flows.

This report summarizes the development and application of a fully-integrated hydrologic model that was developed as a management tool. The tool captures the complex flow conditions and was used to assess the hydrologic impacts caused by hypothetical changes to the current Site configuration.

Objective

The primary objective of the Site-Wide Water Balance (SWWB) study was to create a decision tool to quantitatively assess the integrated hydrologic conditions at the RFETS. Specifically, this integrated model was used to: (1) comprehend and simulate current Site hydrologic conditions; and (2) assess the hydrologic impacts caused by hypothetical modifications to the current Site configuration.

The integrated model was designed to simulate important drainage basin-scale processes that control RFETS hydrology. It was not designed to simulate localized flows in features such as individual pipes or culverts, directly to model contaminant transport or evaluate engineering designs. However, the model was developed so that its input and

output could be used to facilitate contaminant transport evaluations or engineering design calculations.

General Approach

To achieve the SWWB objectives, the following tasks were identified and conducted:

- Collected Site-specific data to support development of the conceptual and numerical hydrologic models (data included surface water and groundwater hydrology, surface and sub-surface Industrial Area structures, topography, geology, soils and vegetation);
- Developed the conceptual hydrologic model based on existing knowledge;
- Developed the modeling approach appropriate for the Site (including code selection and verification);
- Developed the numerical model based on a selected computer code;
- Evaluated model performance (including calibration, validation and sensitivity analysis);
- Applied the model to two hypothetical Site scenarios; and
- Assessed the model results for implications to Site closure.

Conceptual Flow Model

In order to develop the numerical model framework, a conceptual model was developed for the Site-wide flow system. The RFETS conceptual model considered the relevant surface and subsurface flow processes, their interactions and Site features affecting flows. The conceptual model development was comprehensive and supported by analyzing available Site information, including: (1) past studies; (2) hydrologic and geologic data; and (3) engineering plans and details.

Separate conceptual flow models were developed for the Industrial Area and Buffer Zone. This was necessary to assess the different observed flow responses in each area. The fully-integrated hydrologic model simulates the combined flow characteristics of both areas.

Numerical Model Approach

The complex surface water-groundwater interactions within the RFETS hydrologic flow system required using a fully-integrated computer code to create a flexible, yet comprehensive, management tool. In a detailed comparison of available integrated models, the MIKE SHE computer code was selected for the SWWB modeling.

The complex semi-arid Site hydrology also required using a fully-integrated, transient modeling approach. Steady-state models cannot reliably replicate the observed conditions at the Site, nor could a combination of non-integrated, media-specific model codes. Sub-regional scale models of hydrologic processes were developed to understand basic flow processes prior to simulating the fully-integrated Site-wide model.

Model code verification results showed MIKE SHE was most appropriate code for this application, capable of simulating the important RFETS hydrologic processes and their complex interactions.

Calibration Strategy

Specific parameters and targets were identified and prioritized for the model calibration. Specific focus areas were specified where key decisions or Site hydrology would likely change in response to the hypothetical Site scenarios. Focus areas included: (1) the regional flow system; (2) major surface water drainages; (3) detention ponds; (4) specific contamination areas including the 903 Pad and Lip Area, the Original Landfill and the Present Landfill; (5) *in-situ* groundwater treatment/collection systems; and (6) vegetation/habitat areas. Within the focus areas, additional effort was made to minimize the difference between model-simulated results and field measurements of the hydrologic system. The highest priority was given to accurately simulating surface water discharge

from the Industrial Area to Woman and Walnut Creeks and from those drainages to the eastern Site boundary.

Numerical Model Design

The integrated numerical model consists of surface flow, unsaturated zone and saturated zone components at discrete points on a grid. A 200-x 200-foot (ft) (approximately 61 x 61 meter [m]) regularly-spaced model grid was selected as the most suitable compromise between numerical efficiency versus solution accuracy required to meet the project objectives. In addition, time step ranges were used in the model to capture the rapid dynamics of the surface hydrologic system (0.5-minute time step) and slower response of the groundwater flow system (6-hour maximum time step). Spatial precipitation distributions were specified from 10 stations every 15 minutes, while potential evapotranspiration (PET) was specified every 2 hours.

The surface flow model simulates two-dimensional overland flow and one-dimensional channel flow. The channel flow network included both Walnut and Woman Creeks and most tributary branches. The A-, B-, and C-series ponds and the Present Landfill Pond were also incorporated into the channel network. Both channel flow and pond water interact directly with saturated zone flow. Drainage basin boundaries were used to define overland flow areas within the model, and detailed cross-sections defined the channel flow network.

The subsurface model simulates one-dimensional unsaturated zone flow and three-dimensional saturated zone flow. The unsaturated zone model accounted for spatially-distributed soils. Effects of the time-varying, spatially-distributed vegetation were simulated through the unsaturated zone as evapotranspiration (ET).

The saturated zone model uses four model layers to describe flow within unconsolidated material and weathered bedrock units. Average hydraulic characteristics and properties of subsurface remediation systems, utility trenches and drains, water supply lines and building basements in the Industrial Area were incorporated into the saturated zone model.

Model Performance

After completing the numerical model design, the fully-integrated model was calibrated. Calibration was achieved by adjusting model parameters until the simulated model results compared well with observed data. The calibration data set period was from October 1, 1999 through September 30, 2000 (Water Year [WY] 2000). Model results simulated observed Site-wide flow conditions at RFETS well. Key findings of the calibrated model included:

- For the current Site configuration, the water balance differs greatly in the Industrial Area as compared to the Buffer Zone. For the WY2000 climate, roughly 90 percent of the precipitation was lost through ET, with less than 1 percent running off to streams. In contrast, for the Industrial Area, roughly 60 percent of the precipitation was lost to ET, with 15 percent running off to streams;

- ET dominated near-stream groundwater levels, which in turn strongly affected streamflows. During high ET, groundwater levels declined near Walnut and Woman Creeks at the eastern Site boundary. In Woman Creek, this effectively eliminated stream flow in late spring and summer. During times of the year with low ET, groundwater levels increased. This causes increased baseflow contributions to Woman Creek with resulting increases in the total flow and peak flow rates in that drainage;

- In Walnut Creek, flows were dominated by pond releases. However, during non-pond discharge periods, precipitation events rarely caused streamflow in Walnut Creek because of high soil infiltration rates and low near-stream groundwater levels;

- Groundwater level changes were affected most by vertical processes, such as ET and direct recharge from precipitation, rather than lateral groundwater flow. Groundwater flow directions were strongly influenced by local topographic and bedrock surfaces; and

- Industrial Area surface flows were comprised of fast runoff, baseflow and drain inflows. The fast runoff causes rapid hydrograph peaks, while baseflow and drain inflows produced continuous low flow rates exiting the Industrial Area as surface water.

The performance of the calibrated model was further assessed through a sensitivity analysis and model validation. The purpose of the sensitivity analysis was to identify key parameters to which the model was most responsive. The system hydrologic response was most sensitive to saturated hydraulic conductivity values. The model validation performance was demonstrated using pre- and post-calibration climatic conditions. These simulations showed that the model performed well in simulating hydrologic conditions of the Spring, 1995 and WY2001 (October 1, 2000 through September 30, 2001).

Model Scenario Evaluations

Model simulations were conducted for two hypothetical Site scenarios to evaluate changes based on WY2000 hydrologic conditions. In the first scenario, the No Imported Water Scenario, imported water from off-Site was discontinued (the Site currently purchases an average of approximately 420,000 cubic meters [110 million gallons or 340 acre-feet] of water annually from the Denver Water Board). The second scenario, the Land Configuration Scenario, also discontinued imported water and included hypothetical regraded topography in the Industrial Area, the Present Landfill and the Original Landfill. In the second scenario, Industrial Area changes included removing buildings, pavement and subsurface utilities.

For each hypothetical scenario, three climate conditions were applied to develop a range of simulated hydrologic responses. The three climate conditions represent average, wet and dry years of precipitation for the Site. Finally, a Monte Carlo-type uncertainty analysis was conducted on the second scenario to assess the range of uncertainty in predicted output given uncertainty in sensitive model input parameters.

Several key findings about the change in hydrologic conditions from the present to the hypothetical Land Configuration Scenario were identified. These are summarized as follows:

- Regionally, most of the hydrologic system changes occurred within the regraded Industrial Area, the two modified landfill areas (the Original Landfill and the Present Landfill) and to Walnut Creek, east of the Industrial Area;
- Surface discharge in Walnut Creek was substantially reduced, while flows in Woman Creek were largely unaffected;
- Walnut Creek discharges decreased for the following three reasons: (1) Waste Water Treatment Plant contributions to Walnut Creek were eliminated; (2) impervious surfaces in the Industrial Area were removed, thereby eliminating fast runoff; and (3) drain discharges to Industrial Area streams were eliminated;
- The number of required terminal pond discharges decreased in the hypothetical Land Configuration Scenario because of decreased flow from the Industrial Area;
- Average groundwater levels in the Industrial Area increased. Removing drain discharges and impervious areas caused groundwater to rise, whereas removing leaky water supply lines caused groundwater levels to decrease. The net effect of these changes was to increase Industrial Area groundwater levels; and
- Simulated discharges from groundwater remediation systems slightly decreased.

Implications to Site Closure

Modeling results suggested that significant impacts to the Site's hydrologic system will occur for the hypothetical scenarios. These modeling results provide valuable insight into Site hydrology that will influence the RFETS closure strategy and long-term stewardship. Implications based on the simulated scenario results are summarized as follows:

- Surface and sub-surface flows in Woman Creek will be largely unaffected. Therefore, vegetation along Woman Creek will generally not be affected by the Site reconfiguration. An exception to this may occur in the area south of the Original Landfill. This area may experience some localized diminished flows from hypothetical covers and cutoff walls. A more detailed analysis of this area could be performed; and

- Surface and sub-surface flows in Walnut Creek, in contrast to Woman Creek, will be substantially reduced. As a result of the diminished surface flows, future hydrologic conditions in Walnut Creek downstream of the Industrial Area will be dominated by pond operating protocols and any pond routing or structural modifications. An additional effect of reduced flows in Walnut Creek is the possible impact to vegetation downstream of the ponds caused by lower groundwater levels along the stream channel.

Potential Applications

A fully-integrated, hydrologic model has been developed for RFETS. The model performance and sensitivity have been demonstrated for a range of climatic conditions. Two hypothetical Site configuration scenarios were simulated as a preliminary application of the model. Additional applications of the model may include evaluating additional Site configuration scenarios. Other model uses could involve local-scale modeling, contaminant transport evaluations or more detailed assessments of potential hydrologic impacts to vegetation and wildlife habitat.

1.0 INTRODUCTION

1.1 BACKGROUND

The Rocky Flats Environmental Technology Site (RFETS or Site) is a former nuclear weapons component production facility that is currently being closed and converted into a National Wildlife Refuge (Figure 1-1). Anticipated closure activities will involve reconfiguring portions of the existing Site. These modifications will impact the current Site surface and subsurface hydrology.

The semi-arid, 6,585-acre Site is hydrologically complex. The hydrology is complicated with a 385-acre Industrial Area containing basements, building drains, underground piping, groundwater extraction/treatment systems and domestic water operations. The Buffer Zone includes a network of detention ponds. Site closure planning will require a thorough understanding of this complex hydrology and a decision tool to evaluate the hydrologic implications of future changes to the Site's configuration.

1.2 OBJECTIVE

The primary objective of the Site-Wide Water Balance (SWWB) study was to create a management tool to quantitatively assess the integrated hydrologic conditions at the RFETS. Specifically, this integrated model was used to: (1) comprehend and simulate current Site hydrologic conditions; and (2) assess the hydrologic impacts caused by changes to the current Site configuration.

The model developed for the SWWB simulates important drainage-scale processes that control hydrologic conditions at RFETS. It was not designed to simulate localized flows in features such as individual pipes or culverts. It was not designed to simulate localized flows in features such as individual pipes or culverts, to directly model contaminant transport or to evaluate engineering designs. However, the model was developed so that its input and output could be used to facilitate contaminant transport evaluations or engineering design calculations.

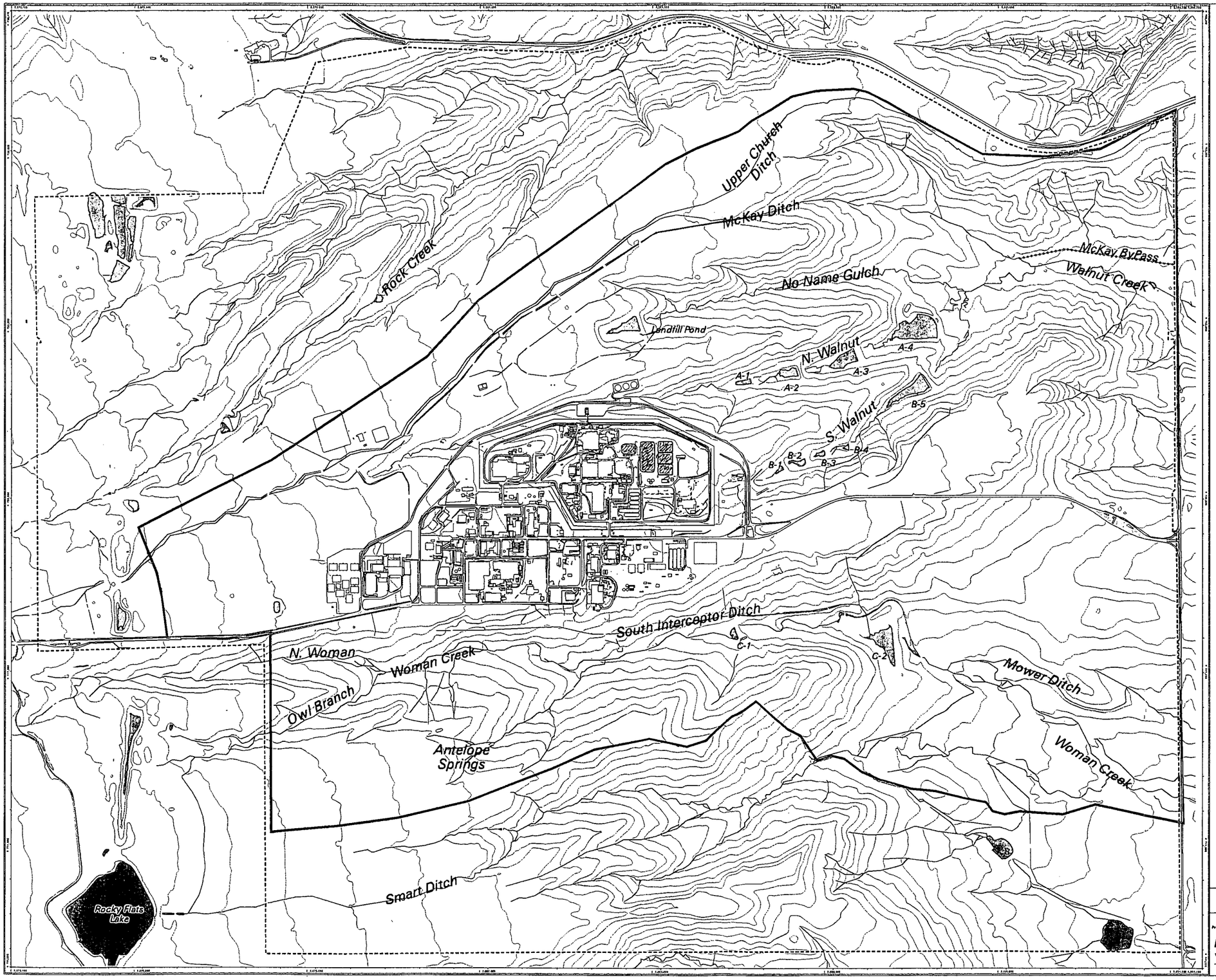

Figure 1-1

Site-Wide Water Balance Report

Site Map

EXPLANATION

Standard Map Features

- Buildings and other structures
- Paved roads fill
- Solar Evaporation Ponds (SEPs)
- Lakes and ponds
- Streams, ditches, or other drainage features
- Topographic Contour (20-Foot)
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95 Topographic contours were derived from digital elevation model (DEM) data by Morrison Knudson (MK) using ESRI Arc TIN and LATTICE to process the DEM data to create 5-foot contours. The DEM data was captured by the Remote Sensing Lab, Las Vegas, NV, 1994 Aerial Flyover at ~ 10 meter resolution. DEM post-processing performed by MK, Winter 1997.

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

U.S. Department of Energy

Rocky Flats Environmental Technology Site

GIS Dept. 303-966-7707

Prepared by: DynCorp — THE ART OF TECHNOLOGY

Prepared for: KAISER-HILL COMPANY

May 09, 2002

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1.3 SCOPE

To meet project objectives, the following tasks were identified and completed:

- Collected Site-specific data to support development of the conceptual and numerical hydrologic models (Data collected include surface water and groundwater hydrology, surface and sub-surface structures in the Industrial Area, topography, geology, soils and vegetation);
- Developed the conceptual hydrologic model based on existing knowledge;
- Developed the modeling approach appropriate for the Site, including code selection and verification (Kaiser-Hill, 2001b);
- Developed the numerical model based on the selected computer code;
- Evaluated model performance (including calibration, validation and sensitivity analysis);
- Applied the model to hypothetical Site configuration scenarios; and
- Assessed the model for implications to Site closure.

A detailed description of these tasks, including assumptions, work performed and findings, are presented in this report. The hypothetical scenarios simulated by the numerical model represent only a limited application of the integrated management tool. The conceptual understanding and numerical model developed by this study may have further application at the Site. Refinements may be made to the model for other applications in the future.

1.4 REPORT ORGANIZATION

The main text of this report presents a condensed summary of the SWWB study. Introductory information is presented first, followed by more detailed discussion of the main tasks (identified in Section 1.3). Key points and findings are briefly summarized at

the end of each section. Technical details that support the main text are presented in Appendices. The report is organized as follows:

- Section 1 introduces the SWWB study purpose and scope, the organization of the report, model code selection and focus areas of particular interest to Site closure;
- Section 2 presents a brief introductory description of the Site, including industrial and natural features relevant to the hydrology. A comprehensive description is provided in Appendix A;
- Section 3 summarizes the model boundary and general description of the conceptual hydrologic model for the Site. A comprehensive description of the conceptual model is presented in Appendix B;
- Section 4 describes the modeling approach applied to develop the integrated numerical model;
- Section 5 presents the integrated numerical flow model developed for this study. Each hydrologic component is described and related to the conceptual model;
- Section 6 describes the numerical flow model performance. Calibration, validation and sensitivity analysis are presented;
- Section 7 summarizes findings developed from application of the numerical model to hypothetical scenarios. Results are organized according to focus areas identified in Section 1.6;
- Section 8 provides brief conclusions of the SWWB study and implications to Site Closure;
- Section 9 lists references; and
- Appendices provide additional technical detail to support the content of the main report. Each chapter in the main body of the report, starting with Chapter 2, has a

supporting Appendix. Each Appendix is organized with a table of contents and list of figures.

1.5 MODEL CODE SELECTION

A variety of hydrologic models have been used at RFETS to study the hydrologic behavior of the Site. These have ranged from single-process models, such as the U.S. Geological Survey (USGS) code MODFLOW (McDonald and Harbaugh, 1988), to the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC) codes, to more complex coupled-process models using the U.S. Environmental Protection Agency (EPA) code SWMM, and the USGS HSPF code. More recently, the U.S. Department of Agriculture Watershed Erosion Prediction Project (WEPP) code was used for hillslope erosion and transport modeling at RFETS (Kaiser-Hill, 2000d). None of these models considered the fully-integrated system, coupling surface flows and subsurface flows including the unsaturated and saturated zones.

To meet the project objectives, the numerical code MIKE SHE (Refsgaard and Storm, 1995) was applied. MIKE SHE was selected as the most appropriate code following a thorough analysis of options. The code selection process is detailed in the Model Code and Scenario Selection Reports (Kaiser-Hill, 2001a; Kaiser-Hill, 2001b). Primarily, the model was chosen for its ability to simulate and integrate the following major flow processes affecting the hydrology and water balance at the RFETS Site, namely:

- Rapid, intense storm runoff from the Industrial Area;
- Groundwater discharge from subsurface pipes and treatment systems in the Industrial Area;
- Leakage from pressurized water supply lines (Denver Water Board [DWB] water);
- Infiltration and drainage through the unsaturated zone;
- Exchange between unsaturated and saturated zones (recharge);

- Dynamic exchange between saturated zone and channels (leakage and baseflow);
- Groundwater flow and storage;
- River/channel flow, water levels and pond operations;
- Evapotranspiration (ET) losses; and
- Potential overland sheet flow.

MIKE SHE is an integrated and distributed, physically-based, finite difference model. The spatial scale of MIKE SHE may be chosen either to address regional drainage basin-scale issues or to provide a detailed local hydrological analysis. The code comprises a number of flow modules, which may be combined to describe flow within the entire land-based part of the hydrologic system including developed urban areas.

For the RFETS SWWB study, the MIKE SHE computer modules listed in Table 1-1 were applied.

1.6 FOCUS AREAS

To efficiently use and communicate the large quantity of information generated by the numerical model, focus areas were identified within the model boundary. These focus areas were chosen to address Site interests and concerns for closure, including: (1) potential contaminant transport; (2) groundwater treatment system performance; (3) wetlands sustainability; and (4) hydrologic changes in Threatened and Endangered Species habitat.

Table 1-1. MIKE SHE Modules Applied for the RFETS SWWB Model

MIKE SHE* Module	Process Simulated	Fully dynamic coupling with:	Dimensions	Governing equations
MIKE SHE OL	Overland sheet flow and water depth, depression storage	MIKE SHE SZ, UZ and MIKE11	Two-dimensions	Saint-Venant's equation
MIKE 11	Fully dynamic river and canal hydraulics (flow and water level)	MIKE SHE SZ, OL	One-dimension	Saint-Venant's equation (dynamic wave approximation)
MIKE SHE UZ	Flow and water content of the unsaturated zone, infiltration and groundwater recharge	MIKE SHE SZ, OL	One-dimension	Richard's equation
MIKE SHE ET	Soil and free water surface evaporation, plant transpiration	MIKE SHE UZ, OL	n/a	Kristensen & Jensen / Penman-Monteith
MIKE SHE SZ	Saturated zone (groundwater) flows and water levels	MIKE SHE UZ, OL and MIKE11	Three-dimensions	Boussinesq's equation

*For a more detailed description of the MIKE SHE code, see Appendix D.

Six focus areas were identified for the study. These areas are described below and presented in Figure 1-2 and Figure 1-3.

- Site flow system – The Site flow system corresponds to the entire model area (Figure 1-2).
- Major surface water drainages – The major surface water drainages refer to the Walnut and Woman Creek basins (Figure 1-2).
- Detention ponds – The detention pond focus area includes all Site managed ponds (Figure 1-3).

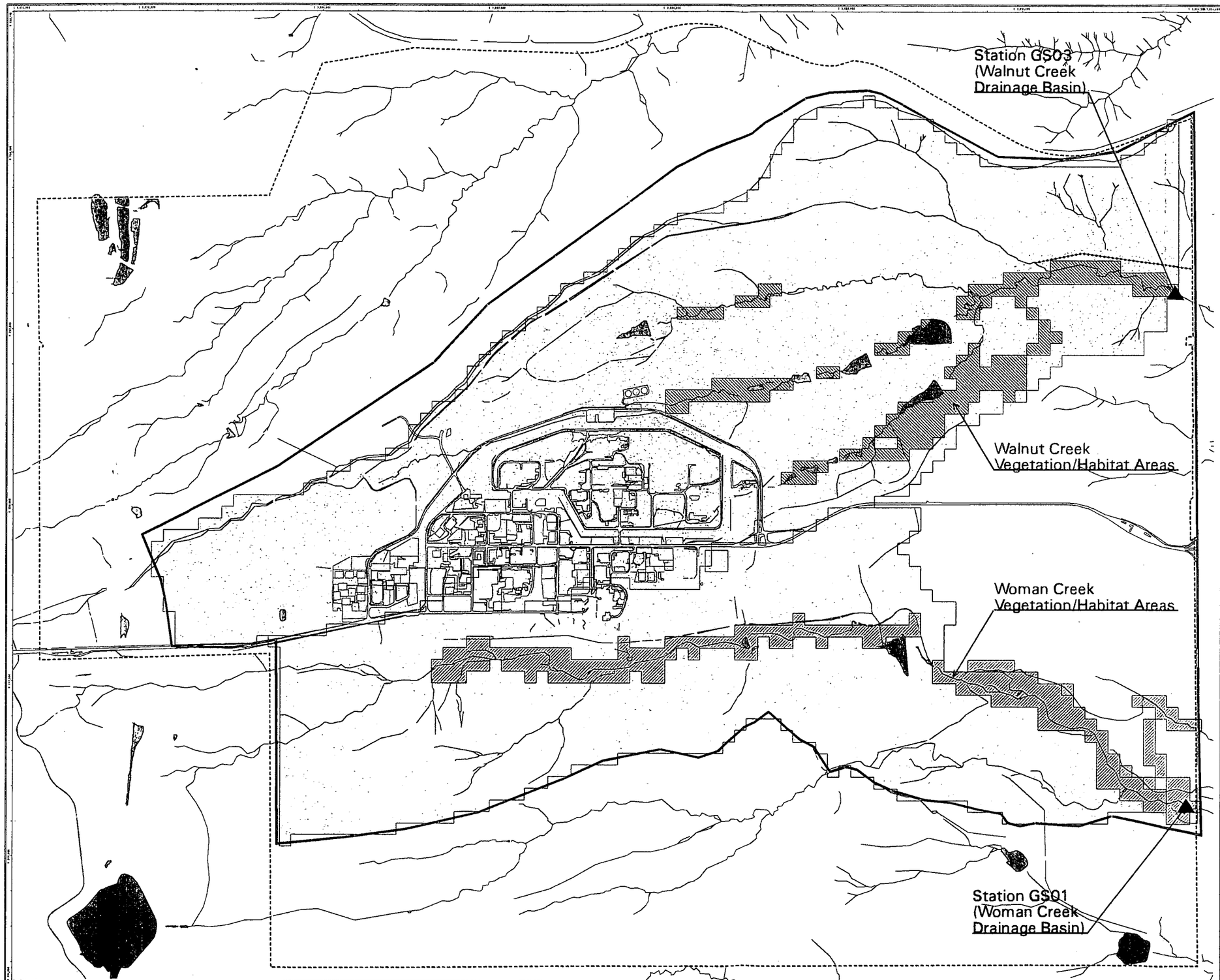

Figure 1-2

Site-Wide Water Balance Report

Focus Areas - Map 1

EXPLANATION

Major Drainage Basin
- Walnut Creek (GS03)
- Woman Creek (GS01)

Vegetation/Habitat Areas
- Walnut Creek
- Woman Creek

Standard Map Features
- Lakes and ponds
- Streams, ditches, or other drainage features
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary
- Gaging Station

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:
Vegetation/habitat areas defined by Preble's Jumping Mouse and Wetland areas.

Zones were described based on the numerical model representation.

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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Prepared for: KAISER-HILL COMPANY

May 31, 2000

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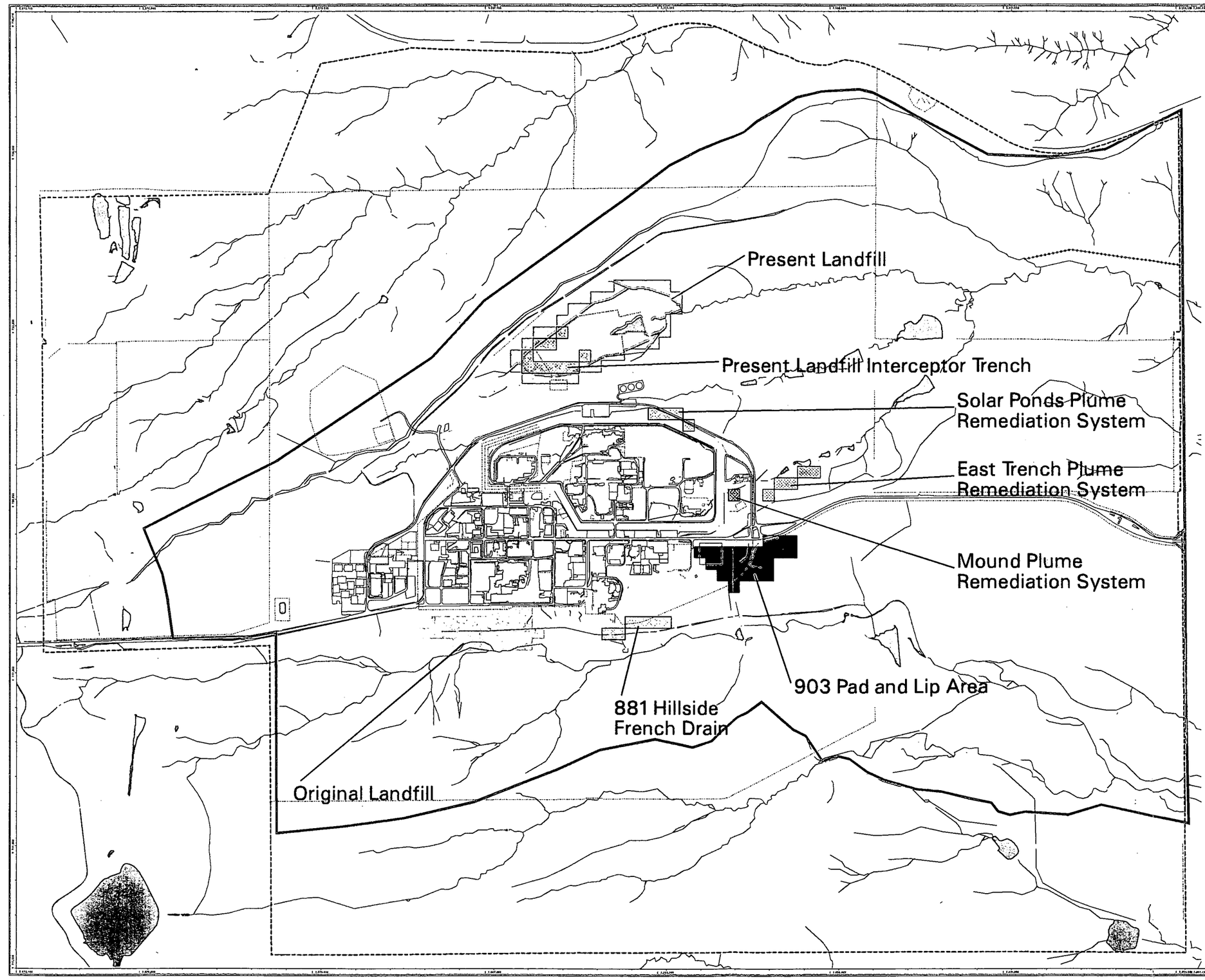

Figure 1-3

Site-Wide Water Balance Report

Focus Areas - Map 2

EXPLANATION

Groundwater Treatment Systems
- Solar Ponds Plume Remediation System
- East Trench Plume Remediation System
- Mound Plume Remediation System
- 881 Hillside French Drain
- Present Landfill Interceptor Trench

Contamination Areas of Concern
- 903 Pad and Lip Area
- Original Landfill Area
- Present Landfill Area

Standard Map Features
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:
Zones were described based on the numerical model representation.

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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May 14, 2003

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- Contamination focus area – The contamination focus area consists of the following : (1) the 903 Pad and Lip Area; (2) the Original Landfill; and (3) the Present Landfill (Figure 1-3).

- *In-situ* groundwater treatment/collection systems – This focus area includes: (1) the Solar Ponds Plume Remediation System; (2) the Mound Plume Remediation System; (3) the 881-Hillside French Drain; (4) the Present Landfill Interceptor Trench; and (5) the East Trenches Remediation System (Figure 1-3).

- Vegetation/habitat – The vegetation/habitat focus area was defined as the combined areas identified as wetlands or Preble's Meadow Jumping Mouse habitat. This focus area is subdivided into Walnut and Woman Creek vegetation/habitat areas (Figure 1-3).

These focus areas are applied to guide the modeling results discussion in Chapter 7.0.

2.0 BACKGROUND SITE DESCRIPTION

The following section provides a brief description of the Site, including physical features and a history of operations. This background information provides a basis for discussion of the hydrologic conceptual model presented in Section 3.0.

2.1 GENERAL FEATURES AND HISTORY

RFETS is located 16 miles northwest of Denver in Jefferson County, Colorado. The former nuclear weapons component facility is owned by the U.S. Department of Energy (DOE) and encompasses approximately 6,585 acres of federally-owned land (Figure 1-1). Major plant structures, including all former production buildings, are located within a centralized 385-acre Industrial Area that is surrounded by a 6,200-acre Buffer Zone (Kaiser-Hill, 2000a). Construction at the Site began in 1951. The complex evolved, during the next four decades, into more than 440 permanent and temporary structures used as manufacturing, chemical processing, laboratory, support and administrative facilities.

The plant produced nuclear weapons components made from plutonium, uranium, beryllium and stainless steel. Other production activities included chemical recovery and purification of recyclable transuranic radionuclides, metal fabrication and assembly and related quality control functions. Production operations occurred from 1952 until 1989, at which time RFETS was added to the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) National Priorities List for environmental cleanup. Site-specific regulatory requirements for remediation and closure were established in 1996 when the Rocky Flats Cleanup Agreement (RFCA) was signed by the DOE, EPA and Colorado Department of Public Health and Environment (CDPHE) (DOE, 1996).

The Site is currently in the process of deactivating, decontaminating, decommissioning and demolishing the weapons production facilities and buildings in the Industrial Area. The objective of the final closure is to remediate the environmental legacy of nuclear

weapons component production and to transition to long-term stewardship as a National Wildlife Refuge.

2.2 INDUSTRIAL AREA FACILITIES

The 385-acre Industrial Area has approximately 440 buildings. Several of the structures have basements, some multiple stories deep, with foundation drains that influence groundwater movement at shallow depths. This impact of foundation drains on shallow groundwater flow required the incorporation of foundation drains into the simulation model. Additionally, other sub-surface features of the Site that impact groundwater or surface flows, include: (1) communication lines; (2) water lines; (3) new and old process waste lines; (4) sanitary sewer lines; and (5) storm drains. These are all represented in the model. Section 5.2.3 describes the process to incorporate these sub-surface Industrial Area features into the model.

2.3 CLIMATE

The RFETS climate is temperate and semiarid, characteristic of Colorado's Front Range. The low humidity at 1,830 meters (m) (6,000 foot [ft]) elevation above mean sea level (MSL) often causes wide temperature fluctuations between daytime and nighttime. Summer high temperatures are typically in the upper-20 degrees Centigrade (°C)(mid-80 degrees Fahrenheit [°F]), with nighttime lows falling to approximately 16°C (60°F) (EG&G, 1993b). During the winter, temperatures typically range from 4°C to 7°C (40°F to 45°F) during the day and -9°C to -4°C (15°F to 25°F) at night. Arctic and Siberian air masses occasionally bring frigid air during the winter when low temperatures may drop to between -21°C and -24°C (-5°F and -12°F) (EG&G, 1993b).

The average annual precipitation, based on 30 years of record, is approximately 368 millimeters (mm) (14.5 inches [in]) (DOE, 1995a). Roughly half of the precipitation occurs as rain and half as snow, with precipitation falling primarily as snow from late October through early April and as rain during the remaining months (Rocky Mountain Remediation Services [RMRS], 1997). Annual snowfall averages approximately 1,778

mm (70 in), with the highest monthly snowfall average (approximately 406 mm [16 in]) occurring in March (EG&G, 1993b). Rainfall is highest from April through June, with nearly 42 percent of the average annual precipitation, as either rain or snow, occurring during those months (EG&G, 1993b).

2.4 HYDROLOGY

Streams and seeps at RFETS are largely ephemeral, with stream reaches gaining or losing flow, depending on the season and precipitation amounts. Surface water at the Site flows generally from west to east, with three major drainages traversing the Site. Two of these drainages capture runoff from the Industrial Area. They are: (1) Walnut Creek, which drains the northern portion of the Site, including the majority of the Industrial Area; and (2) Woman Creek, which drains the southern portion of the Site, including the southern Industrial Area, after it has been diverted by the South Interceptor Ditch (SID) through Pond C-2. Pond C-2 is one of 14 Site detention ponds, 10 of which are actively managed. The third major drainage at the Site, Rock Creek, does not receive runoff from the Industrial Area and is not within the SWWB model boundaries (Figure 2-1). Details on surface water features, including detention pond management, are provided in Appendix A.

2.5 GEOLOGY AND HYDROGEOLOGY

The Site is situated approximately two miles east of the Front Range of Colorado, on the western margin of the Colorado Piedmont section of the Great Plains Physiographic Province (Spencer, 1961). Geologic units at RFETS can be grouped into two general categories: unconsolidated surficial deposits and underlying consolidated bedrock (RMRS, 1999a). Brief descriptions of major geologic units and hydrogeology at RFETS are provided below. Additional detail is provided in the Geologic Characterization Report for the Rocky Flats Environmental Technology Site (EG&G, 1995b), the Hydrogeologic Characterization Report for the Rocky Flats Environmental Technology Site (EG&G, 1995a) and in Appendix A of this report.

2.5.1 Unconsolidated Surficial Deposits

Nearly all the Site is covered with unconsolidated surficial deposits. These include: (1) Rocky Flats Alluvium (debris flow); (2) fluvial Valley-Fill Alluvium along Walnut and Woman Creeks; (3) Colluvium along the margins of the creek floodplains; and (4) artifical fill in the Industrial Area. The unconsolidated surficial deposits range in thickness from 0 to 30.5 m (0 to 100 ft) (EG&G, 1995b). These deposits, combined with the weathered portion of subcropping bedrock formations, are the most important geologic units in terms of groundwater flow at the Site (RMRS, 1999a).

2.5.2 Consolidated Bedrock Deposits

Bedrock from the Arapahoe, Laramie, Fox Hills and uppermost Cretaceous Pierre Formations are present at RFETS (EG&G, 1995b). Only the weathered portions of the Arapahoe Formation transmit significant groundwater flow and were incorporated into the SWWB study. The Arapahoe Formation is generally less than 8 m (25 ft) thick at the Site, occurring as claystone and silty claystone with lenticular sandstone in the basal portion of the formation (EG&G, 1995b).

Below the Arapahoe Formation, the unweathered Laramie Formation is approximately 180 to 250 m (600 to 800 ft) thick. It is composed of an upper, thick claystone interval and a lower sandstone/claystone/coal interval. The claystones have low hydraulic conductivities which inhibit downward groundwater flow. Shallow groundwater is therefore directed laterally along the surface of the unweathered bedrock surface. Beneath the unweathered Laramie Formation is the regional Laramie-Fox Hills aquifer. A USGS study and a separate, peer-reviewed Site investigation both indicated that this aquifer was not impacted by RFETS activities because of the low permeability of the overlying Laramie Formation (Hurr, 1976; RMRS, 1996b). The Laramie-Fox Hills aquifer is approximately 200 to 300 m (650 to 1,000 ft) below the Site. Below the Laramie-Fox Hills aquifer is the 2,300 m (7,500 ft) thick Pierre Formation that acts as the aquifer's lower confining layer. The thick marine shale Pierre Formation subcrops only in the extreme western part of the Site (RMRS, 1999a).

2.5.3 Structural Geologic Features

The Site is located along the western margin of the Denver Basin, an asymmetric basin with a steeply east-dipping western flank and a gentle eastern flank. The interpretation of the subsurface structure is generalized in the west-east generalized geological cross-section of the Site area presented in Figure 2-2. A monoclinal fold limb exposed west of the Site is the most significant surficial structural feature in the Site area. Along the west limb of the fold, an angular unconformity exists between the Upper Cretaceous bedrock and the base of the Quaternary Rocky Flats Alluvium.

No active faults have been identified at the Site. Several high-angle bedrock faults have been inferred to exist in the Industrial Area based on various stratigraphic and borehole correlation criteria. These faults appear to have only a limited hydrologic significance with regard to vertical groundwater movement (RMRS, 1996b).

2.6 VEGETATION

The Site's topography and close proximity to the mountains support a unique, diverse array of prairie and foothills plant communities that have been extensively characterized in multiple studies (Kaiser-Hill, 1997a; Kaiser-Hill 1997b; Kaiser-Hill 1997c). Six hundred plant species were reported to grow at the Site through the 2001 field season, though no threatened or endangered plant species are known to exist (Murdock, 2002). Plant communities range from xeric (dry) grassland communities to more hydric (wet) communities such as wet meadows and marshes. Vegetation is an important component of the SWWB study because of the impact that ET, from plant surfaces to the atmosphere, has on the hydrologic system.

The most significant plant communities in the study area include:

- The Xeric tallgrass prairie, which comprises approximately 28 percent of the total area, occurs on flat upland areas and ridges on the western half of the Site;
- The Mesic mixed grasslands cover approximately 34 percent of the area and occur on more damp hillsides primarily in the eastern half of the Site;

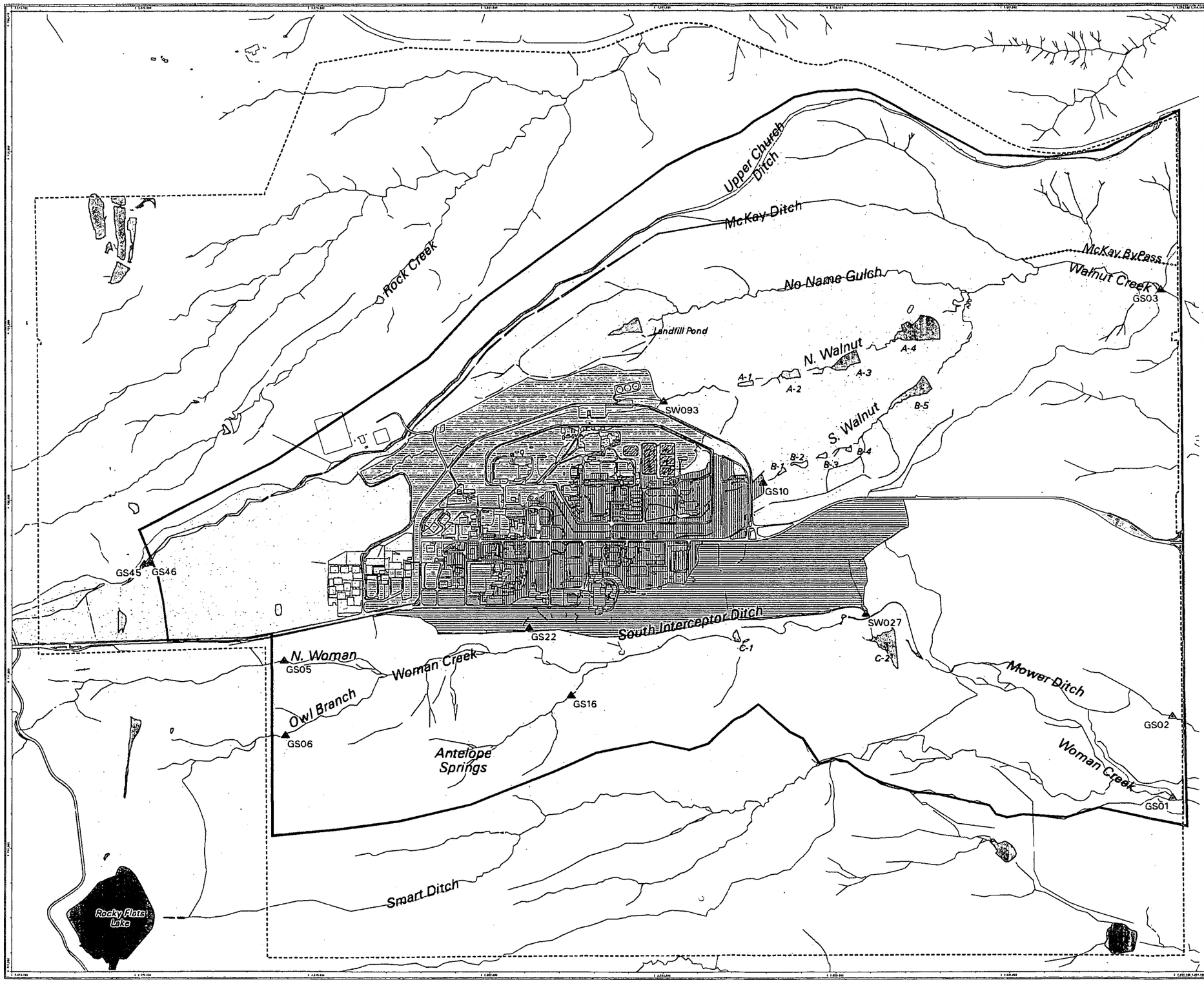

Figure 2-1

Site-Wide Water Balance Report

Major Surface Water Features and Drainage Areas

EXPLANATION

Walnut Creek Basin
- GS03 Major Drainage
- SW093 Sub-Drainage
- GS10 Sub-Drainage

Woman Creek Basin
- GS01 Major Drainage
- SW027 Sub-Drainage

Other Features
- Gaging Station

Standard Map Features
- Buildings and other structures
- Paved roads fill
- Solar Evaporation Ponds (SEPs)
- Lakes and ponds
- Streams, ditches, or other drainage features
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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May 09, 2002

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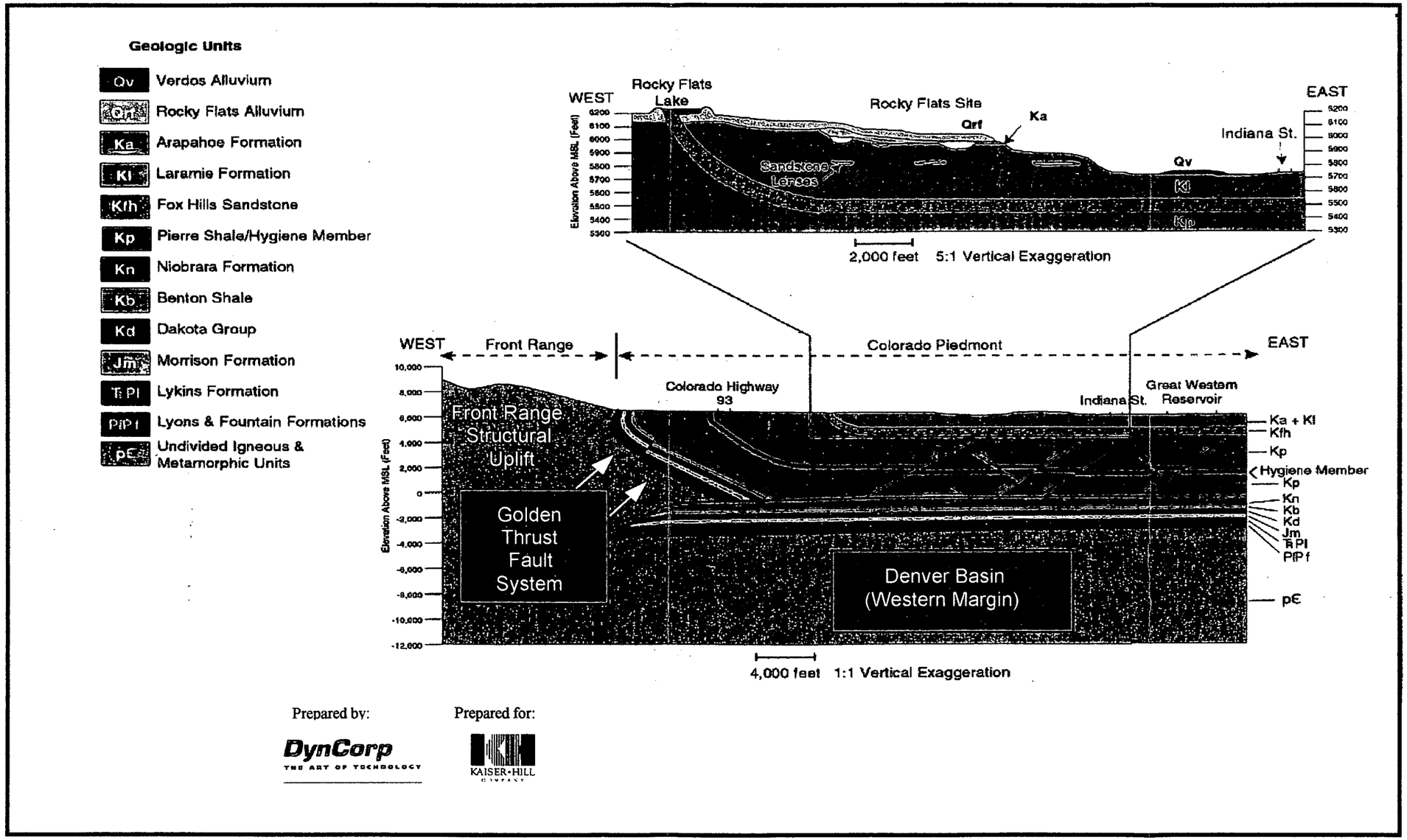
Figure 2-2. Generalized Geologic Cross-Section



- The Great Plains riparian community, mapped as riparian (stream channel) woodland and shrubland, is found along streams. It comprises approximately 1 percent of the Site area. Cottonwood trees and willows predominate in this plant community; and

- Wetlands are most common on north-facing hillsides as expected because of higher ET on south-facing slopes. The combined area of wet meadow, short marsh and tall marsh comprise approximately 6 percent of the Site area. The largest Site wetland, Antelope Springs, is located south of the Industrial Area (Figure 1-1).

A map of plant communities is presented in Appendix A along with more detailed descriptions of plant species and characteristics.

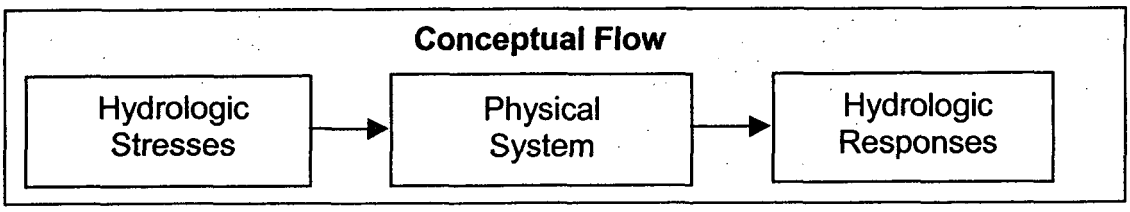
3.0 CONCEPTUAL MODEL FOR THE INTEGRATED FLOW SYSTEM

This section summarizes the model boundary and key features of the conceptual model developed for the integrated RFETS flow system. A conceptual model describes the physical framework and flow and storage within the system. It is important because it forms the basis for developing the numerical flow model. Only Site features and flow processes that impact the Site-wide hydrology within the study area are considered. It was continuously refined through model simulations so that it represents the best understanding of the hydrologic system.

Current literature on integrated hydrologic modeling indicates that specific guidelines for developing an integrated conceptual model are not available (authors like Refsgaard [1996] follow the general approach used in traditional groundwater modeling [Anderson and Woessner, 1992], that are not directly applicable to integrated models). American Society for Testing and Materials (ASTM) (1993) standards for developing groundwater models define a conceptual model as "an interpretation or working description of the characteristics and dynamics of the physical system". The complexity and integrated behavior of the hydrologic components of the RFETS system required a more detailed and clearly defined conceptual flow model than used in traditional groundwater models.

Basic elements of the integrated conceptual model developed for the RFETS system are shown on Figure 3-1. The *physical system* defines the underlying surface and subsurface hydrogeologic framework and hydraulic properties that control flow in the RFETS system. For example, the surface topography is the main feature controlling overland flow. Channel profiles and streambed topography define the streamflow network, and hydrostratigraphy defines the subsurface flow structure.

Figure 3-1. Conceptual Flow Model Components



The physical system is acted upon by different external *hydrologic stresses* (including anthropogenic and natural stresses) that produce different types of *hydrologic response.* (The term *hydrologic stress* is used instead of more traditional terminology like "boundary conditions" to emphasize that important internal processes are not simplified in a fully-integrated model.) Hydrologic stresses vary temporally, and in some cases, vary spatially. Hydrologic stresses in the RFETS model include: (1) precipitation [rain, or snowfall]; (2) meteorological changes; (3) imported DWB water; (4) surface inflows; and (5) pond operations.

The combined effect of external stresses acting on the physical system produces several different types of hydrologic responses. These responses occur as changes in flows and system pressures within the surface or subsurface flow systems. For example, as precipitation reaches the ground it infiltrates the subsurface, unless the intensity is high enough or the soils are saturated from below and water begins to pond at the ground surface. Under these conditions, flow can develop on the ground surface (overland flow) that can concentrate and begin flowing in stream channels. The flow rate at any point in the stream (stream hydrograph) changes over time in response to lateral inflows from overland flow or groundwater (baseflow).

Within the unsaturated zone, moisture content of the soil adjusts in response to infiltration of multiple annual precipitation events and to daily and seasonal changes in soil evaporation and plant transpiration. Eventually, a small portion of the infiltrating precipitation reaches the groundwater table as groundwater recharge (most of this is lost to ET). The groundwater table responds by increasing during recharge events, but then decreases in response to direct loss through ET or by adjustments in three-dimensional groundwater flow within the system. When the groundwater levels change, groundwater flow directions and velocities can also change. When groundwater reaches the ground surface at locations other than streams, seeps and overland flow are produced.

3.1 MODEL BOUNDARY

The model boundary for the conceptual and numerical model is described in this Section. The general hydrologic behavior of the regional flow system, described below in Section 3.2, was used to describe key aspects of the conceptual model developed for the RFETS system. The dominant hydrologic processes and their interaction with each other are described and important Site features, conditions controlling these processes, are identified. To support this conceptualization of system behavior, a substantial amount of data were reviewed and interpreted. These data and interpretations are described in more detail in Appendix B. Appendix B is organized into hydrologic stresses, system structure and hydrologic response.

The SWWB model boundary was defined based on an initial evaluation of hydrologic conditions at RFETS (Kaiser-Hill, 2000a and 2000c). A simple description of the model boundary is presented here, and more detailed rationale for defining the model boundary is presented in Appendix C.

Model boundaries were defined within the study area so that realistic boundary conditions could be specified in the fully-integrated hydrologic flow model. Horizontal and vertical flow conditions were used to define the subsurface boundaries. Horizontal conditions were specified for the surface system.

The horizontal extent of the model boundary (Figure 2-1) encompasses an area of approximately 3,700 acres (~5.8 sq. mi.). Vertical (upper and lower) boundaries for the integrated model consist of the topographic surface and the contact between the weathered and unweathered bedrock, respectively. The bottom boundary is similar to that used in earlier modeling efforts (Roberts, 1997; DOE, 1995b; EG&G, 1995a) and consistent with the Upper Hydrostratigraphic Unit (UHSU) described in the Hydrogeologic Characterization Report (EG&G, 1995a). The rationale for the lower boundary selection is that the unweathered bedrock or Lower Hydrostratigraphic Unit (LHSU) transmits a negligible amount of flow compared to the UHSU (EG&G, 1995a).

Surface flow boundaries for the model are also shown on Figure 2-1. The western, northern and southern model boundaries effectively represent no-flow boundaries for overland flow. Although overland flow can cross the eastern model boundary, it is negligible compared to channel and groundwater flows.

3.2 GENERAL SYSTEM BEHAVIOR

The RFETS flow system is described in terms of the basic conceptual model elements defined on Figure 3-1. In addition, flow behavior within the Industrial Area is described separately from the Buffer Zone because of response differences. Site features that affect hydrologic flow conditions in each of these areas are very different. For example, the high percentage of impervious area and subsurface drains within the Industrial Area is not present in the Buffer Zone. System flow described below incorporates information gained through development and application of the fully-integrated hydrologic model.

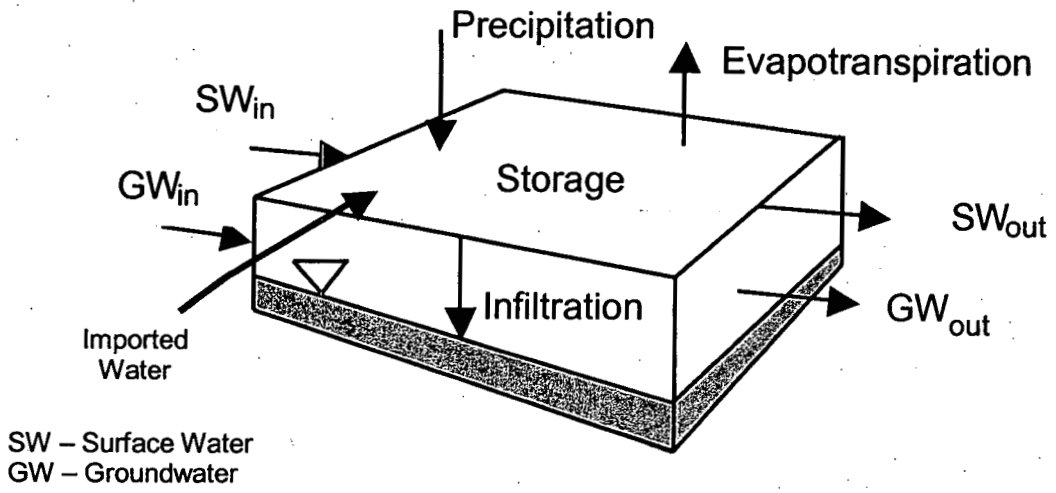
Figure 3-2 illustrates the key external system water balance components considered in the SWWB model. The box represents the physical flow system at RFETS, where the top is ground surface, and the subsurface flow domain is beneath this. The external system water balance simply requires that all inflows to the system equal all outflows minus the change in storage over a given time. Therefore, as shown on the figure, inflows include, both surface and groundwater flows (GW_{in} and SW_{in}), precipitation and imported DWB water. System discharges also include surface and groundwater flows at the eastern boundary (GW_{out} and SW_{out}) and ET. ET is the most significant system discharge. Infiltration is shown as an internal process within the model, but is not part of the external water balance.

3.2.1 System Stresses

Precipitation at RFETS is the main external climatic stress to the system. It is the main component of the Site water balance component and occurs as rain or snow. Review and analysis of available Site data (Appendix B) indicated that during precipitation events, distributions are quite heterogeneous over the model area, especially during the local summer-time convective storms. Based on interpretations of the annual precipitation data

for Water Year (WY) 2000 (October 1, 1999 through September 30, 2000), the annual distribution varied significantly over the Site. For this same time period, higher intensities occurred over the northwest portion of the model area and decreased to the southeast, generally following the direction of highest winds over the Site.

Figure 3-2. Conceptual System Water Balance



ET is the second largest water balance component at RFETS and is nearly equal to the total Site precipitation. This is typical of arid/semi-arid areas. It varies temporally and spatially in the model, and depends on several factors including meteorologic conditions, vegetation, soil conditions and topography (Appendix B). ET consists of plant transpiration and surface evaporation. During winter months, soil evaporation is typically greater than plant transpiration;, transpiration accounts for most of the ET in summer months. Vegetation types in stream areas, where groundwater levels are shallow, typically use more water and exhibit much higher vegetation densities. Vegetation on hillslopes and mesa areas, where groundwater depths are deeper, use less water.

Air temperature varies over the Site throughout the year. When temperatures drop below about 0 °C (32 °F), precipitation occurs as snow. Review of Site data on surface flows shows that snowmelt occurs in direct response to changing air temperature.

Site water, imported from the DWB, acts as an external stress on the subsurface system through leaky water supply lines. Much of this water is routed to the Waste Water Treatment Plant (WWTP), where it is discharged to the B-ponds and eventually discharges to Walnut Creek. Further discussion is provided in Appendix B.

Surface and subsurface flows enter the system along the western boundary as external stresses to the system. Groundwater flow is small compared to total surface inflows along this boundary at Owl and Woman Creek and McKay Ditch. This is due to low permeabilities and hydraulic gradients at this boundary. Details of these surface flows are described further in Appendix B.

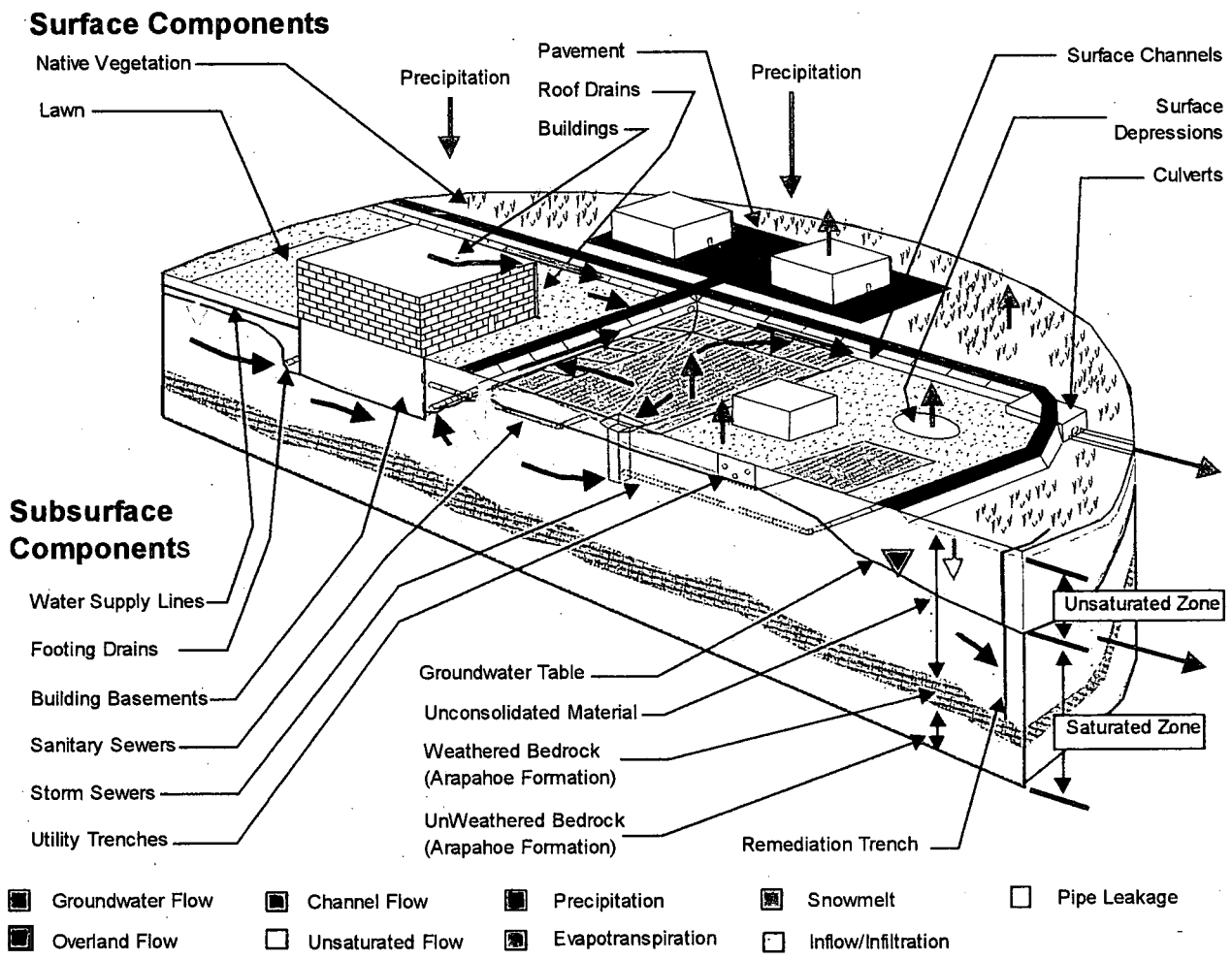
Surface water in ponds is subject to controlled releases as part of the Site pond management. Discharges from Ponds A-4 and B-5, occurring 10 to 15 times a year, result in rapid and significant changes to downstream hydrologic conditions. As such, these releases are considered external stresses to the system and are discussed further in Appendix B.

3.2.2 Industrial Area

3.2.2.1 Structures

Key Site features in the Industrial Area that affect hydrologic flow conditions are depicted pictorially on Figure 3-3. Arrows represent flow directions of important surface and subsurface flow processes. Specific features or structures affecting flow include: (1) subsurface utility trenches and pipelines; (2) remediation systems; (3) subsurface hydrostratigraphic structure; (4) surface channels and overland flow planes (paved and unpaved areas and buildings); (5) surface depressions and culverts; and (6) vegetation. Details of these structures are described further in Appendix B.

Figure 3-3. Industrial Area Flow Characteristics



3.2.2.2 System Response

Several types of system response (namely: drain discharges to surface flow, fast runoff of impervious areas, and leaks from water supply lines and groundwater collection systems) occur within the Industrial Area due to structures. A detailed discussion of system response is presented in Appendix B.

Subsurface pipelines within utility trenches affect both groundwater and surface water flows (see Appendix B). Footing drains decrease groundwater levels along the perimeter of buildings by extracting groundwater. This water is then routed into nearby surface streams or subsurface storm drains. Storm and sanitary drains can either extract or recharge the groundwater system, depending on the level of the groundwater and water level within the drain. When groundwater levels are higher than the levels in the storm or sanitary pipe, groundwater enters the pipe and becomes part of the surface flow system. When groundwater is lower than the water level in the pipe, pipe flow can enter the groundwater system. Available reports suggest that there is a net groundwater discharge over the Industrial Area from storm and sanitary lines (Kaiser-Hill, 2000a).

High-permeability backfill material within subsurface utility trenches redirects groundwater flow locally when levels rise above the bottom of trenches. Appendix B describes trench effects on groundwater flow.

Local groundwater flow conditions are also influenced by the groundwater collection systems, including: (1) Solar Ponds Remediation System; (2) 881-Hillside French Drain; (3) East Trenches Remediation System; (4) Mound Plume Remediation System; and (5) the Present Landfill Interceptor Trench. Structural configurations and flow response in these systems is presented in Appendix B. In addition to the interception trench to the west, the Present Landfill System includes slurry (cutoff) walls to prevent inflow of groundwater. Groundwater extracted from the Present Landfill and 881-Hillside French Drain is routed to nearby surface streams.

Groundwater flow within the Industrial Area is controlled by several factors including: (1) subsurface drain discharge; (2) impervious areas; (3) unconsolidated material

thickness; (4) recharge; and (5) ET. The variability in depth to top of the weathered bedrock surface, combined with the variable thickness of the more permeable overlying unconsolidated material, control the directions of local groundwater flow within the Industrial Area. Groundwater flow rates are slow within the Industrial Area because of low hydraulic gradients and relatively low saturated hydraulic conductivities. Flow directions remain relatively constant over the year because the UHSU is relatively thin compared to the large changes in both topography and bedrock surface elevations, especially at hillslopes.

Groundwater within the Industrial Area is recharged by direct infiltration of precipitation and by leaky water supply lines. Groundwater flow directions, determined from seasonal potentiometric surfaces, suggest that lateral inflow from the west does not occur (Appendix B). Instead, upstream groundwater flow is diverted to either Woman or Walnut Creeks prior to reaching the Industrial Area.

Paved or roofed areas in the Industrial Area prevent infiltration and promote rapid runoff to nearby subsurface storm drains or surface channels. Industrial Area flow response (see gaging stations [GS or SW for surface water] SW093, GS10 and SW027 on Figure 2-1) is characterized by short, peaky flow events caused by precipitation events, superimposed on the relatively constant baseflow and subsurface drain discharges (see Appendix B). The amount of surface runoff from the southern Industrial Area towards Woman Creek (SW027) is less than that towards Walnut Creek (SW093 and GS10). Data (GS22 and SW027) show that a portion of the runoff generated in the upper SW027 drainage basin is lost by infiltration along the SID prior to reaching the SW027 gage. The SID routes water from the southern hillside of the Industrial Area to Pond C-2.

The lack of infiltration in impervious areas prevents recharge to the groundwater, causing decreased groundwater levels locally. In pervious areas of the Industrial Area, recharge rates can be much higher than direct precipitation recharge due to run-on from adjacent impervious areas.

As surface flow is routed overland towards channels, a portion is lost to surface depressions (depression storage), where it is evaporated (Appendix B). If the depression is located in a pervious area, the water infiltrates into the subsurface. Undersized or debris-filled culverts may cause channel flow to back up. These effects on the surface water response at principal Industrial Area gages (SW093, GS10 and SW027) are minimal, but may contribute to lags in streamflow hydrograph peaks.

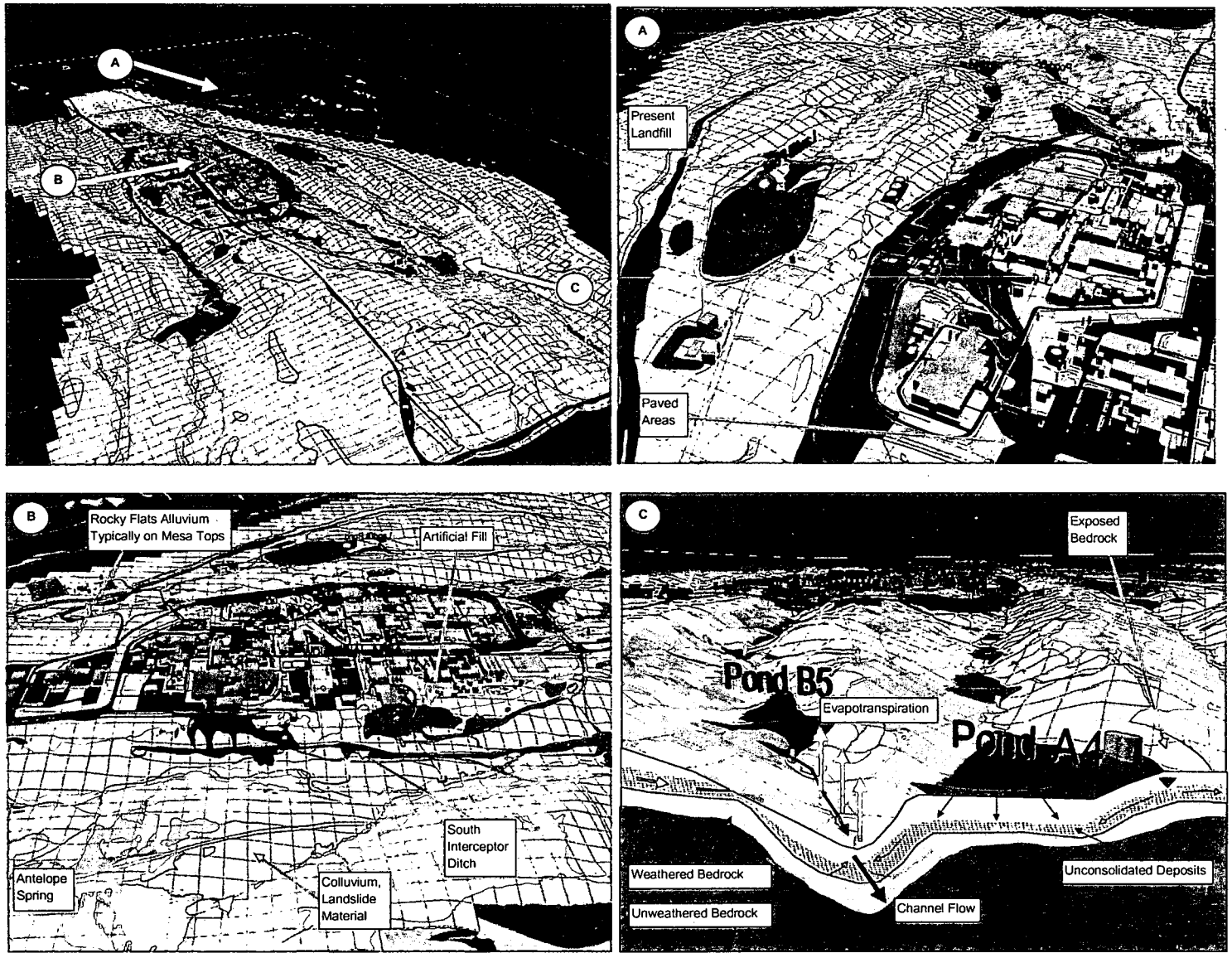
Variations in vegetation occurrence and vegetation density along stream channels affect the surface flow response, and likely decrease the local groundwater table due to ET. In pervious areas vegetation also enhances the total ET loss from the subsurface; water on impervious surfaces is only subject to evaporation.

3.2.3 Buffer Zone

3.2.3.1 Structure (Key Features)

Key Buffer Zone features affecting system flows are graphically illustrated on Figure 3-4. These include: (1) pond structures; (2) seeps; (3) regional hydrostratigraphy; and (4) local hillslope structure. The three-dimensional Site overview in the upper left of the figure also shows viewing directions for the remaining visualizations (A to C). Surficial geologic material distributions and seep locations are also shown on each figure. The Rocky Flats Alluvium occurs principally in mesa areas, colluvium and landslide material on hillslopes and alluvium in near-stream areas. Dark brown areas represent artificial fill material, mostly made up of local Rocky Flats Alluvium and Colluvium (Picture A). Picture C shows a subsurface profile through a hillslope and pond area to illustrate typical groundwater flow directions.

Figure 3-4. Integrated Conceptual Flow Diagrams



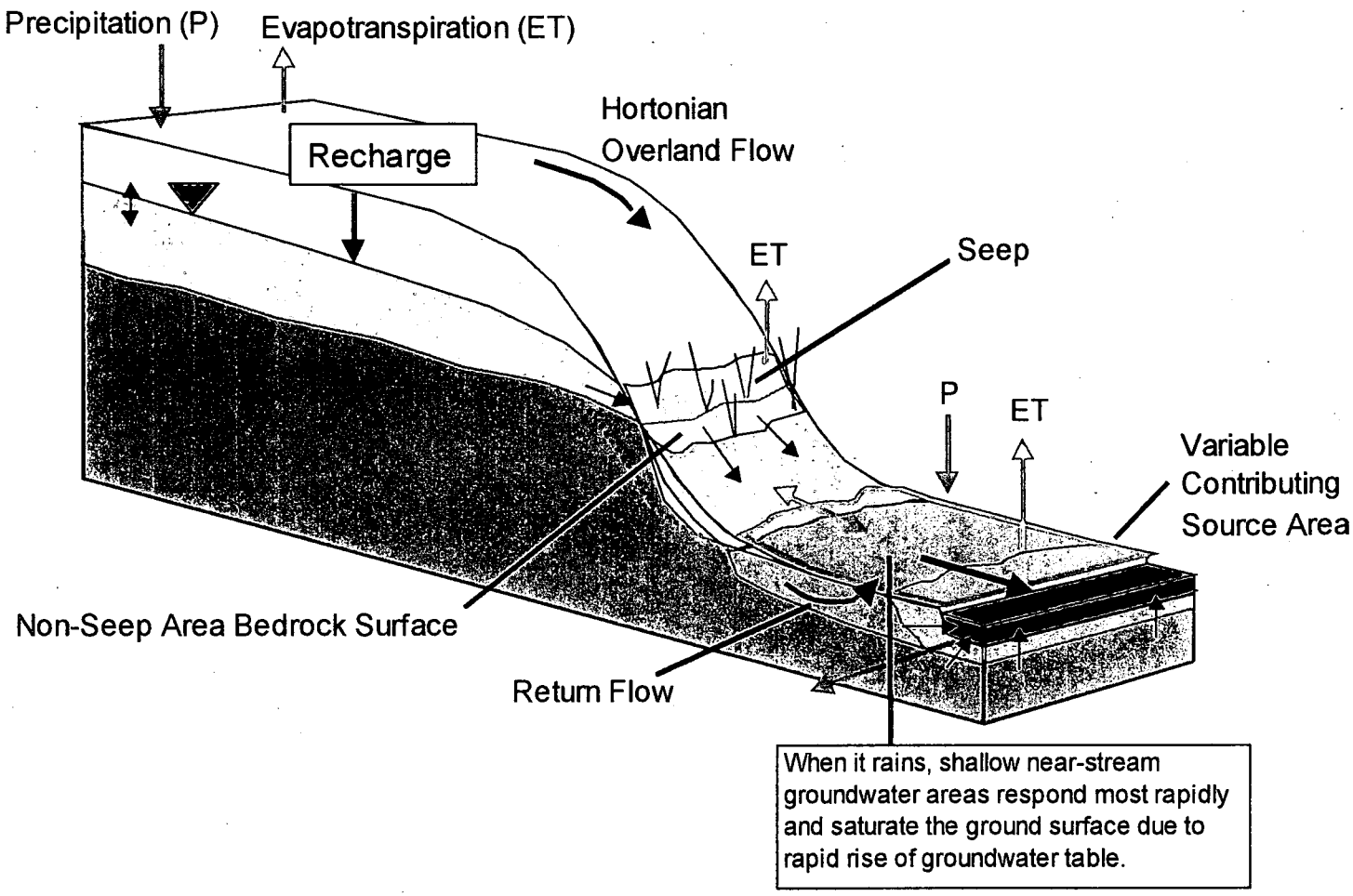
3.2.3.2 System Response

Surface water response in the Buffer Zone is influenced by interactions with groundwater and by upstream inflows. Stream flow response monitored along Woman and Walnut Creek at the eastern model boundary (GS01 and GS03, respectively) represents the cumulative effects of upstream inflows and groundwater impacts. Along Woman Creek, between the western surface inflows (GS05 and GS06 gages), Antelope Springs (GS16 gage) and the Industrial Area (SW027 gage and Pond C-2), all streamflow is lost to the groundwater system during warmer months. During winter months, streamflow along this reach is routed off-site as a result of higher near-stream groundwater levels. Near-stream groundwater levels play an important role in controlling the amount of surface flow discharged from the system and lost to the subsurface. During warmer months, ET decreases the groundwater levels near streams, while in colder months, ET is lower and levels increase. When these levels increase, less streamflow is lost to the groundwater and peak flows increase (see Appendix B).

Regionally, both surface and subsurface water flows from west to east because of the gentle eastward dip of the topographic and bedrock surfaces. Locally, groundwater flow is dominated by the physical structure of the hillslope (Chorley, 1978), as illustrated on Figure 3-5. This concept is important because its structure dominates the natural, local groundwater flow conditions. At RFETS, most groundwater flows in the unconsolidated material, with a lesser amounts flowing in the weathered bedrock. These hydrostratigraphic units are thin compared to hillslopes structures within the model. As a result, the low-permeability unweathered bedrock surface focuses local groundwater flow directions towards streams as shown on Figure 3-5.

A number of groundwater seeps occur in areas where shallow, less-permeable bedrock outcrops because of slumping or landslides along steeper, upper hillslope areas. The seeps discharge groundwater into the surface flow system, where the water flows to adjacent streams or infiltrates into the subsurface system. For most of WY2000, only Antelope Springs, south of the Industrial Area, produced any significant quantity of surface flow.

Figure 3-5. Hillslope Model



Within the Buffer Zone, groundwater is recharged mainly by direct precipitation through the unsaturated zone. Recharge clearly occurs over the entire model area. Based on observed groundwater level data in continuously-monitored wells (see Appendix B), recharge is typically higher in mesa or hilltop areas because the Rocky Flats Alluvium is relatively permeable. The continuous well data also indicate that recharge in areas of deeper unconsolidated material, like in mesa areas to the west and east of the Industrial Area, take several months to respond to spring recharge events compared to weeks for wells in shallow groundwater areas. Despite groundwater flow towards nearby streams (Figure 3-5), slow groundwater flow rates and a shallow water table result in local ET loss prior to reaching streams. As a result, stream-saturated zone interactions are dominated by local groundwater conditions adjacent to the stream, and are not strongly influenced by groundwater flow conditions on hilltops or hillslopes. In general, streams in the higher western areas of the Site exhibit continual baseflow year-round, while lower, less hilly areas exhibit little if any baseflow (Fedors and Warner, 1993).

Streamflow generated in the Antelope Springs area represents a significant portion of the gaged response at the eastern boundary on Woman Creek (gage GS01) during colder months. Streamflow is generated at Antelope Springs by two mechanisms: (1) continuous annual discharge of groundwater; and (2) saturation runoff caused by precipitation falling directly on saturated ground area. The latter mechanism produces the peaky response to precipitation events that are observed at the GS16 gage, located just above the confluence with Woman Creek. The long tail portions of streamflow hydrographs (days to weeks) for the GS01 gage further indicate delayed effects of subsurface storage. This is discussed in greater detail in Appendix B.

It is generally assumed that runoff in arid/semi-arid areas occurs as Hortonian overland flow (Abrahams, 1994), where the infiltration capacity of soils is exceeded by the rainfall intensity. However, near-stream areas can become quickly saturated at the surface during precipitation events because groundwater is shallow (saturation excess). These saturated areas (variable source areas) generate additional fast runoff during precipitation events that contribute to observed streamflow responses (Dunne, 1978). At RFETS, surface soils in hillslope and mesa hilltop areas are generally too permeable to allow Hortonian

overland flow (precipitation rates exceed infiltration capacity of the soils) for the typical annual low-intensity precipitation events. As a result, for typical annual precipitation events, streamflow response within the RFETS system is dominated by near-stream, surface-groundwater conditions (i.e., Antelope Springs) or by controlled pond discharges (i.e., Walnut Creek). It should be noted that lower soil permeability areas of RFETS probably produce Horton overland flow (partial source areas) under typical annual precipitation event intensities, though this has been observed by Site personnel. For extreme events, higher precipitation intensities are produced which will result in Hortonian overland flow that will dominate streamflow hydrographs.

Several Site ponds are key features of the Buffer Zone. They control runoff from the Industrial Area and interact with groundwater. Woman Creek is largely unaffected by pond releases (Pond C-1 is flow-through and C-2 is rarely discharged), and its flow conditions represent more natural flow conditions. The eastern part of Walnut Creek, downstream of the ponds, responds to roughly monthly pond releases each year from both Terminal Ponds A-4 and B-5. During pond retention periods, groundwater levels in downstream areas typically drop below the bottom of the streambed. As a result, when pond water is discharged, up to one-third of the surface flow is lost to the groundwater system by the time it reaches gage GS03 near Indiana Street. Evaporation and groundwater loss from the ponds is low compared to the total discharge amounts.

3.3 SECTION 3 SUMMARY

A conceptual model was developed to provide an integrated conceptualization of the Site surface and subsurface flow processes. It was developed primarily through interpretations made from observed data from WY2000. Historical data were also applied where available to further support conclusions.

A conceptual model was developed to include the Walnut Creek and Woman Creek subdrainages of the Site (as shown on Figure 2-1). Vertically, the conceptual model was bounded below by the top of the unweathered bedrock, corresponding to the UHSU (EG&G, 1995a).

The conceptual model identified the following important stresses to the system: (1) spatial and temporal distribution of precipitation; (2) potential evapotranspiration (PET); (3) imported DWB water; (4) surface inflows; and (5) pond management activities. These stresses, combined with the structure and properties of the system, determine the hydrologic response in the Industrial Area and the Buffer Zone.

Key features affecting the complex hydrologic response in the Industrial Area include: (1) subsurface utility trenches; (2) pipelines; (3) drains; (4) groundwater collection systems; (5) paved surfaces; (6) buildings; and (7) complicated surface water routing. Some of these features cause rapid runoff of surface flow in response to precipitation, and they often affect groundwater levels and local groundwater routing.

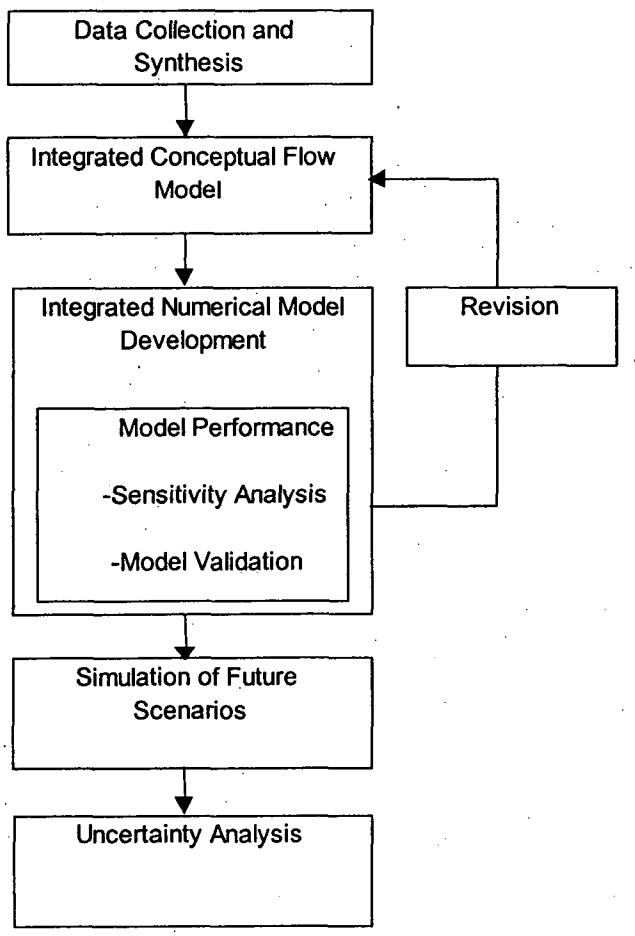
Key features affecting the hydrologic response in the Buffer Zone include ponds, seeps and regional hydrostratigraphy. In the Buffer Zone, groundwater is recharged mainly through direct precipitation. Stream-saturated zone interactions are dominated by near-stream groundwater conditions. They are not strongly influenced by groundwater conditions on the mesas or hillslopes. Saturation excess, in areas like Antelope Springs, dominates streamflow during typical annual precipitation events. Hortonian overland flow dominates hydrographs under higher, more extreme precipitation intensities. Otherwise, most precipitation infiltrates the relatively high permeability of soils on the hillslopes and mesas, where most of it is later discharged as ET to the atmosphere. Surface flow in Walnut Creek is dominated by pond discharges. The Walnut Creek system is typically an overall losing reach throughout the year as a result of pond management. In Woman Creek, pond discharges are much less frequent (less than one per year). Woman Creek gains water throughout the year from Antelope Springs, but loses water to groundwater during spring and summer due to ET from the near-stream vegetation.

The conceptual model was developed to provide the basis for the numerical model. The following section discusses the approach applied to developing the numerical model from the conceptual model.

4.0 MODELING APPROACH

The RFETS modeling approach was introduced in the SWWB Modeling Work Plan (Kaiser-Hill, 2000c). This approach considered the integrated nature of the RFETS flow system, project objectives and available code capabilities. The basic steps of this approach, outlined on Figure 4-1, generally follow the protocol suggested by Refsgaard (1996) for integrated modeling. They are largely based on the standard groundwater modeling protocols presented by Anderson and Woessner (1992). The term "model" used herein refers to an "integrated model" of the surface and subsurface saturated flow systems coupled through the unsaturated zone.

Figure 4-1. Modeling Approach

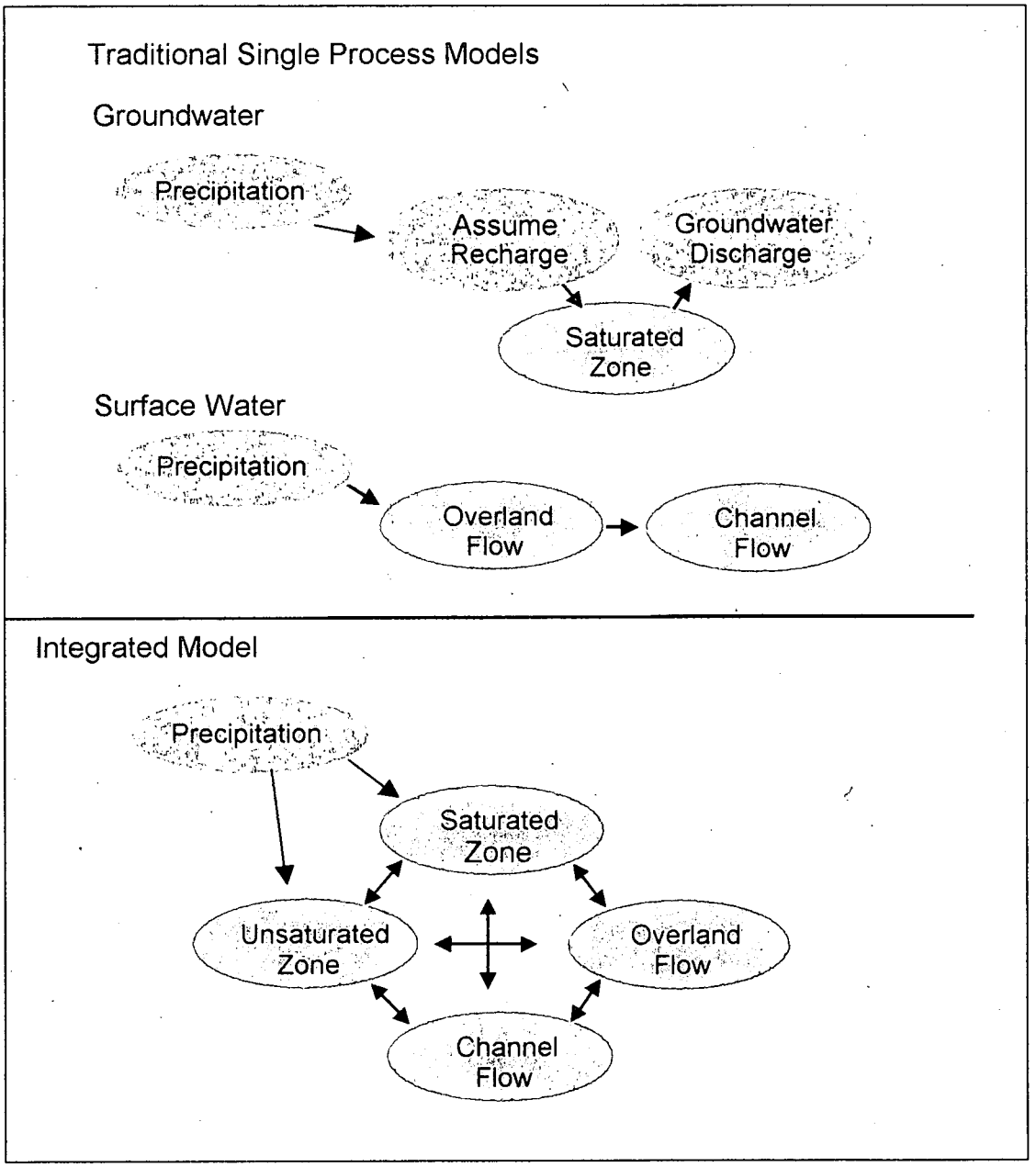


The first steps of the integrated model development approach (data collection, data synthesis and development of a conceptual flow model) were summarized in Sections 2.0 and 3.0. Results from this analysis and understanding of system flow strongly suggested that an integrated flow computer code was required to simulate both surface and subsurface flows and their dynamic interaction. Several integrated codes were identified and reviewed in detail (Kaiser-Hill, 2001b). Based on this review, the MIKE SHE code, developed by the Danish Hydraulic Institute - Water and Environment (DHI) (version 2000), was selected as the best for meeting SWWB modeling objectives.

Integrated codes remain largely untested in arid/semi-arid conditions. This is because higher temporal and spatial resolution climate data and system response data are required to capture near-surface hydrologic system response (Prucha, 2002). The MIKE SHE code has been tested in a large-scale arid/semi-arid basin application (Prucha and Illangasekare, 2001). Further, Illangasekare et al. (2001) assessed the physical and numerical flow equations in MIKE SHE, developed a detailed code verification procedure to test the code and evaluated its performance using this procedure. Results showed the computer code was capable of simulating the important hydrologic processes and their interaction at RFETS.

Another important aspect of the integrated model is the additional constraint on system parameters that results from coupling each of the hydrologic processes (overland flow, channel flow and unsaturated/saturated zone flow) as shown on Figure 4-2. Single process codes do not provide this constraint. For example, if a model parameter is poorly specified in one process (e.g., unsaturated zone hydraulic conductivities), the simulated hydrologic response in other processes typically behave incorrectly (e.g., surface runoff or groundwater recharge). Therefore, reasonable model parameters must be specified for each hydrologic process in the integrated model to avoid inconsistent simulated behavior. This allowed for increased confidence in model parameter values.

Figure 4-2. Comparison Between Single Process and Integrated Models



Following code selection, a fully-integrated numerical flow model was developed. This involved four steps: (1) preparing model input for the MIKE SHE code based on the conceptual model framework (described in Section 3); (2) calibrating model parameters to observed responses; (3) conducting a sensitivity analysis; and (4) completing model validation. Initial estimates for model parameters were adjusted (calibrated) to improve overall model performance in simulating observed hydrologic conditions at RFETS (especially in focus areas).

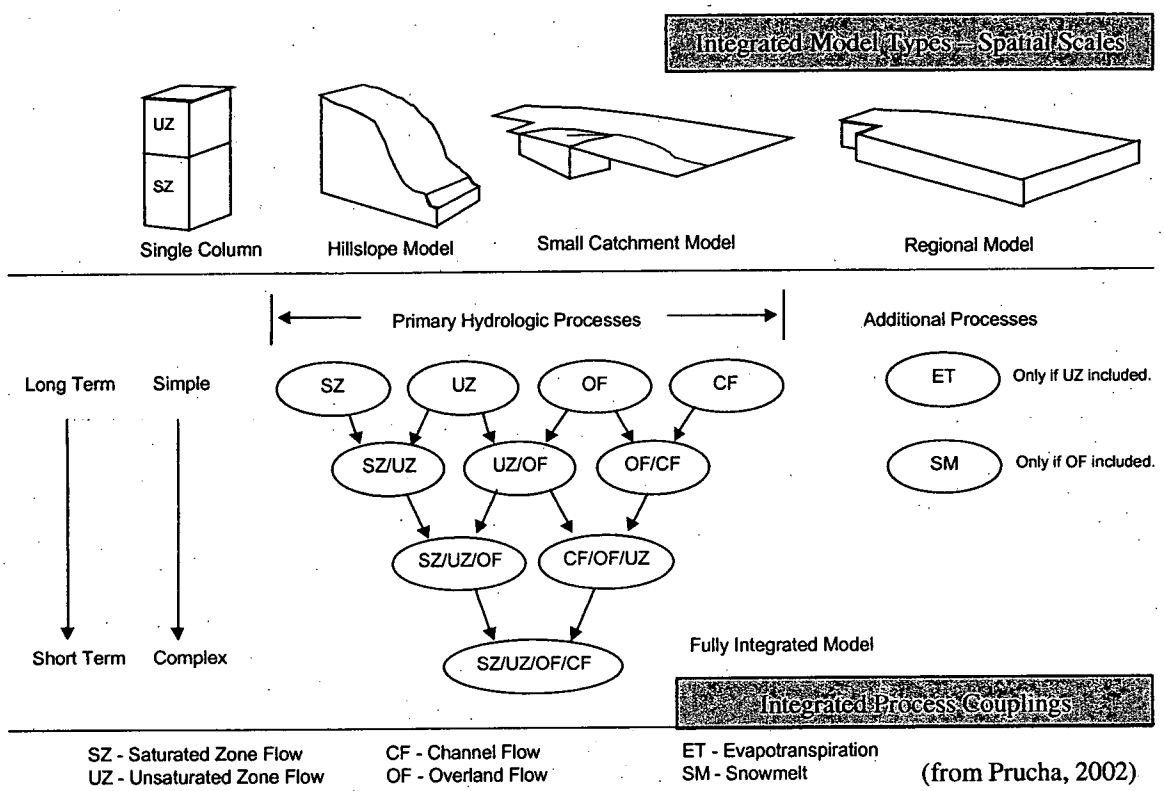
4.1 PROCESS-COUPLING AND SUB-REGIONAL SCALE MODELS

Developing the integrated hydrologic model in a semi-arid environment was an iterative process, particularly for the complex hydrologic system at RFETS. The MIKE SHE model development was based on a modeling framework suitable for arid/semi-arid areas (Prucha, 2002). Two important aspects, spatial scales and process couplings, are shown on Figure 4-3. Flow dynamics in a fully-integrated model are complex. Combined with the substantial number of possible calibration parameters, model calibration using a fully-integrated model can be difficult to achieve. One way to avoid these difficulties is to develop sub-regional-scale models to better understand the fundamental local-scale hydrologic processes and interactions. Single-column, hillside and sub-catchment (drainage basin) models (shown on Figure 4-3) were initially developed and evaluated prior to simulating fully-integrated conditions. They were better constrained, the dynamics were easier to understand and computationally, they were more efficient than the fully-integrated model. Application of the local-scale models made the estimation of model parameter values more realistic.

Models using individual or simpler process couplings are computationally more efficient than the fully-integrated model, and longer-term simulations could be performed to evaluate the hydraulic responses of individual processes. This was important because three years of simulation are necessary to stabilize the unsaturated zone from prescribed initial conditions. If these types of simulations had not been performed, the more complex hydrologic response generated from the fully-integrated model may not have been attributed to the correct hydrologic stress or model calibration parameter.

Figure 4-3. Modeling Framework for Semi-Arid Climates

(from Prucha, 2002)



(from Prucha, 2002)

Different hydrologic process couplings were used extensively throughout the model development and calibration. This approach improved understanding of individual processes based on the combined hydrologic response of the system. Understanding the sensitivity of the hydrologic system response to individual processes was an important factor in developing and calibrating the integrated model.

4.2 SENSITIVITY ANALYSIS

Once acceptable model performance was achieved through calibration, a sensitivity analysis was performed to determine the sensitivity of system response to different model parameters. The sensitivity analysis demonstrated that reasonable model response was produced for a given range of input parameters. The most sensitive model parameters were selected for later use in the uncertainty analysis, as part of the scenarios simulations.

4.3 VERIFYING MODEL PERFORMANCE

The calibrated model was also tested using external system stresses for other years to further demonstrate model performance. Input data from the first half of 1995 and the entire WY2001 were used to test calibrated model performance. This step is termed "model validation" in this study to demonstrate that the integrated model performance is reasonable but should not be confused with "validation" as used by Konikow and Bredehoeft (1992) in traditional groundwater modeling.

4.4 SCENARIO SIMULATIONS

The calibrated model was then used to simulate two hypothetical scenarios (No Imported Water Scenario, and a Land Configuration Scenario) to assess changes in the hydrologic system. Performance of the scenarios was also evaluated using wet and dry climate conditions in addition to the calibration year climate. Results of the Land Configuration Scenario were further qualified in a Monte-Carlo type uncertainty analysis, which provides an approximate indication of the range of predicted uncertainty in response given the uncertainty in sensitive model parameters.

4.5 DESIGN PROCESS SUMMARY

This Section described the approach applied to develop the fully-integrated, hydrologic model. This approach consisted of the following: (1) collection and interpretation of data; (2) conceptualization of the integrated flow system; and (3) development of the integrated numerical model. Final calibrated parameter values were determined by using progressively more complex sub-regional scale models and by using different combinations of hydrologic system processes. After calibration, model performance was further assessed through a sensitivity analysis and validation against data from other years. Finally, the model was used to simulate two hypothetical Site configuration scenarios. An analysis on one of the scenarios was conducted to assess uncertainty in model predictions. The following section presents the numerical model developed from this approach.

5.0 INTEGRATED NUMERICAL FLOW MODEL DESIGN

This section describes the structure and parameterization of the fully-integrated numerical MIKE SHE model. The design of the MIKE SHE model was based on the conceptual model, the MIKE SHE code structure and data requirements (see Appendix D for details on MIKE SHE code).

Integrated codes like MIKE SHE are sophisticated and data intensive. The integrated model presented herein is the result of a comprehensive effort to include important surface and subsurface features that affect the Site hydrology. Earlier modeling studies at the Site have simulated only individual or partially-coupled components of the system hydrology. The model developed here simulates the entire integrated hydrologic response described in Section 3.0. As such, it is important to understand how the basic model framework is structured and how the numerous input model parameters are spatially and temporally distributed. The description of the model is substantial; therefore, this section summarizes the important model features, while the more technical aspects are described in Appendix D.

5.1 SPATIAL AND TEMPORAL DISCRETIZATION

The first step in developing the integrated model was to discretize the different flow domains into a numerical framework (grid system). The grid was superimposed over the flow domain and appropriate time intervals (at which calculations were performed) were determined. After the basic numerical framework was established for each hydrologic process, initial conditions, boundary conditions (describing external stresses on the system) and the hydraulic properties distributions for each process were prescribed. Initial estimates of these hydraulic properties were based on the conceptual flow model presented in Section 3.0. To improve model performance, some of these values (referred herein as calibration parameters) were refined. The description of the model presented below represents the current calibrated fully-integrated model. Where relevant, the original assumptions about the input parameters are discussed.

The different hydrologic components of the integrated model are described in Section 5.2. Components include: (1) the surface flow system, including overland and channel flow processes presented in Section 5.2.2; (2) the saturated zone process presented in Section 5.2.3; (3) the unsaturated zone process, including ET presented in Section 5.2.4.4; and (4) hydrologic stresses like climate are discussed in Section 5.2.1.

5.1.1 Discretization

The first step in developing the integrated model was to prepare a numerical grid that adequately represented essential features of the conceptual flow model. The model was designed to simulate regional, Site-wide flow conditions and not localized flow conditions. Although a more accurate representation of the system could be obtained using a finer grid (larger number of calculation points), this can becomes computationally inefficient for a regional model. Furthermore, resolution can only be refined to the extent and detail that data are available for input.

Initial simulations using different grid sizes for just the subsurface flow system indicated that a 200-by 200-ft (~61 m x 61 m) grid was the most suitable compromise between numerical efficiency versus solution accuracy required to meet the project objectives. Typically, it is the saturated and unsaturated zone model components typically that are most computationally intensive. (In MIKE SHE, the numerical discretization for the channel flow network used a variably-spaced, finer resolution grid than for the subsurface [as fine as 15 m {49 ft} in some areas] to fully-capture hydrodynamic surface flow behavior.)

The numerical model is a simplified representation of a complex flow system. Although the system parameters and structural information that control flows were known reasonably well at RFETS, point-scale hydraulic data, like hydraulic conductivities from wells, had to be converted into "effective" values within each MIKE SHE model cell (200 x 200 ft or ~61 x 61 m). In addition, the simulated response also represented average conditions over each model cell. As a result, special care was taken in comparing average simulated groundwater levels to specific well response data.

A generalized diagram, showing how the integrated model grids for the four basic hydrologic flow processes, is shown on Figure 5-1. The 200-by 200-ft (~61 m x 61 m) specified for the horizontal grid was used to define the two-dimensional overland flow and three-dimensional saturated zone equations. The channel flow and unsaturated zone used one-dimensional discretizations to solve the full St. Venant equations (Chow, 1988) and Richard's equation (Stephens, 1996), respectively. The rapid response of channel flow and the non-linear unsaturated zone required finer resolution grids for these processes than for the slower groundwater flow system.

5.1.2 Temporal Discretization

Time step specification is important in the MIKE SHE model because it affects the solution accuracy and strongly influences the computational efficiency. If time steps are too large, instabilities in the model solution occur and important dynamics may not be captured. If time steps are specified too small, simulations become computationally inefficient.

In addition to defining spatial grids for the model, the numerical solution of the flow equations also required appropriate time steps for each process. Figure 5-2 illustrates the general time stepping protocol used in MIKE SHE. All time steps must be specified as multiples of each other in the MIKE SHE code as part of the integrated solution algorithm. The numerical time stepping is dictated by the different response time scales for each hydrologic process. For example, the saturated zone responds much more slowly to external stresses, like precipitation, than do surface flows. As a result, the saturated zone time step is typically specified much larger than for the other processes to improve the integrated model efficiency. Time stepping for the surface water flow is controlled by the MIKE 11 portion of the MIKE SHE code, but also is partially controlled by the unsaturated zone, overland flow and saturated zone time steps. Specifying time steps must also consider the amount of precipitation that occurs during a time step (i.e., intensity), and the specified frequency of model output as shown on Figure 5-2. Time steps are internally adjusted in the code to account for both of these conditions.

Figure 5-1. General Integrated Model Discretization

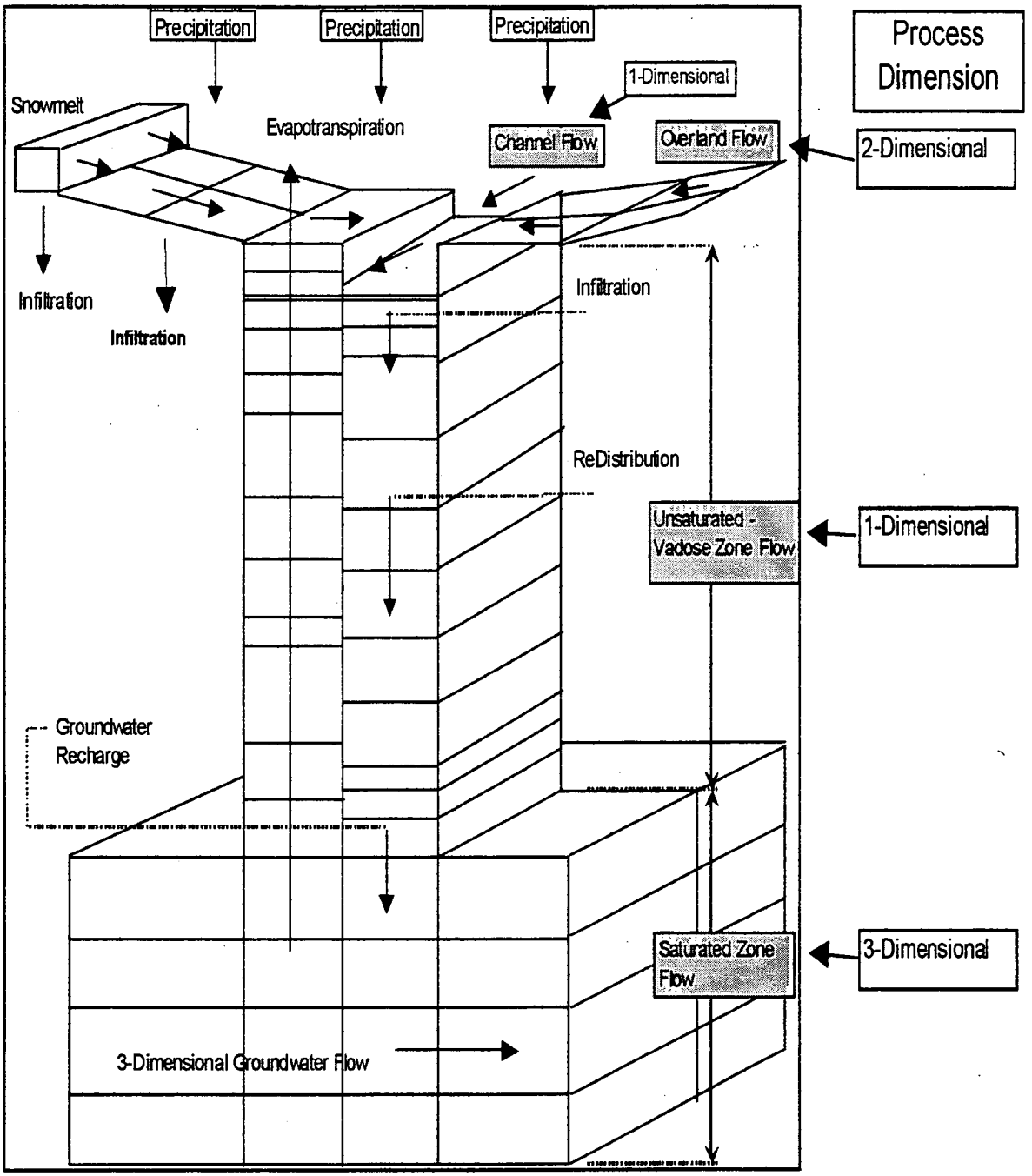
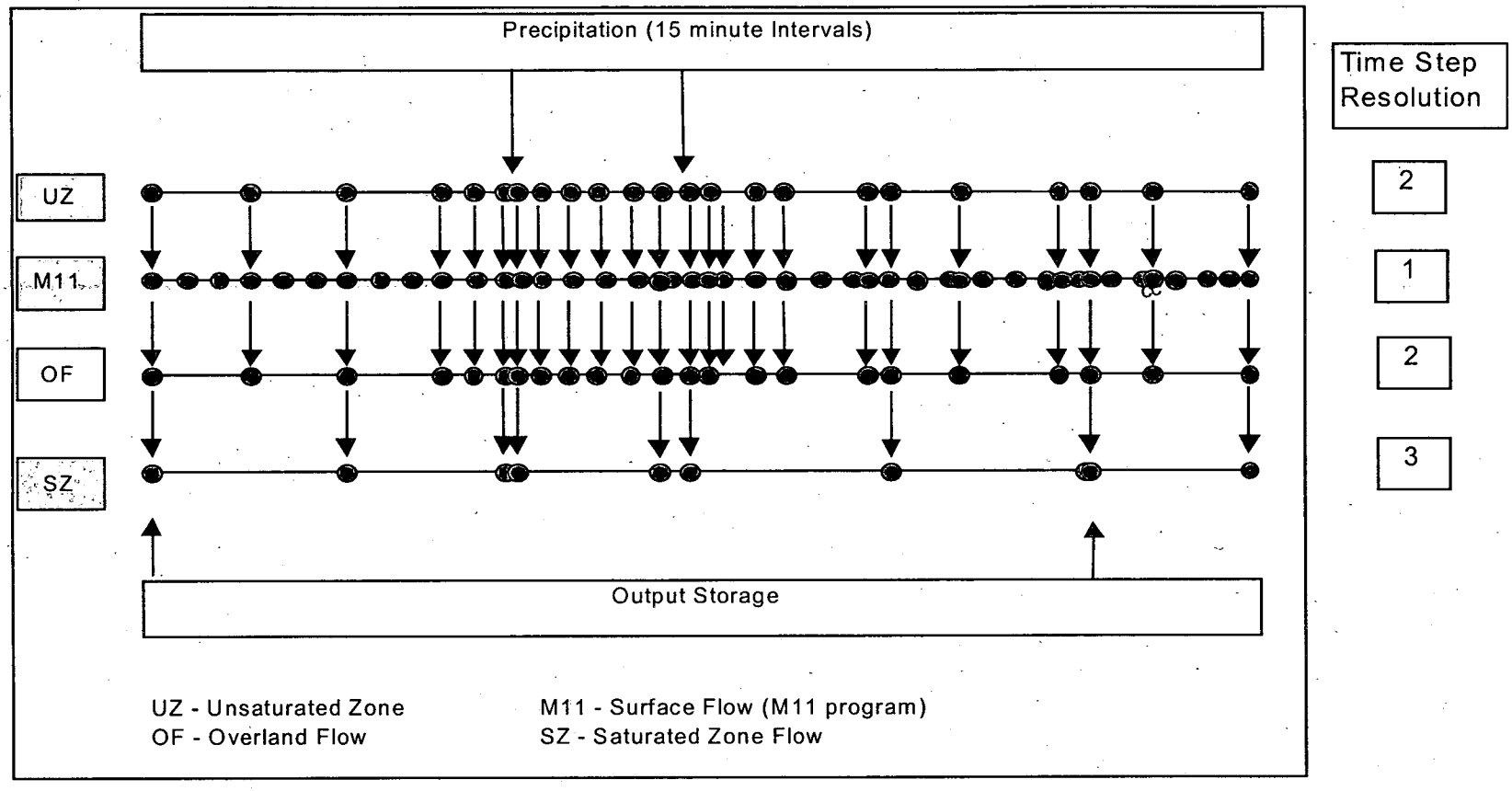


Figure 5-2. MIKE SHE Time Discretization



Notes: 1. Arrows denote order of internal calculations.
2. Precipitation and printout times control timesteps.

Internal process calculations are started by first solving the unsaturated zone flow equations because overland flow is generated only if ponding occurs (i.e., Horton or saturation excess overland flow). Results from this calculation are then passed to the surface flow algorithm and then back to the unsaturated zone, unless a saturated zone time step occurs. After calculations are conducted in the saturated zone algorithm, results are then passed back to the unsaturated and surface flow system algorithms. Unsaturated zone flow behavior is typically non-linear and requires more time steps than saturated zone flows.

To capture the important, but short-duration, semi-arid surface flow responses observed in the surface flow system, external stresses were specified at a fine time resolution (short time steps). For example, precipitation was specified every 15 minutes, PET and temperature were specified hourly, and boundary surface inflows every 15 minutes. The model was simulated for one full year (October, 1999 to October, 2000 defined as WY2000) to assess the overall model performance, to demonstrate that seasonal differences in response are correctly simulated and to allow the slower hydraulic response of the saturated zone to adjust to initial conditions. Longer time periods could have been used to better constrain model parameterization better, but the quality and quantity of precipitation and PET input data are poorer for earlier years. Moreover, annual cyclic groundwater level variations from 1990 to 2000 (analysis in Appendix B) suggest that simulating a single year is probably adequate for parameterizing the subsurface flows.

In the SWWB model, the maximum time steps are specified as follows:

- Channel Flow (MIKE 11) = 0.5 minute;
- Overland and Unsaturated Zone Flow = 0.5 hours; and
- Saturated Zone Flow = 6 hours.

5.2 MODEL COMPONENTS

This section describes the different physical components used to define the MIKE SHE fully-integrated flow model. Climate data are described first, followed by descriptions of model input for surface, saturated and unsaturated zone flow domains.

5.2.1 Climate

Model precipitation and snowmelt input are described in the following sections.

5.2.1.1 Precipitation

Precipitation drives most of the system response at RFETS. As a result, it was important to consider its spatial and temporal distribution. Initially, standard Theissen polygons were specified to estimate the spatial distribution of precipitation. However, typical summer-time heterogeneous precipitation was not represented well using this methodology (because the estimated spatial distribution depends on the number of active stations). Therefore, a more robust interpolation methodology was used to spatially distribute the 15-minute precipitation data available from the 10 on-Site stations. A total of 40 precipitation zones of roughly-equal size (and based on surface topography) were created to distribute precipitation over the model area in 15-minute intervals for the calibration year. The interpolation method used to distribute the precipitation and graphs of the 40 precipitation zones are described further in Appendix D.

5.2.1.2 Snowmelt

The numerical model applies a simple degree-day method to determine the rate of snowmelt. The two variables, degree-day factor and threshold value, were set through calibration. The threshold (°C) defines the temperature at which snowmelt can begin. The degree-day factor (mm snow/day/ °C) sets the rate of snowmelt as a function of temperature relative to the threshold value. The simple degree-day snowmelt model included in MIKE SHE does not account for effects of ground temperature, development of crust, salting of roads, or distributed effects of solar radiation on snowmelt. Despite

this, simulations show air temperature is probably the dominant factor, and the degree-day method provided adequate results.

Calibration of the threshold value and degree-day factor was accomplished by systematically varying the values of the threshold and degree-day factor from –3.0 to 2.0 °C and from 0.5 to 5 mm snow/day/ °C, respectively. The system response, in terms of surface water volume match and hydrograph shape, was considered at gages GS10, SW093, GS16 and GS01 for a large snowmelt event during March, 2000. The resulting settings of –2.6 °C for threshold and 1 mm snow/day/ °C for degree-day factor were then tested for another snowmelt event in January, 2001. These settings provided good results.

Time varying air temperature data were input uniformly across the Site based on records from the Site Meteorological Tower located in the western Buffer Zone. Spatial analysis of air temperature, available from CDPHE data (five stations surrounding the Site), showed little variability in daily temperatures across the Site.

General Site observations indicated that snow melts slower on north facing slopes than on south facing slopes, which is due to differences in incident solar radiation. Over the scale of the Site model, effects of different incoming solar radiation on north and south facing slopes on snowmelt average out (incident solar radiation on a horizontal surface was assumed for the model). Simulated surface flows using just the snowmelt feature in MIKE SHE showed that amount and timing of delayed runoff in the days after snowfall events could be captured well.

5.2.2 Surface Flow

Overland and channel flow were set up in the numerical model to honor the conceptual model described in Chapter 3.0.

5.2.2.1 Overland Flow

In the numerical model, overland flow is defined by four main data specifications:

- Initial water depth;
- Depression storage;
- Surface Manning; and
- Overland flow areas.

The initial water depth setting specifies the water depth on the ground surface at the beginning of the model run. This depth is set at zero in the model, which is reasonable considering the runs were not initiated during intense events.

Depression storage is the water depth on the ground surface that must be filled before overland flow will occur. This depth accounts for micro-topography and is averaged over the area of each model cell. Depression storage was spatially defined in the model. From calibration efforts to match channel flow observations, depression storage is set to 1 mm (0.04 in) in the Buffer Zone and 0 mm in the Industrial Area. The Solar Ponds (once used to evaporate water from brine solutions) were specified with a depression storage depth of 1 meter (3.3 ft) to allow for capture of rainfall. In MIKE SHE, depression storage is referred to as detention storage. It should be noted that detention storage does not include interception, which is the depth of precipitation intercepted by plant cover. Interception in included in the model as part of ET (Section 5.2.4.3). The detention storage defined for the model area is shown graphically in Appendix D (Figure D-2).

The Surface Manning (M) value, with units of $m^{(1/3)}/s$, is a numerical representation of the roughness of the surface. M-values correspond to 1/n, where n is a common n-value applied in the Manning's equation. Decreasing M-values represent increasing roughness. In the model, M-values were set based on values applied for previous Site modeling efforts (Kaiser-Hill, 2002a and Kaiser-Hill, 2002b) and refined with calibration simulations. Overland roughness is specified spatially for three surface conditions:

- Impervious Surface (A roughness of M=20 [n = 0.05] was specified for cells with >45 percent imperious coverage);
- Partially-Impervious Surface (A roughness of M=5 [n = 0.2] was specified for cells with 5 – 45 percent impervious coverage); and
- Vegetated Surface (A roughness of M=3 [n = 0.33] was specified for all other cells).

These settings fell within ranges identified by Chow (1959). The distribution of surface resistance values (different from channel resistance) are shown graphically in Appendix D (Figure D-3).

Overland flow was solved for in two dimensions, according to topography specified for the model grid cells. Overland flow boundaries were provided as additional constraint on the overland routing. These boundaries were applied to account for local topographical and routing features, such as berms or roof drains, which were not captured by the specified topography. The model applied 21 overland flow areas, concentrated largely in the Industrial Area. These areas were specified based on digital subdrainage delineation of topography and extensive field-truthing. These 21 areas represent the minimum number of overland flow areas required to define all the subdrainages of interest. The overland flow areas applied are shown graphically in Appendix D (Figure D-4).

5.2.2.2 Channel Flow

In the MIKE SHE code, the MIKE 11 program module calculates channel flow that interacts dynamically with overland runoff and the subsurface system. The MIKE 11 model requires input specifications defining the network structure, boundary conditions, hydrodynamic parameters, solution settings and time step. The calibrated input data sets, developed from the conceptual model are described below.

5.2.2.2.1 Network Structure

The network structure consists of a system of channels defined in plan view by points and in profile and section view by cross-sections. Ponds are also defined within the network by points and cross-sections. Routing follows gravity according to specified channel connections and the resulting profiles. Sources of data for channel cross-sections and rationale for determining the appropriate network complexity are discussed in Appendix B. The final network is a very thorough representation of the Site surface system, consisting of 71 branches defined by 408 cross-sections. The plan view of the surface water network is shown graphically in Appendix D (Figure D-4).

Cross-section data were refined in some cases for purposes of model stability or accurate integration with overland flow. Refinements were applied cautiously, with the goal of improving the representation of the system, and considering the project objectives. Refinements were limited to maintain appropriate elevations relative to the Site topography. These refinements included reshaping, trimming, adding and removing cross-sections. Data sources, refinements and related assumptions are described in Appendix D.

5.2.2.2.2 Boundary Conditions

Boundary conditions were applied within the numerical model to both channels and ponds to simulate inflows and pond transfers. Appendix D (Figure D-5) shows the location of boundary conditions and control structures on the Calibration Year Model.

Along the channels, boundary conditions of water depth or flow rate are required at all free ends of channels within the model. Free ends of channels occur within the numerical model at:

- Inflow locations along the system boundary (Upper Church/McKay Ditches, Woman Creek, and Owl Branch);
- Upstream ends of tributaries originating within the model boundary; and

- Downstream ends of channels leaving the Site Boundary (McKay Bypass Pipeline, Walnut Creek, Mower Ditch and Woman Creek).

Boundary conditions at surface water inflow locations were set as times-series flow rates, according to observed 15-minute flow record (see Appendix B). Boundary conditions at upstream ends of tributaries were set to constant zero inflow to reflect no upstream, channelized connection. Finally, constant water depth boundary conditions (less than 0.1 meter or 0.3 ft) were specified at downstream channel ends. This essentially simulated an infinite reservoir beginning at the extreme end of the channel, therefore allowing all water to flow out without backwater effects. All channels were assumed to be dry at the beginning of simulation, except ponds which were provided the appropriate initial depths.

Boundary conditions are also applied in the ponds to simulate discharges and transfers for the calibrated model. This includes inflow of WWTP discharge to Pond B-3. All discharges were set up based on the actual transfer records to facilitate calibration efforts. Where 15-minute flow records were unavailable, daily transfer volumes were used, assuming constant pumping rates for the recorded hours of pump operation.

5.2.2.2.3 Control Structures

To simulate evaporation within the ponds, control structures were applied. MIKE 11 does not link to the ET portion of MIKE SHE directly, so evaporation from ponds was simulated using control structures. The control structures determined the evaporation rate for the ponds by applying three types of information:

- Pond surface area: pond surface area is converted from the simulated pond level using Site pond charts;

- Maximum evaporation rate (depth/time): this value is based on the maximum WY2000 calculated PET value for the Site (see Appendix B). This value was applied, then scaled based on Site-specific monthly evaporation rates supplied by the Office of State Engineers Water Resources Division and cited by Wright Water Engineers (1995b); and

- Relative PET time series: this is the same PET time-series generated for input into the MIKE SHE portion of the numerical model (see Appendix B), but normalized to a value of one.

The control structures operate at the time step of MIKE 11, applying the maximum evaporation rate, scaled to the relative PET, over the surface area corresponding to the simulated pond level. The evaporation estimates compare well with those generated for Site ponds by RMRS (1999b). Specifically, SWWB-simulated total pond evaporation for WY2000 was within 20 percent of that estimated by RMRS (1999b) for WY1999.

5.2.2.2.4 Hydrodynamic Parameters

The main hydrodynamic parameter set within the MIKE 11 portion of the model is channel roughness. As a first step, channel resistance values were set based on survey information gathered as part of the Site Actinide Migration Evaluation (AME) project (Kaiser-Hill, 2002a). Data gaps in the AME project were filled in using Site knowledge and field notes, following trends in the AME data set. Roughness values were then refined through the calibration process by matching observed hydrographs.

Manning M-values ($m^{(1/3)}/s$) ranged from 10 to 33.3 (n = 0.1 to 0.03). This range was considered reasonable when compared to published values in Chow (1959), and a MIKE SHE maximum recommended range of M = 10 to 100 (DHI, 2000b). More discussion on observations of channel roughness is provided in Appendix B.

5.2.2.2.5 Solution and Time Step

Specifications for the solution settings and time step complete the input for the numerical channel flow model. These solution settings include the wave approximation, solution interval and time step. These settings specify how the numerical solution is determined.

The wave approximation was set as fully-hydrodynamic for all channels except one short, steep tributary to North Walnut Creek within the Industrial Area. The high-order, fully-

dynamic wave approximation provided the most consistently stable solution. It was chosen to allow for back-watering effects (required to allow for filling of ponds).

The solution interval (dx) determines the maximum interval between model H (water level) and Q (flow rate) solution points along a channel. The interval is determined based on the dx value and the placement of cross-sections. The dx value proved to be a sensitive parameter for stabilizing the solution. A dx value range of 15 to 200 m (50 ft to 650 ft) was applied, set specifically for each branch. Typically, ponds and branches with a high cross-section density were given low dx values for a more detailed solution.

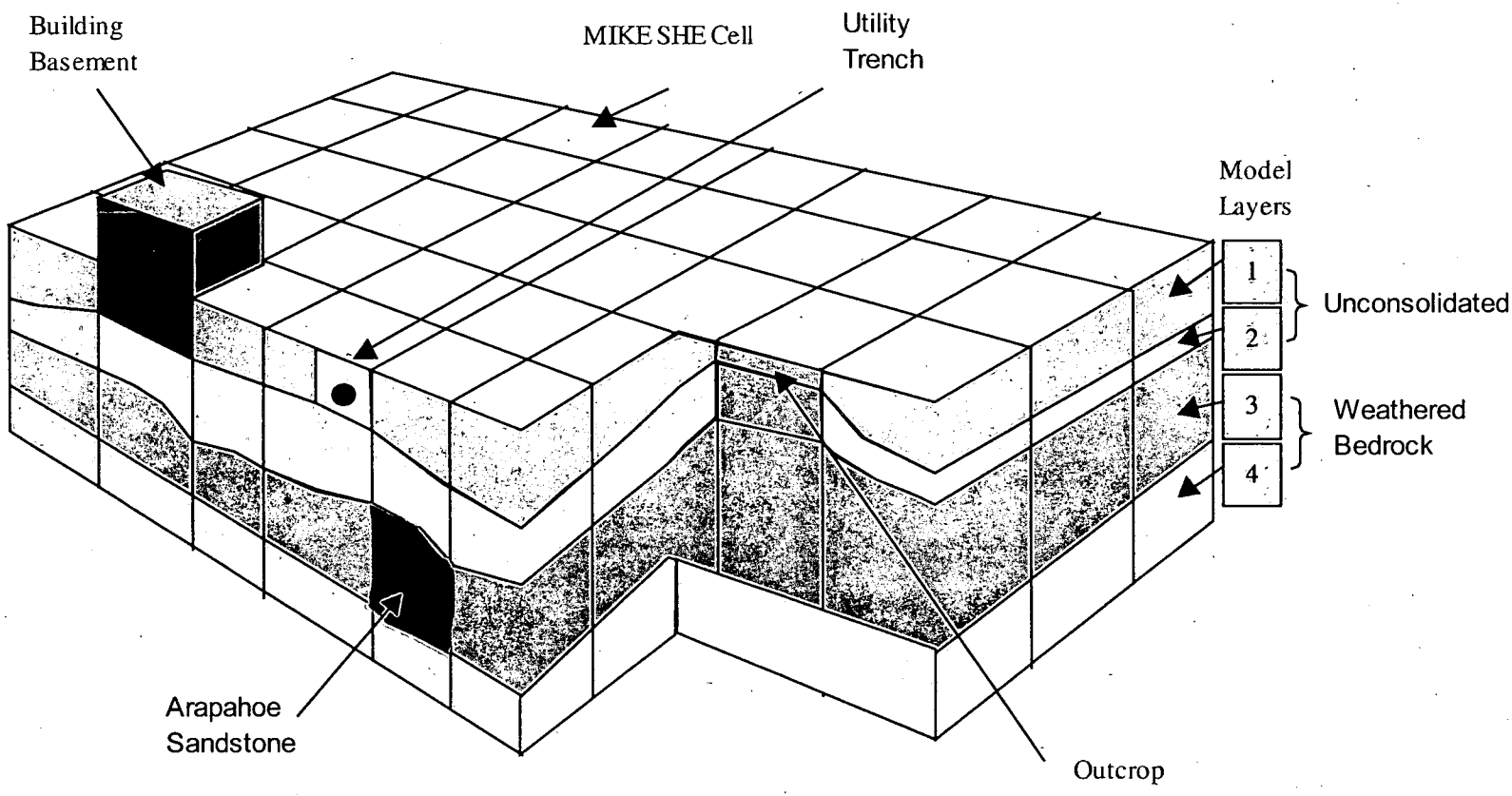
The solution time step was set to provide solution stability at an adequate solution frequency while considering computational efficiency. With input data and observation data for comparison available at 15-minute intervals, the limiting factor for setting the time step was solution stability. Since the channel network was complex, including back-watering at ponds and sharp changes in channel slope, a small time step was required to generate a stable solution for all channels. To maximize computational efficiency, the time step was set as high as possible while still providing a stable solution. The final MIKE 11 time step was set at 0.5 minutes.

5.2.3 Saturated Zone

5.2.3.1 Model Layers

The saturated zone was vertically discretized into four model layers in the SWWB model. Figure 5-3 shows a general diagram of the four layers, and different factors considered in its development. The upper and lower two layers represent the unconsolidated material and weathered bedrock, respectively. The unconsolidated material was divided into two layers to allow more accurate description of flow beneath subsurface utilities and basements that do not extend to the weathered bedrock. Two layers were used to describe the weathered bedrock. This was done to incorporate Arapahoe Sandstone lenses that subcrop unconsolidated materials or are entirely embedded in the claystone/siltstone matrix of the Arapahoe/Laramie Formation. This layering description also permitted flexible description of exposed bedrock, as shown on Figure 5-3.

Figure 5-3. Saturated Zone Model Layers



The thickness of the unconsolidated material (Model Layer 1 and Layer 2) and weathered bedrock (Model Layer 3 and Layer 4) are shown graphically in Appendix D. Model layer thicknesses were developed by averaging the finer spatial resolution geologic surface information (see Appendix D) onto the 200- by 200-ft (~61 m x 61 m) MIKE SHE grid. Unconsolidated material thickness is greatest in the west (100 ft) (30.5 m) and thins to the east (1 to 10 ft or 0.3 to 9.1 m). Within the Industrial Area, thicknesses are quite variable, ranging from near 0 ft to about 50 ft (15.2 m) in the western area. Model layers were modified in the Industrial Area where subsurface drains are present to more accurately represent these features. The weathered bedrock thickness is variable over the model area, ranging from near 0 ft to almost 90 ft (27.4 m) in the western model area. This is described in more detail in Appendix D.

5.2.3.2 Initial and Boundary Conditions

Boundary conditions are required for the saturated zone portion of the integrated model. The analysis of saturated flow conditions (Appendix B) indicated that lateral inflows and outflows occur only on the western and eastern boundaries, respectively. Temporally, constant groundwater levels (pressures) were specified along these boundaries; spatially, they varied along the boundaries based on seasonally-averaged conditions (determined through the groundwater analysis discussed in Appendix B). Uniform vertical groundwater levels were assumed given the low vertical gradients at the Site. A no-flow boundary condition was assumed for the bottom of the saturated zone (unweathered bedrock conductivities were much lower than for the weathered zone).

Initial conditions were important in the integrated model, particularly for the saturated zone. In an integrated semi-arid hydrologic model, the slow response time of the unsaturated zone, combined with the even slower response of the saturated zone to assumed initial conditions, requires repeated simulation of the fully-integrated system to approach steady conditions. Initially, the groundwater system stabilized to the hydraulic conductivity distributions, spatial and temporal recharge response of the unsaturated zone and initial conditions. Repeated simulations allowed the system to approach a quasi-steady condition. Although repeated simulations using the same calibration year input

stresses (precipitation and PET) do not represent the actual time-varying stresses applied to the system, the system did approach an annual state of dynamic equilibrium. The same year of precipitation and PET were applied repeatedly because they represented the most complete (entire year) observed data set available.

The October, 1999 potentiometric surface (assumed the same for all layers) was used as the initial condition for an initial simulation. From this initial simulation, final groundwater level distributions were extracted and then used as input to another one-year simulation. The conditions at the end of this second simulation provided the initial conditions for the saturated and unsaturated zones for the model runs.

5.2.3.3 Hydraulic Properties

Only the saturated hydraulic conductivities and storage coefficients (confined and unconfined) were required in the saturated zone model component. These control the flow rates and transient flow behavior within the saturated zone, and they are described below.

5.2.3.3.1 Hydraulic Conductivities

The USGS surficial geologic map (Appendix B) was used as the basis for the spatial distribution of horizontal hydraulic conductivities within Model Layers 1 and 2 over the model, (where subsurface drains were absent). Conductivity values for the weathered bedrock (Layers 3 and 4) include Arapahoe sandstone deposits (seen within the claystone/siltstone matrix of the Arapahoe and Laramie Formations distributions (Appendix B). Appendix D shows the hydraulic conductivity distributions for Layers 1 through 4.

Within the Industrial Area, saturated hydraulic conductivities and model layers were adjusted to account for the effect of the subsurface utility trenches, basements and footing drains. (This approach used to adjust the hydraulic conductivities is described in Appendix D). As a result, hydraulic conductivities within the Industrial Area for Layers 1 through 4 (shown graphically in Appendix D) were higher in cells where basements and

footing drains occur. This was done to better simulate the combined effect of basements and footing drains, both of which occur within a single cell. The higher hydraulic conductivity allowed groundwater to be extracted by the footing drains and decreased the groundwater table below the basement inverts.

Vertical saturated zone hydraulic conductivity data are limited at RFETS. As a result, this parameter value was evaluated primarily through calibration. Published data and the fact that individual material types (unconsolidated, or bedrock) at the Site-wide scale are relatively homogenous (not much layering) suggest it is reasonable to assume uniform properties for the unsaturated zone. As such, the vertical anisotropy, or the ratio of the horizontal to vertical hydraulic conductivity within a given model layer, ranged from 1 to 5 based on calibration. Sensitivity analysis for hydraulic conductivity is presented in Section 6.2.

During calibration, saturated hydraulic conductivities (Table 5-1) were adjusted primarily near streams in combination with stream leakage coefficients (lower section of Walnut Creek and Woman Creek) to simulate the observed stream response. Locally, the hydraulic conductivity distributions were adjusted as an entire geologic unit within a model grid cell (as opposed to adjusting values in individual cells to match local observed responses).

Table 5-1. Saturated Hydraulic Conductivities

Model Layer Number	Geological layer	K_h (m/s)	K_v/K_h anisotropy ratio
1	Unconsolidated deposits	$2x10^{-5} – 2x10^{-4}$	1:5
2	Unconsolidated deposits	$1 x10^{-7} – 3 x10^{-5}$	1:1
3	Weathered bedrock	$1 x10^{-10} – 8 x10^{-6}$	1:1.25
4	Weathered bedrock	$1 x10^{-10} – 8 x10^{-6}$	1:1.25

5.2.3.3.2 Storage/Specific Yield

Confined (S_p) and unconfined (S_y) storage coefficients were specified for the four model layers. The UHSU is unconfined at RFETS, and thus, S_y was an important parameter. S_y describes the specific yield of the UHSU, which is higher for the near-surface alluvial layers and decreases with depth for the weathered bedrock.

The S_y values (Table 5-2) were chosen considering the unsaturated zone soil properties, available Site data and the groundwater response to the April recharge events.

Table 5-2. Storage Coefficients Applied for the Groundwater Layers

Model Layer Number	Geological layer	S_y	S_p
1	Unconsolidated deposits	0.10	0.001
2	Unconsolidated deposits	0.10	0.001
3	Weathered bedrock	0.02	0.001
4	Weathered bedrock	0.02	0.001

5.2.3.4 Subsurface Utilities and Remediation Systems

Subsurface utilities and remediation systems affect both the groundwater and surface flow systems. Because the MIKE SHE code extracts water from the saturated zone and specifies it as input to simulated streamflow, specification of the subsurface utilities and remediation systems were not considered boundary conditions. Utilities and remediation systems were treated as drains and were represented by specifying drain cell locations, drain inverts and drain leakance. Details of drain specifications in the SWWB model are described in more detail in Appendix D.

5.2.4 Unsaturated Zone

5.2.4.1 Vertical Discretization

The numerical solution scheme used to simulate the soil water content and flow in the unsaturated soil columns required discretizating of the entire unsaturated zone column into vertical computational nodes. The discretization had to be sufficiently detailed to describe the following: (1) the rapid changes in hydraulic potential and soil water content following rainfall input to a dry soil; (2) the numerically stable solution given the strong non-linearities of the Richard's equation; and (3) a reasonable computation time for the entire integrated model.

Unsaturated zone soil columns were defined from the soil surface down to a depth below the lowest simulated groundwater table. The thickness of the unsaturated zone varied throughout the model areas and temporally with seasonal fluctuations of the groundwater table. The unsaturated zone numerical grid was the finest at the ground surface to simulate the infiltration process accurately. It is also kept relatively fine within the root zone (0.02 m to 0.1 m or 0.8 in to 4 in) to avoid numerical instabilities caused by ET. Below the root zone, the grid dimensions were increased with depth and kept constant at 0.4 m (15 in). This was done because unsaturated zone flow dynamics decrease with depth, and computational efficiency was improved. Vertical unsaturated zone column grid cell sizes ranged from 0.02 to 0.4 m (0.8 to 15 in), with 0.02-0.10 m (0.8 in to 4 in) within the root zone. The unsaturated-saturated zone coupling algorithm did not require further unsaturated zone refinement.

5.2.4.2 Initial and Boundary Conditions

The response times for flow and soil moisture content vary across the unsaturated zone. For example, in the near-surface soils, capillary pressures and moisture contents changes on the order of minutes in response to precipitation and ET. In the deeper sections changes in these variables are more similar to the time scale of groundwater flows (i.e., days).

Antecedent soil moisture distribution was important to simulate the key hydrological processes, specifically, the volume of water stored in the unsaturated zone. Incorrect antecedent conditions will (if not lost by ET) affect groundwater recharge and, potentially, baseflow contributions to the stream.

Because the initial soil moisture content could not be specified from field measurements, a "hot-start" option in the model was used. In the "hotstart", an initial field capacity (capacity of the soil to retain moisture) is assumed. One year was simulated to generate a water content distribution reflecting the seasonal state of the hydrological system (by October, 1999). Meteorological data from 1999-2000 were used for the "hot-start" simulation.

No boundary conditions were needed for the unsaturated component of the integrated hydrological model. The upper boundary shifts automatically from an upper ground surface flux boundary during times of no rainfall and to a head boundary when ponding occurs. A pressure head corresponding to full saturation is applied at the lower dynamic interface between the unsaturated zone and the groundwater.

5.2.4.3 Hydraulic Properties

Appendix D shows the soil distribution specified in the model. The unconsolidated materials have been broadly grouped into the three main surficial deposit material types (Qrf, Qc and Qvf) shown on the surficial geologic map (Appendix B). The Colluvium (Qc) includes all material types except the Rocky Flats Alluvium (Qrf) and Valley-Fill Alluvium (Qvf includes the Piney Creek and Terrace Deposits, Qp and Qt, respectively). Through calibration, the Colluvium was divided into an east and west area, to improve model performance. In addition, a single bedrock material type was used to represent the small, isolated bedrock outcrops, located to the north and east of the Industrial Area. Through calibration, the Qrf and Qc material in the Antelope Springs area were adjusted to better simulate surface flow represented by the GS16 flow gage. Finally, a "pavement" soil type was defined over impervious areas, including building areas.

The broad hydraulic property zonations were specified in the model primarily to address regional differences in unsaturated zone properties that might affect surface infiltration and groundwater recharge. The limited unsaturated zone data, described in Appendix B, prevented definition of a higher number of material types in the model. As such, the hydraulic properties represent effective values over the extent of each model cell. Over the vertical extent of the unsaturated zone, hydraulic properties were assumed to be homogenous, except in impervious areas. In these areas, a very low hydraulic conductivity is assigned to the top 0.4 m (1.3 ft), and Qrf material properties were assigned to the remaining soil column to allow for more realistic unsaturated/saturated zone interaction.

Nine "soil" types were defined in the model for use in the unsaturated zone calculations (UZ module). Although unsaturated flow parameters vary within each of the nine soil types, it was not possible to consider this variation in the model. Furthermore, available field data did not justify adding more soil types. Effective unsaturated zone parameter values for six of the nine soil zones are summarized in Table 5-3. Parameter values for the pavement and bedrock outcrop areas were defined to simulate fast runoff and evaporation at the surface. During calibration, sub-areas exhibited different response within areas assumed to have the same soil properties. Additional soils were introduced to account for response differences between the eastern and the western part of the model area (Qc East and Qc West), and in the GS16 sub-basin near Antelope Springs (Qrf#58 GS16 and Qc West GS16).

Soil moisture retention characteristics were specified for each soil in MIKE SHE. These data are defined by the water content (θ) as a function of capillary pressure, $\Psi(\theta)$. Other unsaturated data specified for each soil in the code included: (1) water content at field capacity (θ_{fc}); (2) wilting point (θ_w); (3) saturation (θ_s); (4) saturated hydraulic conductivity (K_s); and (5) n is an exponent controlling the shape of the $K(\theta)$ curve.

The saturated moisture content and field capacity (θ_s and θ_{fc}) for each soil type were adjusted so that their difference approximately equals the specific yield of the upper

UHSU. This was done to avoid inconsistencies between the unsaturated and saturated zone.

Table 5-3. Unsaturated Zone Hydraulic Properties

Soil profile ID	Description	θ_s (-)	θ_{fc} (-)	θ_w (-)	K_s (m/s)	n (-)
Qrf#58	Rocky Flats Alluvium	0.37	0.18	0.16	$1x10^{-4}$	15
Qc East	Colluvium (east section)	0.40	0.33	0.17	$7x10^{-5}$	20
Qal#3	Valley-Fill Alluvium	0.40	0.35	0.17	$5x10^{-5}$	20
Qc West	Colluvium (west section)	0.37	0.18	0.16	$1x10^{-5}$	15
Qrf #58 GS16	Rocky Flats Alluvium, GS16	0.37	0.18	0.16	$2x10^{-4}$	15
Qc West GS16	Colluvium (west section), GS16	0.37	0.18	0.16	$5 x10^{-6}$	1

Note: (-) indicates a dimensionless parameter.

During calibration, K_s and θ_{fc} were adjusted to provide a balance between overland flow contributions caused by insufficient infiltration capacity, soil moisture profiles, ET losses and groundwater recharge. Groundwater table observations indicate that the majority of annual recharge occurred in April; this was used to derive the unsaturated zone parameters.

5.2.4.4 ET Parameters

The ET module of MIKE SHE is an integral part of the unsaturated zone component. ET losses include: (1) interception by the vegetation; (2) evaporation from free water surfaces; (3) soil evaporation; and (4) plant transpiration. The actual evapotranspiration (AET) rate is simulated as a fraction of the specified time-varying potential ET rates. In MIKE SHE, AET represents a "sink" term in either the unsaturated or saturated zone. Unsaturated or saturated zone discharge as AET can vary as a function of depth on specified root zone distributions and depths. Soil evaporation only occurred from the upper numerical grid cell in the unsaturated zone model. PET rates specified in the model are described in Appendix B; other ET parameters are discussed in the following section.

5.2.4.4.1 Potential Evapotranspiration

PET data for the calibration year were estimated every two hours using the data described in Section 3.2.3 and calculated by the methodology outlined in Appendix D. Although time-varying, PET is simulated as spatially constant in the model. It varies as a function of topographic slope and aspect; however the PET is calculated for a horizontal surface, which on average is reasonable over the model area.

5.2.4.4.2 Vegetation

Although 17 detailed vegetation categories were identified in Appendix B, only five vegetation zones were included in the model based on discussions with Site ecology personnel. These included: (1) Wetland; (2) Mesic; (3) Xeric; (4) Riparian Woodland; and (5) non-vegetated zones (pavement and buildings). The hydrologically-important Woody Riparian vegetation occurs in stream areas typically less than 25 feet (7.6 m) across. To represent the effects of this vegetation type more accurately in the SWWB model (where its percent coverage within a 200- by 200-ft [~61 x 61 m] grid cell is less than 50 percent), the five zones were converted to the following nine zones:

- Wetland;
- Mesic;
- Xeric;
- Riparian Woodland;
- 15 percent Riparian Woodland/85 percent Mesic;
- 15 percent Riparian Woodland/85 percent Xeric;
- 37.5 percent Riparian Woodland/62.5 percent Mesic;
- 37.5 percent Riparian Woodland/62.5 percent Xeric; and
- Not vegetated (paved).

The spatial distribution of these nine zones is shown graphically in Appendix Figure D-15; and they are summarized in Table 5-4.

Table 5-4. Parameters for the MIKE SHE ET Component

Vegetation Type	Percent of model area	LAI	RDF (m)	K_c	C1	C2	C3	C_{int} (mm)
Xeric grass	34.5	0-1	1.0	0.25-0.8	0.2	0.05	10	0.05
Mesic grass	49.3	0-1.5	1.0	0.25-1.0	0.2	0.05	10	0.05
Woody riparian	0.4	0-5.0	2.0	0.25-1.5	0.3	0.05	20	0.05
Wetland	4.0	0-3	0.5	0.25-0.8	0.2	0.05	10	0.05
Paved areas	5.7	[1]1.0	0.0	0.1	0.0	0.0	20	0.01
*37percentWR/ 63percentMesic	1.2	0-4.5	2.0	0.25-1.0	0.3	0.05	20	0.05
*37percentWR/ 63percentXeric	0.1	0-3.5	2.0	0.25-1.0	0.3	0.05	20	0.05
*15percentWR/ 85percentMesic	4.2	0-4.0	2.0	0.25-1.0	0.3	0.05	20	0.05
*15percentWR/ 85percentXeric	0.6	0-1.3	1.0	0.25-0.8	0.3	0.05	20	0.05

*Mixed vegetation to describe near-stream ET losses,
[1]LAI is set to 1.0 so that evaporation can be simulated from pavement in MIKE SHE.

The ET component (Kristensen and Jensen, 1975) simulates the actual ET rates as a function of vegetation specific parameters, empirical constants and input potential ET rates. The vegetation is characterized by the time varying density (leaf area index, [LAI]), the root mass distribution with depth (RDF) and a crop coefficient (K_c).

The empirical parameters included: (1) interception storage coefficient (C_{int}); (2) a constant relating ET to LAI (C_1); (3) a coefficient for soil evaporation (C2); and (4) a coefficient relating soil moisture content to ET (C_3).

LAI, RDF and K_c (Table 5-4) depend on season and they are specified for a number of stages. To model the annual variation in ET, low LAI and K_c values are used in the winter season (October-April) with a transition in the spring to maximum values during

June-September. Transpiration varies with LAI, and in the winter season water it is lost only by soil water evaporation.

To simulate the ET rate for the long-term water balance and the seasonal changes observed at the Site, the LAI, RDF and K_c values were specified for each vegetation type (based on vegetation characteristics at the Site). Within the model area, K_c values were important as they were used to directly scale the reference vegetation (used in Penmann estimates of PET) to any vegetation type. Limited references to Kc exist in available literature on the natural vegetation found at RFETS, and thus K_c was estimated through calibration. K_c may influence the actual ET rate, but the total ET losses were often limited by water availability (the soil moisture of the root zone that may be transpired by plants).

The empirical parameters (K_c, C1, C2 and C3) were partially based on the method-specific values and on single-column model runs. The single-column models tested the range of parameters and empirical constants by looking at simulated infiltration rates, ET losses and recharge to the groundwater.

5.3 INTEGRATED MODEL DESIGN SUMMARY

This section describes the design of the integrated numerical MIKE SHE model. Key elements of the model include: 1) the spatial and temporal discretization; and 2) model structure and parameterization for the surface and subsurface flow domains.

A key factor in the model design is the horizontal discretization of the overland and subsurface model components. A 200- by 200-ft (~61 x 61 m) regularly-spaced model grid was selected as the most suitable compromise between numerical efficiency and the solution accuracy required to meet the project objectives. The grid cell resolution also defined the input parameter; values such as drain leakance were average to determine effective values for each grid cell. The surface water network, however, had a finer resolution (as low as 15 m (49 ft) spacing in some areas).

Precipitation, temperature and PET represent the predominant system input stresses. Initial simulations showed that the spatial distribution of precipitation over the model domain was necessary input to capture the complete hydrologic system response. Further, simulations showed that precipitation data at a fine temporal resolution were needed to capture event-level response. The PET data were prescribed every two hours to determine appropriate model parameters during calibration, and to capture sub-daily flow dynamics. Temperature data were included to simulate snowmelt effects and to estimate the two-hour PET input values.

The model surface flow network was defined by the following: (1) the channel network; (2) the Site topography; and (3) anthropogenic structures, like ponds, buildings and pavement. The solution of the surface flow system assumed one-dimensional flow. A detailed network of channels was included to more accurately represent the system dynamics. Channels were defined in plan and section views by a large data set of cross-sections.

The subsurface system describes the saturated and unsaturated flow within the UHSU units (the unconsolidated material and the Weathered Bedrock). A three-dimensional groundwater flow model with four model layers was built to describe flow in the saturated zone. Effects of subsurface utility trenches and drains on the saturated zone flow were incorporated into of the saturated zone model layer description and spatial hydraulic conductivity distribution.

The unsaturated zone flow was the most complex process simulated in this integrated flow model because it strongly influenced groundwater and surface water flow. Description of the unsaturated zone hydraulic properties was restricted by the limited available data. As a result, broader classifications of soil types were defined, but are considered reasonable for the regional scale of the model. Unsaturated zone flow was simulated in every model cell using the full Richard's equation. The vertical discretization of the unsaturated zone was specified much finer than the saturated zone to capture the more non-linear infiltration, ET, drainage and recharge dynamics.

6.0 INTEGRATED NUMERICAL MODEL PERFORMANCE

The performance of the integrated MIKE SHE model is described in this Section, and a more detailed discussion is provided in Appendix E. Model performance is demonstrated in three steps including, calibration, sensitivity analysis and validation. The calibration process involved adjusting model key input parameters to reproduce observed system response. A sensitivity analysis was conducted to identify which model input have the most impact on simulated responses in the focus areas (Figure 1-2 and Figure 1-3) and to demonstrate reasonable model performance. Finally, model performance was further validated using climate and boundary conditions for pre- and post-calibration time periods.

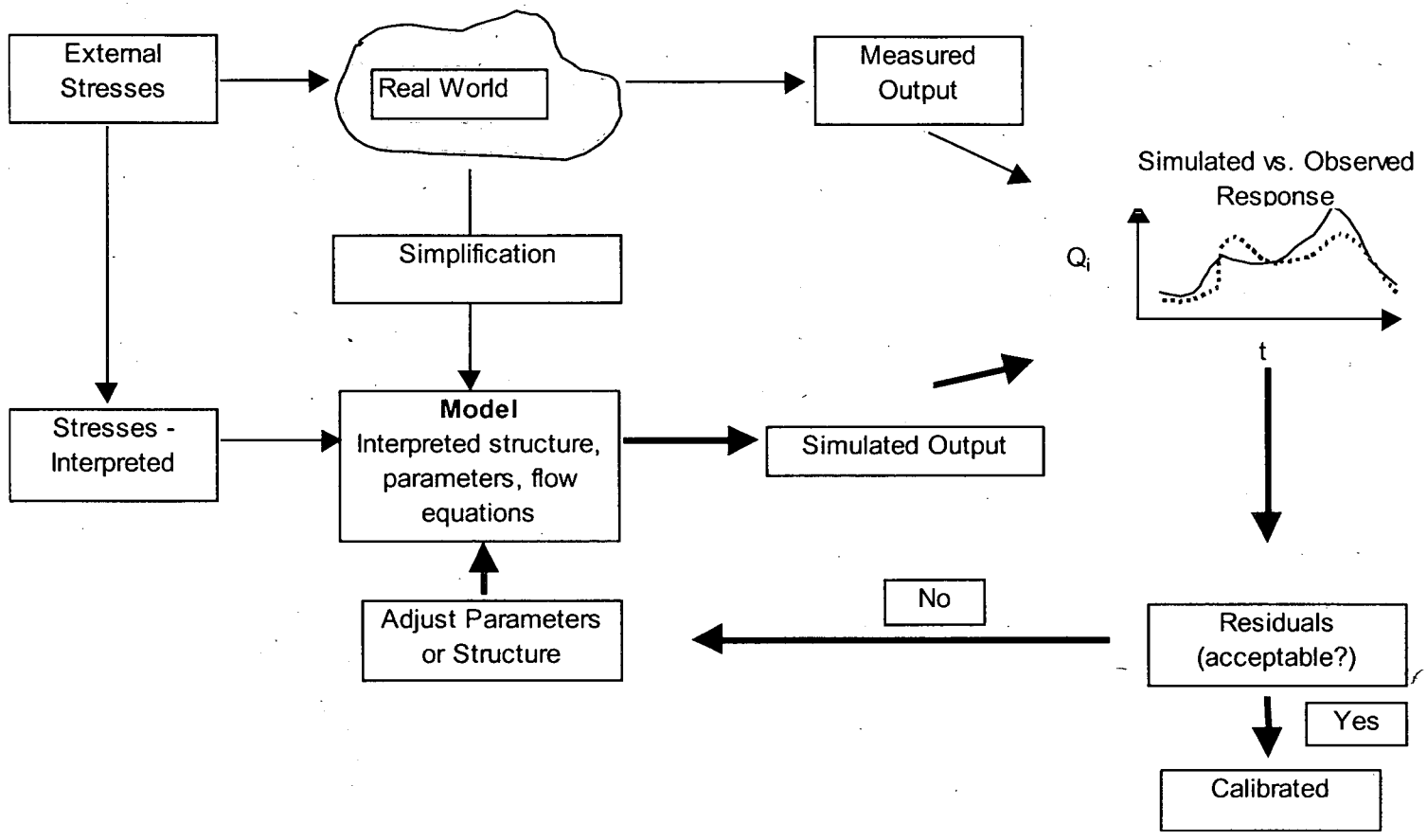
6.1 MODEL CALIBRATION

A general procedure for calibrating a hydrologic model is depicted on Figure 6-1. Key steps are shown in yellow. The process starts by developing the basic model structure and specifying input parameters, both of which must be approximated using available Site data. The model is then run using spatial and temporal interpretations of the actual external stresses. The model simulates various types of system output that are then compared to observed system response data. Model input is then adjusted iteratively, to reduce the difference, or residual, between simulated and observed response. This process is followed until the simulated and observed responses are reasonably close.

Section 6.1.1 describes the approach used to calibrate the fully-integrated model to reproduce observed system response. The success of the calibration process depends on the quality and quantity of available data to define parameter ranges and the observation data. System response data are typically referred to as *calibration targets*, and input parameters adjusted during the calibration process are referred to as *calibration parameters* (ASTM, 1993).

Calibration targets typically only consist of measured system response data. However, in an integrated model, other less quantitative response data can also be used in the calibration process.

Figure 6-1. General Calibration Procedure



For example, observed seeps areas, or general losing or gaining reaches along streams represent semi-quantitative system data. Both quantitative and semi-quantitative calibration targets were presented in the Work Plan (Kaiser-Hill, 2000c). Quantitative targets included streamflow hydrographs and quarterly and continuously monitored groundwater well water levels. Semi-quantitative targets included responses like seep flow, groundwater collection and remediation system discharge, or gaining/losing stream reaches.

Calibration parameters adjusted in the integrated model to better simulate system response are presented in tables in Appendix E. The calibration parameters listed are a subset of the full set of model input parameters. Other types of model input typically not adjusted during model calibration include data like geologic surfaces, topography or channel profiles. These are not typically adjusted because they are generally known more reliably over the model area.

6.1.1 Calibration Approach

As presented above in Section 4.0, the calibration approach developed for the RFETS SWWB model considered several factors that include:

- SWWB project objectives;
- Focus areas;
- Grid resolution; and
- Quality and quantity of calibration parameter and target data.

Objectives outlined originally for the SWWB integrated modeling (Kaiser-Hill, 2000c) were the most important factor in determining how well the model was calibrated. The simulated response was expected to be more accurate in focus areas identified in Section 1.6, where more important management decisions may be made, and where effects of hypothetical land configuration changes may be observed.

The calibration approach emphasized simulating regional flow response, rather than local response. For example, no attempt was made to simulate the flow in individual pipes or utility trenches. Instead, hydrologic conditions associated with more regional Site features were considered more important in the SWWB. Achieving better model calibration within specific focus areas (identified in Section 1.6) was also considered important. Focus areas are areas where critical management decisions will be made and better model predictions are required.

Accurate simulation of hydrologic response in areas where calibration targets or field data to quantify model parameter values were sparse was not possible. The general simulated hydrologic response in these areas was assessed to confirm that it was consistent with the conceptual flow model.

The amount of available, spatially distributed streamflow data alone is substantial. These data are available every 15 minutes over the model area for several years of record. Because of the rapid streamflow response to precipitation in the Industrial Area, every event effectively constituted a different set of calibration data in traditional streamflow models. Instead of trying to calibrate each event for each gage over the model, calibration efforts were prioritized.

Two figures (Figure 6-2 and Figure 6-3) illustrate how the model calibration process was prioritized. Observed surface flows at the eastern model boundary along Walnut and Woman Creeks (gages GS03 and GS01, respectively) represent critical system response data because system discharge (except ET) occurs predominantly as surface flow at these locations. Streamflow hydrographs for these gages are complex because they are influenced by the combined effect of all upstream inflows, or losses, including groundwater interactions. Therefore, correctly simulating streamflow hydrographs at these locations implies that upstream system flows are simulated reasonably well. Simulating flow response at GS01 and GS03 represented the highest priority for calibrating system flows.

Figure 6-2. Spatial Calibration Priority

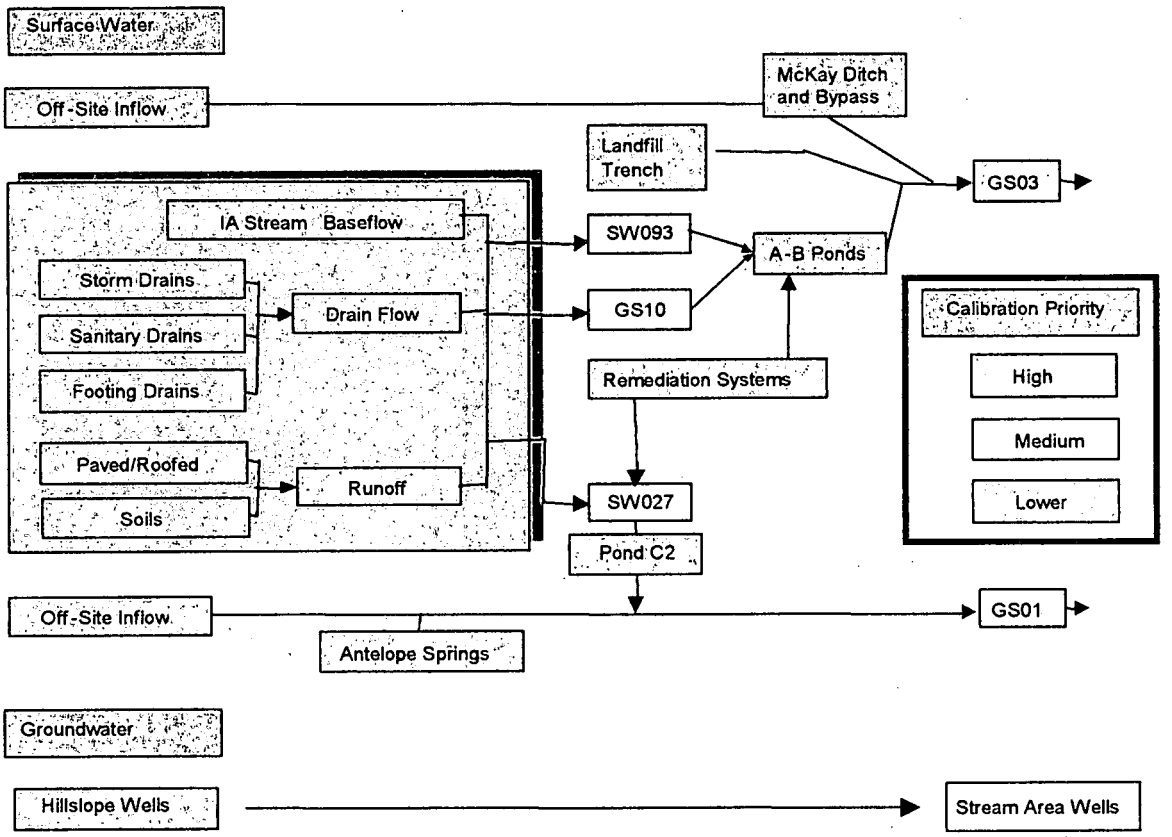
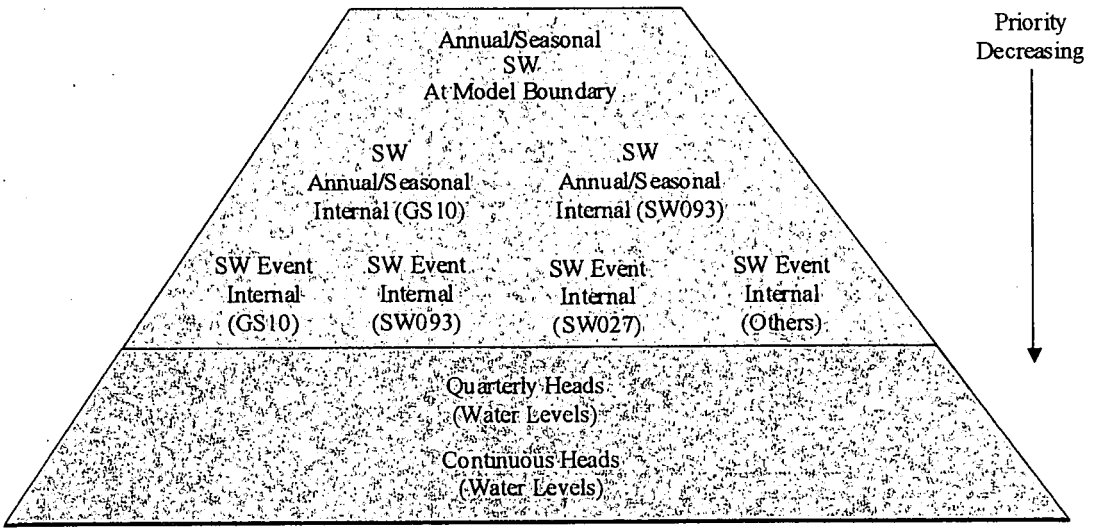


Figure 6-3. Temporal Prioritization of the Calibration Process



Other important Site flow data include response from the Industrial Area at gages SW093, GS10 and SW027. The annual streamflow hydrographs for these gages indicate they also exhibit a complex response due to the combination of upstream inflows including direct groundwater interaction, drain flows (storm, sanitary and footing drains), and rapid runoff from paved and building areas. These gages are also important because they are designated as Points of Evaluation (POE) for water quality monitoring purposes. The calibration of all other surface flow response is assumed to be the next priority. Simulating surface water responses for each runoff event for these gages and other internal model gages was considered at the next level of importance. Simulation of short-term events at the model boundary, given the complexity of their response was not considered as important as simulation of the seasonal response.

Simulating groundwater flow response was important but it has a much longer hydraulic memory and discharges far less water at the model boundary than surface flows. As a result, groundwater calibration was given a lower calibration priority than surface flows in the SWWB model. Of the available groundwater calibration targets, simulating quarterly groundwater data was given a higher priority than simulating the continuous groundwater level data. Results of multiple single-column MIKE SHE models coupling ET, saturated and unsaturated zone flows (Appendix D) showed that it was difficult to accurately reproduce groundwater response in all continuously-monitored wells screened in the same material, using the same set of unsaturated zone properties. As a result, the calibration approach required simulating seasonal (quarterly) groundwater levels in focus areas and near-stream areas. Near-stream areas are important because of their sensitivity to groundwater levels.

Specific groundwater level calibration target values were not selected for two reasons. First, "effective" model parameters are used in each 200-ft by 200-ft (~61 m x 61 m) grid to represent saturated zone flows. Within a grid cell, groundwater levels and their variation in time may depend more on local heterogeneities than the "effective" parameters used in the model. Second, water levels from multiple wells occurring within a single model cell often showed differences of greater than 20 feet (6.1 m). This was particularly evident on hillslopes, where surface topography changes much more than 20

ft (6.1 m) over a 200 ft (61 m) distance. As a result, calibration efforts were focused on simulating reasonable seasonal groundwater levels in focus areas and near-stream areas as indicated above.

A full year was used to calibrate the fully-integrated model. The calibration year coincides with WY2000, or October 1, 1999 to October 1, 2000. This year was selected for calibration because the available dataset was the most comprehensive. The total precipitation for this year is slightly below the average annual precipitation for the Site (see Appendix D for more information). Effects of initial conditions were stabilized by "hotstarting" the climate for several years as described in Section 5.2.1. Repeatedly applying the WY2000 climate data provided additional assurance that the high-resolution, well-correlated, precipitation, temperature and PET input data were used to drive the system response, rather than using data of lower quality or quantity from previous years.

6.1.2 Comparison of Simulated and Observed Response

Model calibration success was measured by comparison of simulation results and observed data. For WY2000, observed quantitative data were available as:

- Surface water flow rates (15-minute record at all gages shown in Appendix B);
- Quarterly groundwater levels (quarterly records for wells identified in Appendix B); and
- Groundwater levels recorded at 4-hour intervals (for wells identified in Appendix B).

The following sections present the calibration results with discussion of model performance and applicability.

6.1.2.1 Surface Water

This section presents comparisons of the simulated and observed surface water response for the calibration year, WY2000. Results are presented in both cumulative (seasonal and annual flow volumes) and high resolution (flow rates and pond levels at 15-minute intervals) formats for a thorough analysis.

6.1.2.1.1 Volume Matches

Cumulative surface flow volume is a broad measure of system response, incorporating the combined effects of all influences on surface water flow. In the model, these influences include: (1) surface inflows; (2) precipitation; (3) ET; and (4) groundwater-channel interactions.

Observed and simulated channel flow volumes were compared for all major Site drainages. Both seasonal and annual volume comparisons are presented graphically in Figure 6-4.

In the Industrial Area, the main subdrainages of GS10, GS22, SW027 and SW093 were simulated well. Differences in the annual total values ranged from 2 percent for SW093 to 26 percent for SW027 (SW027 is discussed in greater detail in the following sections). In general, simulated seasonal volumes also follow observed trends (Figure 6-4). The Buffer Zone simulations varied more from the observations. Woman Creek (at GS01) exhibited a difference of roughly 30 percent, while Walnut Creek (at GS03) produced a 40 percent difference. It should be noted that the hydrograph shapes are well simulated for both these gages (see discussion in following sections). Further, annual flow volume residuals were even less at these gages in the WY2001 simulation prepared for validation as compared to WY2000 (this is further discussed in Section 6.3 and Appendix E). Discussion of potential error sources is presented in Appendix E.

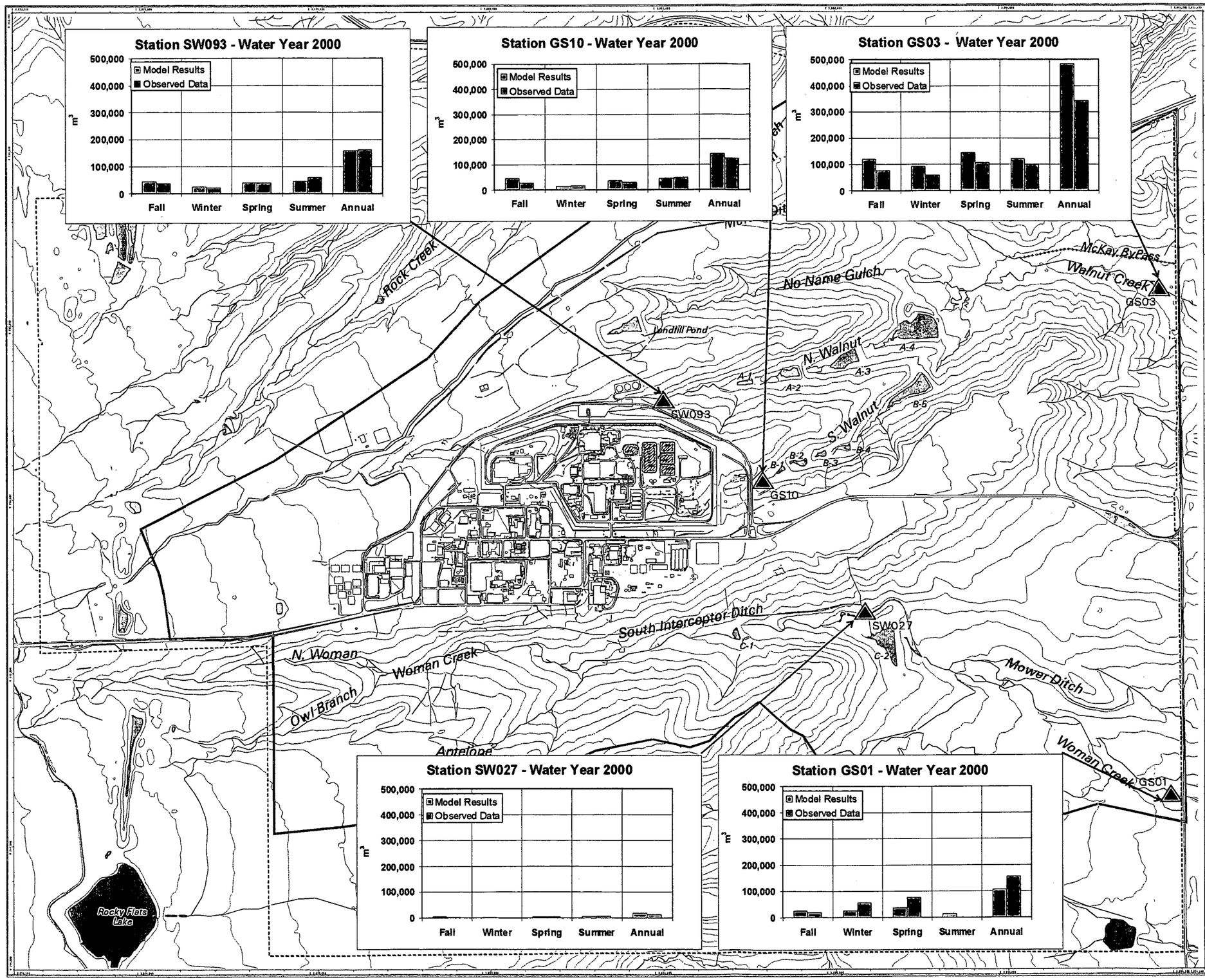


Figure 6-4

Site-Wide Water Balance Report

Observed and Simulated Surface Flow Volumes for WY2000

EXPLANATION

- Gaging Station

Standard Map Features

- Buildings and other structures
- Paved roads fill
- Solar Evaporation Ponds (SEPs)
- Lakes and ponds
- Streams, ditches, or other drainage features
- Topographic Contour (20-Foot)
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95 Topographic contours were derived from digital elevation model (DEM) data by Morrison Knudson (MK) using ESRI Arc TIN and LATTICE to process the DEM data to create 5-foot contours. The DEM data was captured by the Remote Sensing Lab, Las Vegas, NV, 1994 Aerial Flyover at ~ 10 meter resolution. DEM post-processing performed by MK, Winter 1997.

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

U.S. Department of Energy
Rocky Flats Environmental Technology Site

GIS Dept. 303-966-7707

Prepared by: DynCorp — THE ART OF TECHNOLOGY

Prepared for: KAISER-HILL COMPANY

May 18, 2000

NT_Svr w:/projects/swwb/fy2002/section_6/surface_flow.aml

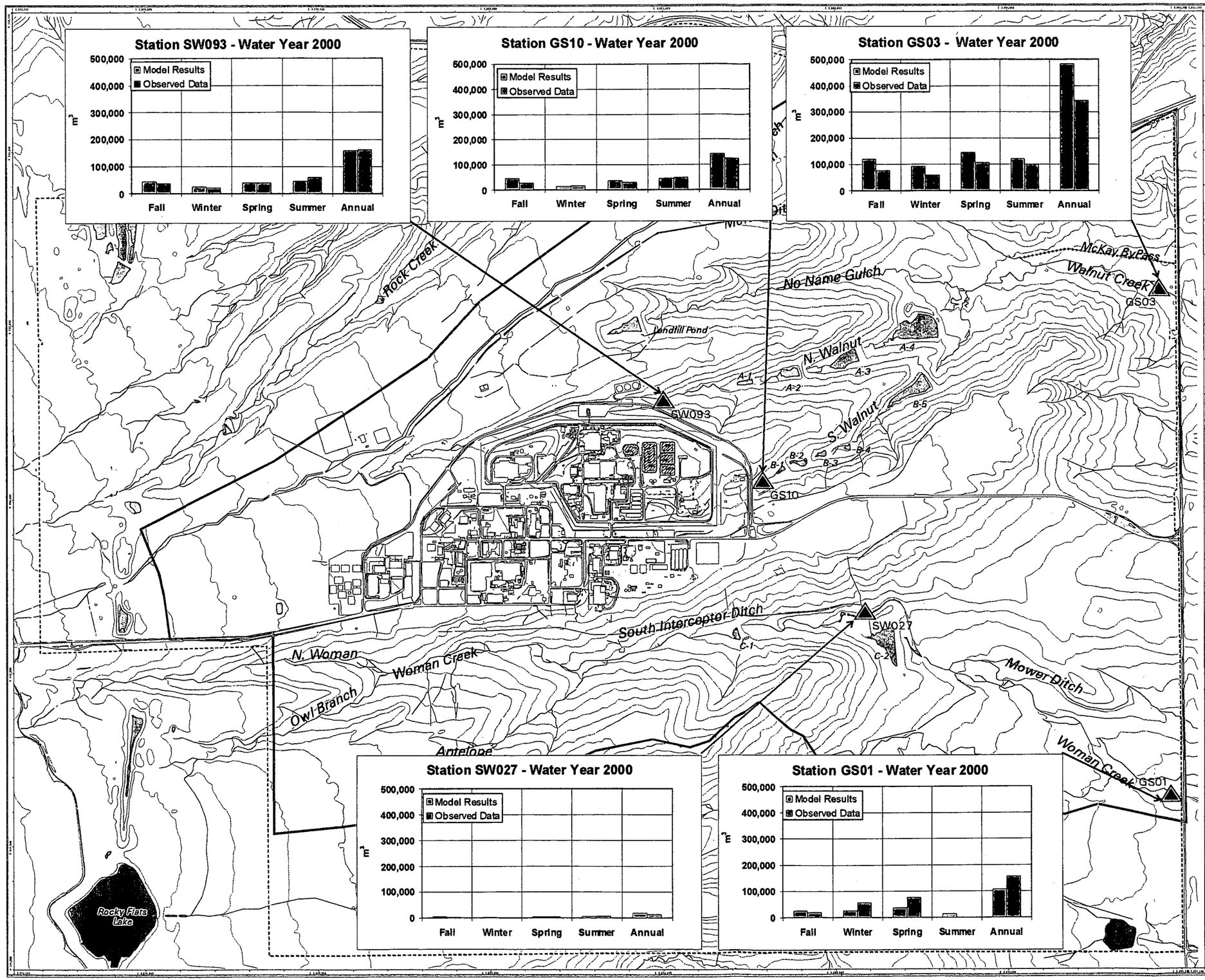


Figure 6-4

Site-Wide Water Balance Report

Observed and Simulated Surface Flow Volumes for WY2000

EXPLANATION

- Gaging Station

Standard Map Features

- Buildings and other structures
- Paved roads fill
- Solar Evaporation Ponds (SEPs)
- Lakes and ponds
- Streams, ditches, or other drainage features
- Topographic Contour (20-Foot)
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

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State Plane Coordinate Projection
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May 18, 2000

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6.1.2.1.2 Flow Rate Matches

The available frequency of observed surface flow rate data (15-minute flow record) allowed for a more detailed assessment of system response than cumulative volume comparisons. Comparisons of observed and simulated flow rates (at 15-minute frequency) for the Industrial Area and the Buffer Zone are discussed in the following sections.

6.1.2.1.2.1 Industrial Area

Comparison of high-resolution flow rate response proved important to model calibration within the Industrial Area, where the model structure is complex and response to precipitation is rapid. The observed and simulated annual hydrographs for these gages are presented on Figure 6-5. The annual hydrographs on Figure 6-5 do not have adequate visual resolution to evaluate the simulation of individual events; however, they are presented to demonstrate the varying dynamics of flow response across the Site and the general model performance in simulating this overall response.

System responses at gages SW093, GS10, GS22 and SW027 were assessed in greater detail for flow conditions ranging from low-flow (no precipitation), to snowmelt events, to a range of rainfall runoff events. Evaluation of model performance for this range of events is presented in the following sections.

6.1.2.1.2.1.1 Gages SW093, GS10 and GS22

As discussed in Appendix B, the subdrainages of SW093, GS10 and GS22 are primarily industrial, and all exhibit baseflow and rapid responses to precipitation. SW093 and GS10 hydrographs are similar in both range and magnitude. Flows measured at both these gages discharge to the Walnut Creek drainage. GS22 is a smaller sub-catchment, flowing to SW027 via the SID.

The total flow from these three gages (SW093, GS10 and GS22) constitutes the majority of surface water exiting the Industrial Area.

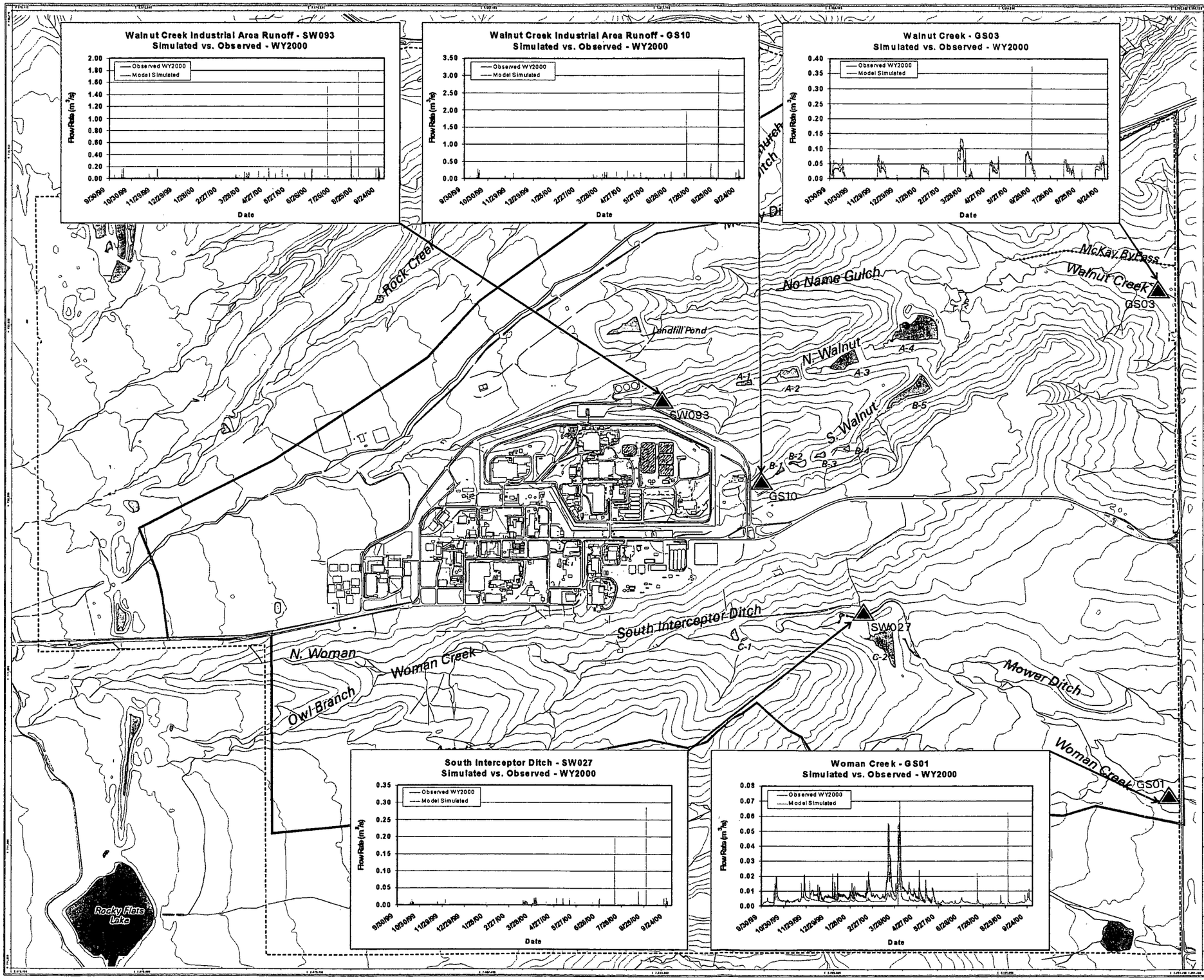

Figure 6-5

Site-Wide Water Balance Report

Observed and Simulated Stream Flow Response for WY2000

EXPLANATION

- Gaging Station

Standard Map Features

- Buildings and other structures
- Paved roads fill
- Solar Evaporation Ponds (SEPs)
- Lakes and ponds
- Streams, ditches, or other drainage features
- Topographic Contour (20-Foot)
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95
Topographic contours were derived from digital elevation model (DEM) data by Morrison Knudson (MK) using ESRI Arc TIN and LATTICE to process the DEM data to create 5-foot contours. The DEM data was captured by the Remote Sensing Lab, Las Vegas, NV, 1994 Aerial Flyover at ~ 10 meter resolution. DEM post-processing performed by MK, Winter 1997.

NOTES:

More detail of observed and simulated stream flow is shown in Figures 6-6, 6-7, 6-9, 6-10, 6-11, E-11, E-12, E-13 and E-14.

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

U.S. Department of Energy
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GIS Dept. 303-966-7707

Prepared by: DynCorp — THE ART OF TECHNOLOGY

Prepared for: KAISER-HILL

May 18, 2000

NT_Svr w:/projects/swwb/fy2002/section_6/hydro_response.aml

In accordance with the conceptual model, sources for this flow include: (1) overland runoff; (2) groundwater returning into the channels; and (3) footing and treatment system drain discharge. Simulation hydrographs were assessed for low flow conditions, rainfall events and snowmelt events.

Figure 6-6 through Figure 6-9 provide examples of calibration matches for these subdrainages under various flow conditions. Additional images, provided in Appendix E, complete the series of response evaluations at each gage along with a discussion of potential sources of error.

In summary, the model performed very well at simulating baseflow and a variety of precipitation events for these three main gages if the Industrial Area. Good simulation at this level of detail offers confidence in both the conceptual and numerical models.

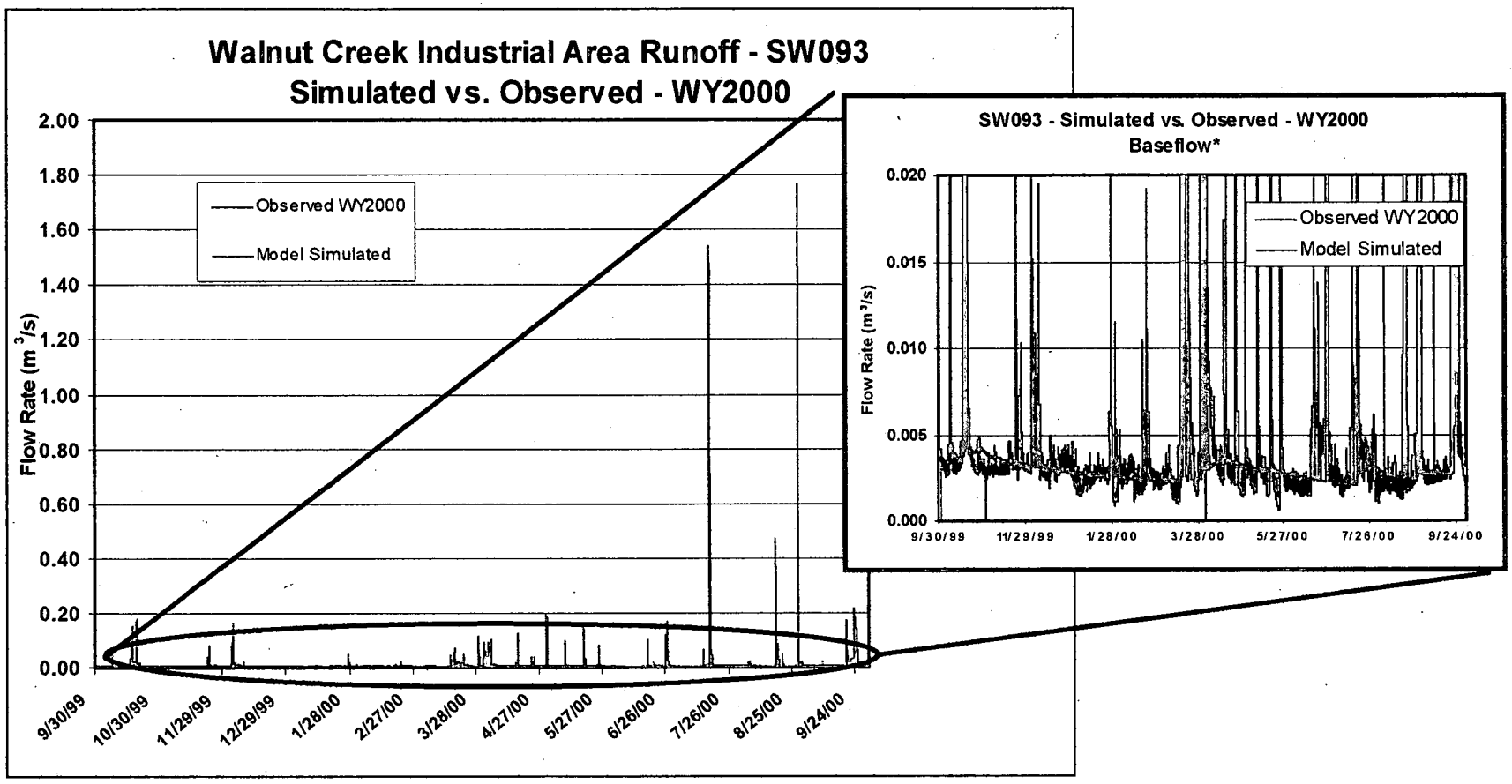
6.1.2.1.2.1.2 Gage SW027

The SW027 drainage corresponds to the drainage for the man-made SID. With the exception of the GS22 subdrainage, the SW027 drainage basin is largely non-industrial. The SID is located on the steep hillside between the Industrial Area and Woman Creek.

For WY2000, no sustained periods of baseflow were recorded in the observed record. As shown on Figure 6-10; however, the model predicts a very low constant baseflow of 0.0002 m^3/s (0.007 cfs).

With the SID located on a steep slope, the correspondingly large groundwater gradients adjacent to the channel are poorly represented by averaging of the water table elevations in a 200 ft x 200 ft (~61m x 61m) cells. As a result, simulated groundwater heads for cells on the uphill side of the SID (single average groundwater head value applied to each cell) were higher than actual heads adjacent to the SID. Consequently, the model predicted larger amounts of groundwater entering the SID than observed. A decreased grid size would allow for greater refinement of the groundwater estimate adjacent to the SID. This was effectively compensated for by assigning higher hydraulic conductivities to the upper model layers between the SID and Woman Creek.

*Figure 6-6. Comparison of Simulated and Observed Flow at SW093 – Baseflow Focus**



* Baseflow occurs in range of 0.001 to ~0.01 m3/s.

Figure 6-7. Simulated and Observed Large Precipitation Event at GS10

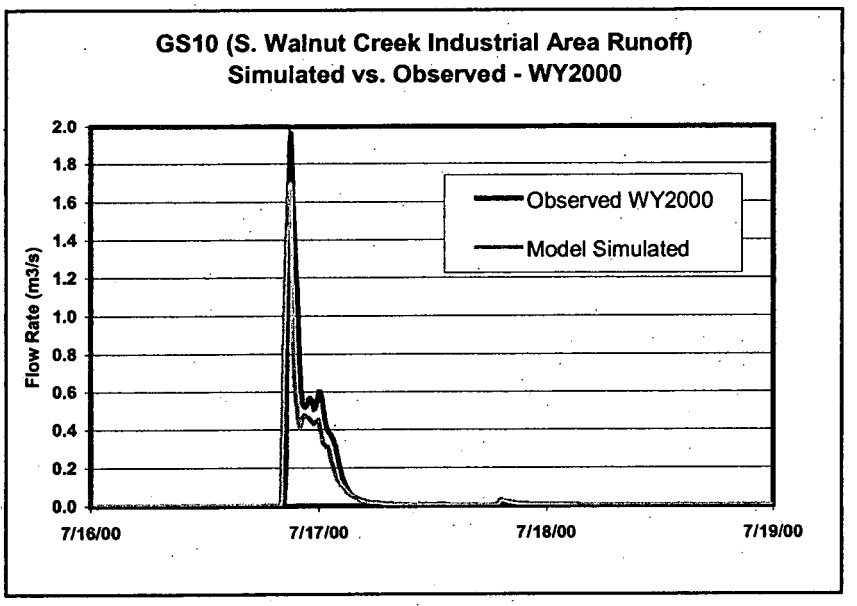


Figure 6-8. Simulated and Observed Moderate Precipitation Events at GS22

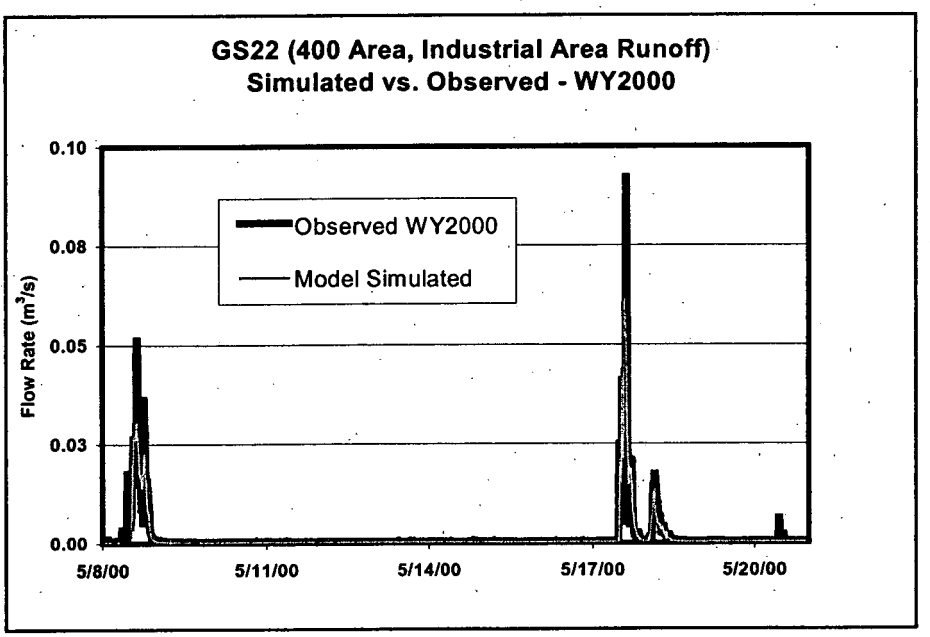
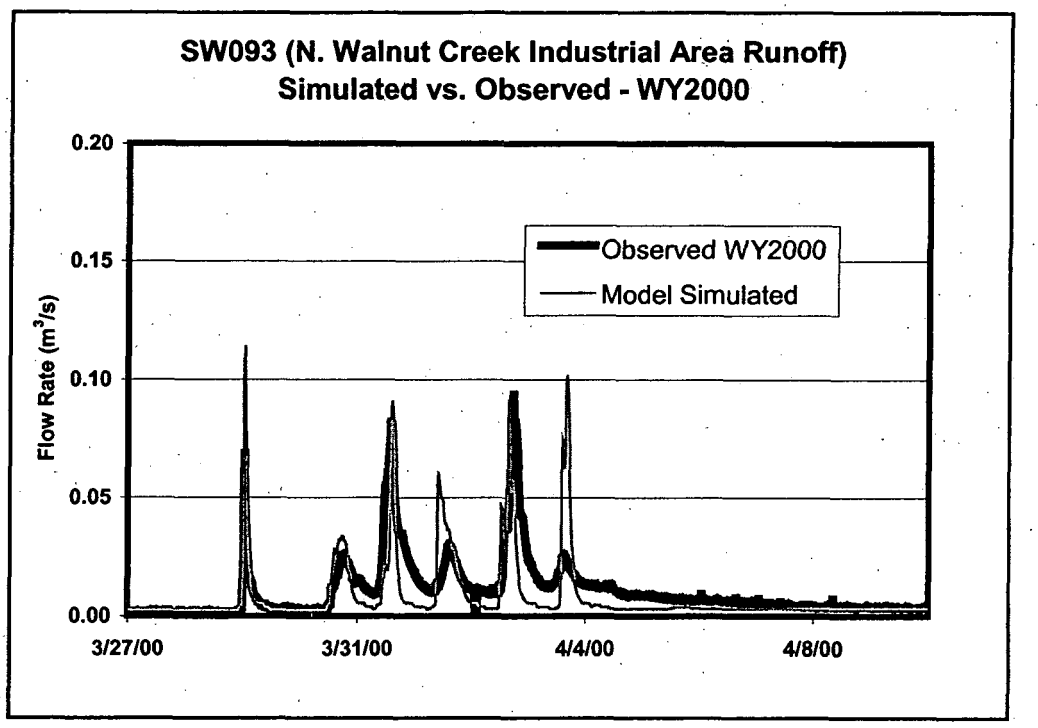


Figure 6-9. Simulated and Observed Snowmelt Event at SW093



Events were simulated well for SW027; however, the model consistently underestimated the observed lag in peak response time (between 2 and 6 hours). An example of this timing error is presented in Figure 6-11.

Modification of channel and overland roughness values could not account for this effect on timing. (Extreme values of roughness were applied, and the observed lag could still not be reproduced.) It was hypothesized that the observed lag can be attributed to small-scale depressions along the channel which create storage. These sections have been observed in the field and often correspond to cattail growth areas. These depressions in the channel were not captured in the detail of the cross-sections incorporated into the model. Attempts to include these depressions in the channel profile created significant stability problems in the model along the steep channel.

Figure 6-10. Comparison of Simulated and Observed Flow at SW027 – Baseflow Focus

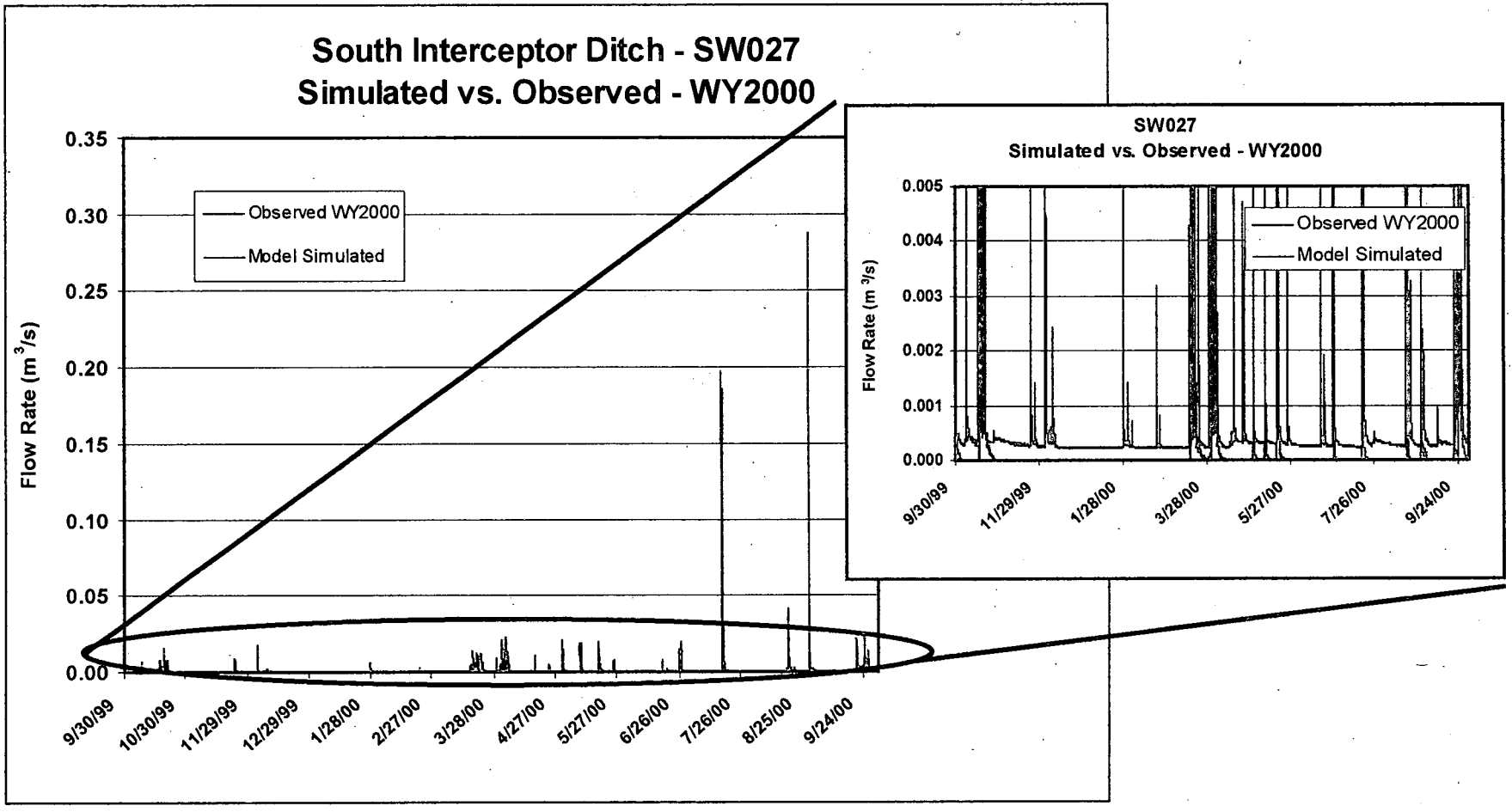
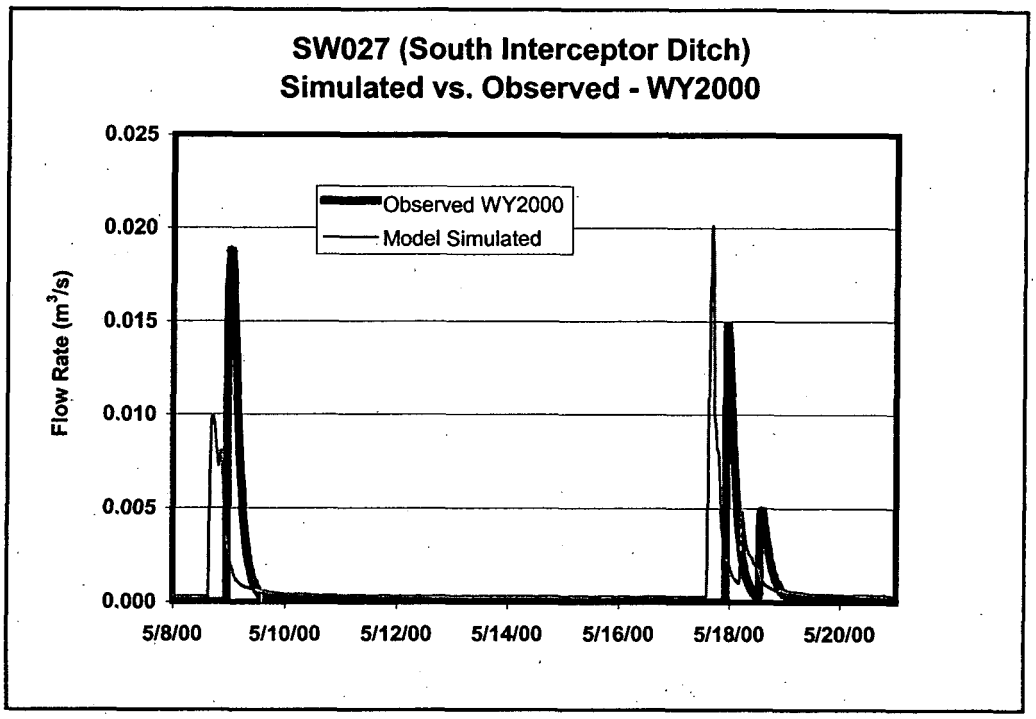


Figure 6-11. Observed and Simulated Moderate Precipitation Events at SW027



In summary, the simulation of the SW027 subdrainage adequately represented observed flow rates for the purposes of this project, based on the following:

- The predicted errors in the cumulative volumes are reasonable;
- Events are well simulated (disregarding the lag); and
- The total flow through this drainage is small relative to GS10 and SW093.

These resolution limitations should be carefully considered when applying the model to this subdrainage for a more detailed analysis. Any future modeling efforts applying this tool for a more detailed assessment of the SW027 subdrainage should consider a smaller grid size. For the purposes of this project, however, the area is adequately represented.

6.1.2.1.2.2Buffer Zone

Buffer Zone responses to system stresses are typically less rapid as compared to the Industrial Area responses. Comparison of high-resolution flow rate information still provided significant insight into the behavior of the model. Buffer Zone responses for both Woman and Walnut Creeks are discussed below.

6.1.2.1.2.2.1 Woman Creek

The Buffer Zone portion of Woman Creek drainage is discussed in this section. This includes the entire Woman Creek drainage within the model boundary, with the exception of the SW027 subdrainage. The SW027 subdrainage is discussed Appendix B as part of the Industrial Area response; this organization of information is reasonable because Pond C-2, connecting the SW027 subdrainage to Woman Creek, was not discharged during WY2000.

As discussed in Appendix B, surface flow response at GS01 is largely seasonal, due to vegetation controlling near-stream groundwater levels. This response can be observed in the annual hydrograph (Figure 6-5). No significant hydrograph response was observed for the period of June 1 through October 1, 2000. During the remaining portion of the year, surface flow at GS01 followed the observed trend, with much of the response attributable to inflow at GS05 and GS06 as well as runoff response from Antelope Springs (GS16). Observed flow at GS16 accounted for roughly 60 percent of the annual flow measured at GS01 for WY2000 (though much was lost to channel infiltration before it reached GS01). For comparison, simulated flow at GS05, GS06, and GS16 are shown below on Figure B-37 with simulated GS01 flow. (Note: GS05 and GS06 were system inflows, input as observed).

While the overall simulation at GS01 was good, one inconsistency between observed and simulated results is worth noting. Low flow rates (~0.003 m^3/s or 0.1 cfs) were simulated at GS01 from June through September, while no recorded flows occurred during this period. The combination of narrow channel profiles, with respect to the 200 ft x 200 ft (~61m x 61m) model cell dimensions, and the shallow hillslope-saturated zone

configuration caused the model to over-estimate near-stream groundwater levels in some areas. As a result, groundwater discharged into the stream during periods when observation data showed no channel flow. Although ET-vegetation parameters and saturated hydraulic conductivities were adjusted to reduce these flows, discharge was not entirely eliminated. Ultimately, the additional groundwater storage would be lost to ET. This difference does not challenge the confidence in the calibrated model for predicting regional-scale behavior for the following reasons:

- The model does simulate the system to be losing water from inflow sources during this period (as observed);
- The hydrograph response to precipitation is reduced during this period (as observed);
- The GS01 volume matches are reasonable; and
- The Woman Creek drainage (excluding the SW027 subdrainage) is expected to change minimally with Site Closure.

6.1.2.1.2.2.2 Walnut Creek

The Buffer Zone portion of the Walnut Creek drainage includes the entire Walnut Creek drainage within the study area except the GS10 and SW093 subdrainages. The GS10 and SW093 subdrainages were considered to be industrial and are discussed in Appendix B.

As discussed in Appendix B, the annual GS03 hydrograph for WY2000 was dominated by 10 pond discharges throughout the year (apparent on the GS03 hydrograph as eight distinct events). Also, the system lost water between the discharge points (terminal ponds) and the end of the study area (measured at GS03) for all discharges in WY2000.

The simulated and observed annual hydrographs for GS03 are presented in Figure 6-5. The simulated hydrograph represented the observed data well, with losses being simulated for each discharge event as observed. Low-flow periods also compare well. The grid resolution issue, discussed for Woman Creek, provided fewer challenges for

Walnut Creek. Though the effect was observed slightly, near-stream groundwater levels seemed to be less controlled by ET (perhaps due to the effects of frequent pond discharges).

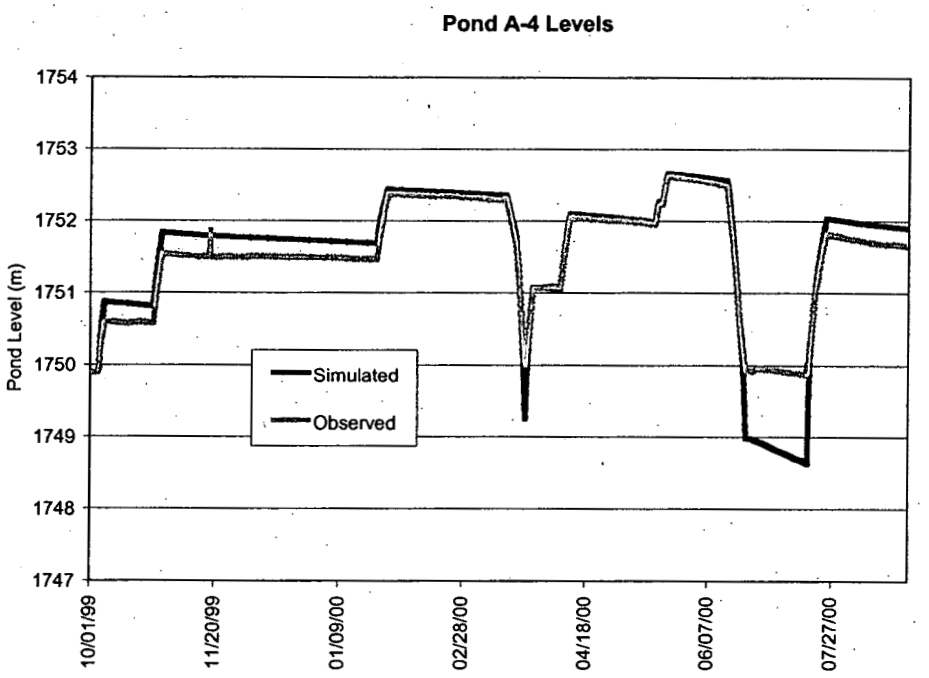
6.1.2.1.3 Ponds

Limited observed data sets from Site ponds are available for comparison to simulated results. Water level data were collected successfully for Ponds A-3, A-4, B-5 and C-2 during WY2000. (Level data collected from the Ponds A-1, A-2, B-1, B-2 and the Landfill Pond contained many missing data points and inconsistencies.) Where these pond data were available, observed and simulated levels compared well. As an example, the observed and simulated pond level records for Pond A-4 (WY2000) are shown below in Figure 6-12. Discharges from and transfers to Pond A-4 are apparent in the figure as sharp decreases and increases in the water level. Similar figures are presented for Ponds A-3, B-5 and C-2 in Appendix E.

Additionally, an algorithm was applied within the model to determine pond discharges for scenarios and climate variations (where no observed data were available; see Section 7.1.1.1 and Appendix F for discussion). This algorithm was designed to simulate current operational protocols. When the model was run with this algorithm for the calibration year, the model produced discharge patterns and volumes similar to the observed discharges. This provided additional evidence that the ponds are being well simulated in terms of groundwater interaction and structure.

All available data and local water balances suggest the calibrated model performs well in simulating the Site ponds; thus the conceptual model assumptions appear valid.

Figure 6-12. Comparison of Observed and Simulated Pond Levels for Pond A-4



6.1.2.2 Groundwater

The total groundwater discharge across the model boundaries is insignificant compared to surface water discharges. Thus, the primary role of the groundwater component of the fully-integrated model was to provide runoff to the stream network as baseflow and drain flow. Consequently, efforts focussed on modeling seasonal recharge and storage change dynamics to capture the seasonal changes in flow exchange between individual reaches of the stream network and the adjacent saturated zone. In the RFETS model, accurately simulating groundwater levels is important where the levels affect surface water flow.

6.1.2.2.1 Groundwater Levels

Simulated groundwater levels were compared against available data from quarterly-measured groundwater wells and averaged continuously-monitored (4-hour reading intervals) groundwater wells. In many instances, multiple wells occurred within a single

200-ft by 200-ft (~61 m x 61 m) model grid cell. Differences in well water levels in each of these cells prevented direct comparison to simulated levels, which are given at the grid cell center, rather than at each well location. The differences were most noticeable on steeper hillslopes, where ground and bedrock surface gradients are greatest (up to 25 feet or 7.6 m). As a result, average groundwater levels in each cell, for four quarters (January, 2000, April, 2000, July, 2000 and October, 2000), were estimated from available data. These observational data were then used to evaluate simulated groundwater levels.

Figures in Appendix E summarize the model performance against observed quarterly data for January, 2000, April, 2000, July, 2000 and October, 2000. Results generally indicate that simulated levels in near-stream and focus areas compared reasonably well against observed data. The largest deviations occurred in the northwestern model area and within hillslopes areas. The average difference between simulated and observed levels in the Industrial Area (defined by about 680 cells) varied from about 0.18 m (0.6 ft) in January, 2000 to 0.36 m (1.2 ft) in October, 2000. Average simulated levels for all quarters were slightly over-predicted, though locally, some areas were over-predicted and under-predicted. For example, levels in the GS22 drainage area in the southwestern Industrial Area, were over-predicted by more than 2 meters (about 7 ft), while levels were under-predicted along Central Avenue.

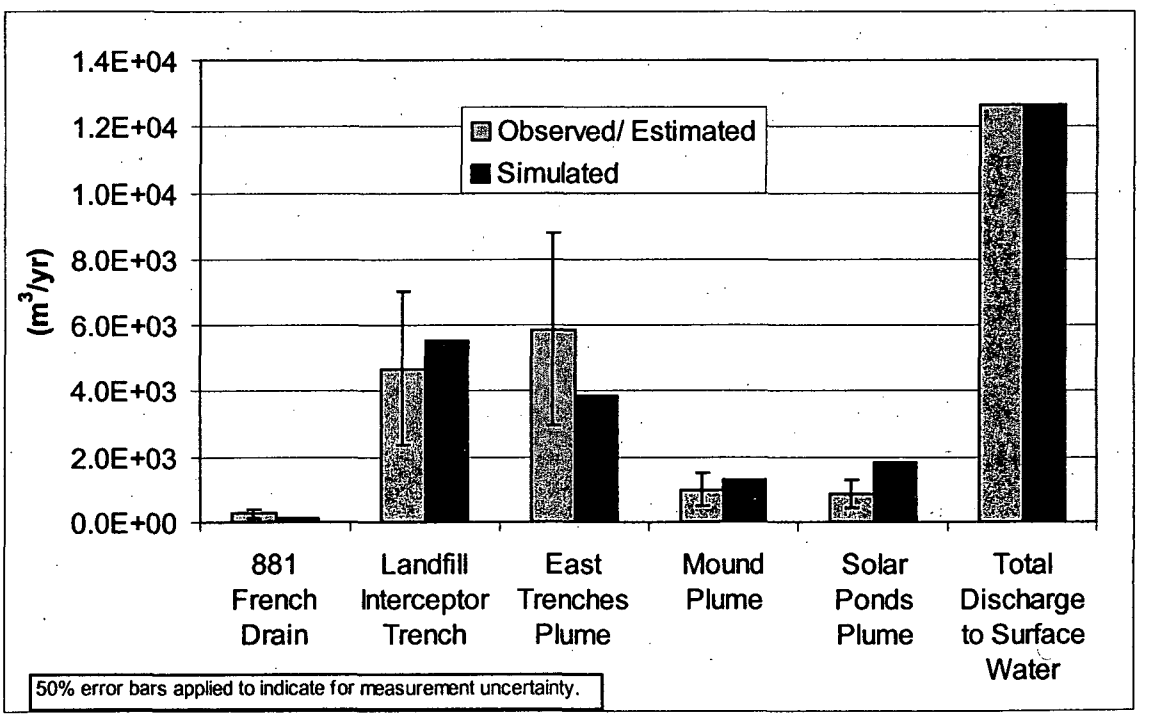
These results are considered reasonable for the purposes of the SWWB model. To better compare observed and simulated response, groundwater depths for each quarter were spatially interpolated onto MIKE SHE grid cells containing at least one well. Although this is a reasonable way to compare simulated and observed data over the effective grid cell dimension, some cells containing multiple wells (particularly in hillslope areas) did not represent the local water table conditions well. Observed water levels within a single quarter for some cells vary several meters. This input uncertainty contributed to differences in observed and simulated responses.

6.1.2.3 Treatment/Drain System Discharges

Simulation results were compared to measured values and estimates for groundwater treatment systems and drains. Groundwater treatment systems include: (1) 881-Hillside French Drain; (2) East Trenches Remediation System; (3) Mound Plume Remediation System; (4) Solar Ponds Plume Remediation System; and (5) the Present Landfill Interceptor Trench. Drain systems consist of storm, sanitary and footing drains. Model calibration was achieved by modifying drain leakance values to match observed data (where available).

For *in situ* groundwater treatment/collection systems, limited measured flow data were available for WY2000; these data are considered to have a 50 percent margin of error based on known measurement limitations. The simulated annual treatment/collection system discharge volumes to surface water were compared to the observed record (see Figure 6-13). Comparison data were not considered adequately detailed to allow for meaningful evaluation at higher resolution.

Figure 6-13. Calibration of Groundwater Treatment and Collection Systems

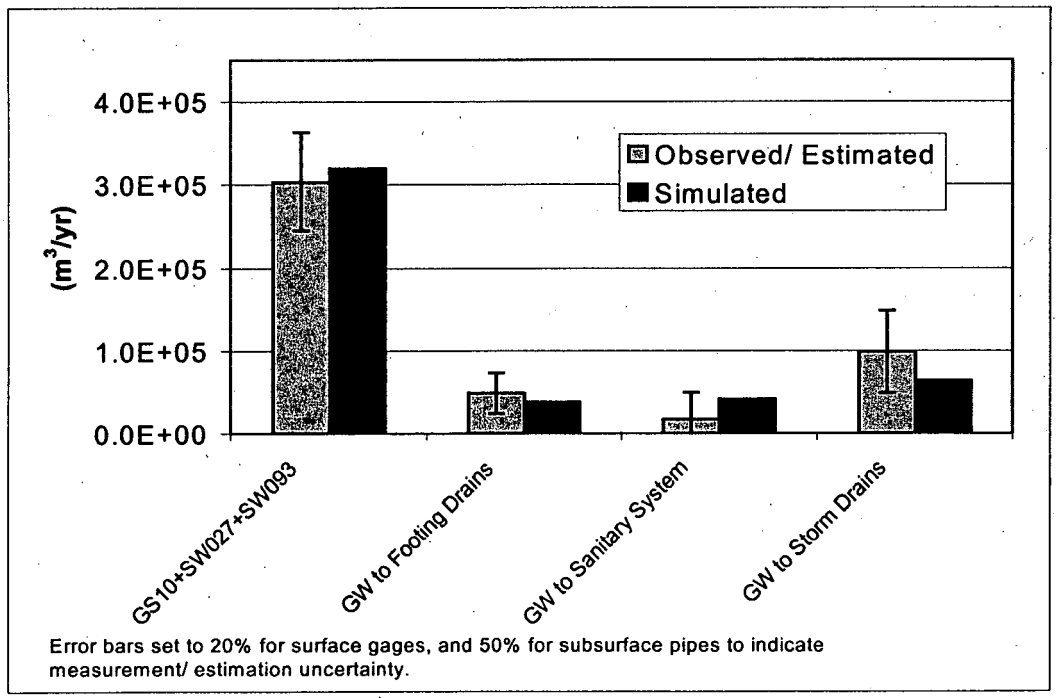


These results demonstrate reasonable simulations for all systems. It is also important to note the small magnitude of these contributions relative to the total water balance (total volume corresponds to less than 3 percent of the discharge measured leaving the Site). Also, these systems are small compared to the scale of the model, ranging from 1 to 10 cells in area (out of 4,035 for the entire model).

General predictions by the model for these systems are adequate; however, decisions requiring additional detail and accuracy would necessitate more focussed modeling.

The Site does not operate a comprehensive monitoring system to measure storm, sanitary and footing drain flows. Many footing drain flows are monitored directly or in combination with surface runoff (as noted above in Appendix B). Flow estimates for storm and sanitary drain flow were taken from estimates reported in previous studies (ASI, 1991a, 1991b and 1991c). Figure 6-14 presents the simulated drain flow compared to observations and estimates. Discharges from the major Industrial Area drainages are also shown for reference.

Figure 6-14. Calibration of Storm Sanitary and Footing Drains



All drain flows are simulated within the estimated 50 percent margin of uncertainty. The footing drain simulation was calibrated to less deviation because comparison values are based in part on observation data (see Appendix B).

6.1.2.4 Water Balance Data

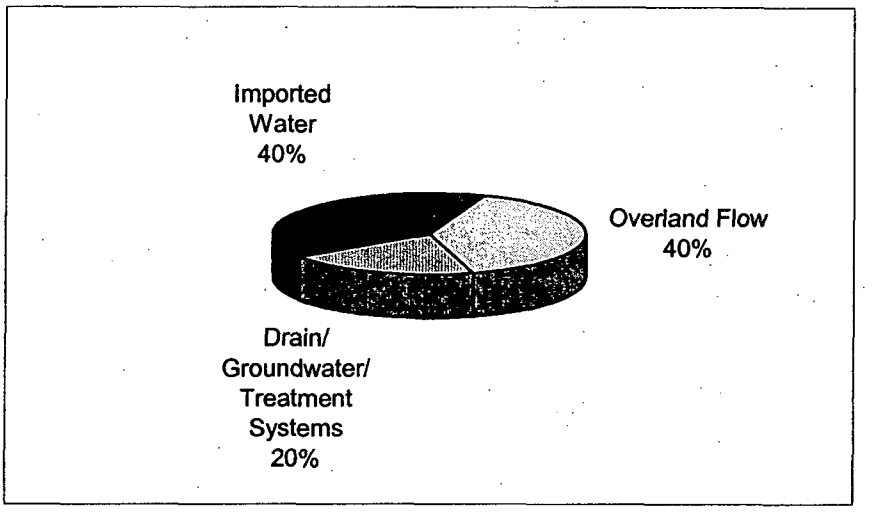
With the model calibrated, previously unquantified information about the system behavior was interpreted from the simulation results. As discussed previously, this information is useful and valid because the system was calibrated as an integrated hydrologic system. The integration of all the hydrologic processes imposes an internal consistency constraint that implies that any misrepresentation of storage or flows in one component of the model is bound to translate to the other components and affect the entire water balance. This provides additional confidence in all output results. The following sections present general information about the current system behavior gathered from water balance information generated by the model.

6.1.2.4.1 GS03 Contributions

Water balance results from the model were studied to determine the relative magnitude of hydrologic processes in the GS03 subdrainage. The GS03 subdrainage is of particular importance because it contains most of the anthropogenic modifications, including most of the Industrial Area and ponds.

Water balance output from the model indicated that, for WY2000, imported water from the DWB comprised roughly 40 percent of the off-Site discharge of water at GS03. Further, roughly 20 percent of the off-Site discharge originated as drain, groundwater or treatment system discharge to surface water. The remaining water originated primarily as overland runoff from the Industrial Area. This information is presented on Figure 6-15. Different ratios of these contributions to flow at GS03 would be expected for years with different climatic conditions.

Figure 6-15. Approximate Simulated Contributions to Surface Flow at GS03 for WY2000



6.1.2.4.2 Industrial Area Versus Buffer Zone

Water balance results from the model were also applied to compare large-scale differences in hydrologic processes for the Industrial Area and the Buffer Zone. For the purposes of this study, the combined GS10, SW093 and SW027 drainage areas comprise the Industrial Area. The Buffer Zone was defined as the remaining area in the system.

Several significant differences were noted from the simulation results for WY2000. First, the Industrial Area produced much more runoff due to the impervious surface area. In the Buffer Zone, less than 2 percent of the precipitation became overland flow, while it was roughly 20 percent of overland flow in the Industrial Area. Second, the relative ET loss was much less in Industrial Area (51 percent) compared to the Buffer Zone (99 percent). These results are consistent with the conceptual model. Again, slightly different ratios would be expected for years with different climatic conditions.

6.1.3 Additional Simulated System Response

This section briefly describes additional system response for which no quantitative calibration data are available. Nevertheless, the simulated system response demonstrates several important findings that result from the calibration of the model to quantitative

data presented above in Section 6.1.2. Overland flow, actual ET, groundwater recharge and discharge are presented in Sections 6.1.3.1 through 6.1.3.4. A brief discussion on total numerical error is presented in Section 6.1.3.5.

6.1.3.1 Overland Flow

Annual total simulated overland flow entering nearby streams is shown graphically in Appendix E. Although, the model areas actually contributing overland flow to streams varied from event to event, the annual distribution clearly shows that only cells immediately adjacent to stream channels provided overland flow. The relatively high, saturated vertical hydraulic soil conductivities compared to precipitation intensities did not produce Horton-type overland flow. Instead, most of the overland flow occurred near stream areas as saturation excess (shallow groundwater reaches the ground surface) due to low relative precipitation intensities compared to saturated hydraulic conductivities of soils. This is consistent with the hillslope flow conceptualization described in Section 3.0.

Most of the upper Industrial Area stream branches received overland flow from adjacent impervious areas. The upper portion of Woman Creek, Antelope Springs, western North Walnut Creek and the Present Landfill area appeared to generate overland flow, due to shallow groundwater. Overland flow was generated at seep areas like Antelope Springs year round. This was also consistent with the flow conceptualization for seeps.

6.1.3.2 Actual Evapotranspiration

The distribution of simulated annual AET (in/year) is shown graphically in Appendix E. The highest rates occurred principally along stream areas where riparian vegetation occurred in a higher density. Simulated rates were also higher in the mesa area north of the Present Landfill, which was likely due to the higher annual precipitation amounts in this area. The lowest rates occurred in impervious areas within the Industrial Area. ET in these areas occurred only as surface evaporation. Simulated ET rates were lower over Rocky Flats Alluvium areas compared with Colluvium, or Valley-fill Alluvium areas. This results mostly from the lower water use vegetation (xeric) combined with relatively

high infiltration rates. Although annual rates were not monitored at RFETS, the simulated distribution appeared consistent with the conceptual understanding of where actual ET would be highest.

6.1.3.3 Groundwater Recharge

The simulated distribution of annual groundwater recharge (in/year) is shown graphically in Appendix E. Recharge is an important process to consider in simulating the integrated response of the system because it controls the groundwater flow and also reflects unsaturated zone conditions, including effects of ET. Net groundwater discharge (no recharge) occurred mainly along lower stream areas where the relatively high actual ET (see figure in Appendix E) rates were produced. No recharge occurred in impervious areas. Local areas within the Industrial Area show recharge rates that were much higher than the annual precipitation. Overland flow from adjacent impervious areas provided the additional source of recharge to these local cells.

Higher positive recharge rates occurred mainly in the mesa areas where Rocky Flats Alluvium is present. This is generally realistic, however, higher rates did not occur over all mesa areas. This is probably because the unsaturated zone storage in deeper groundwater table areas (western model area) had not fully stabilized to the initial conditions, despite recycling the calibration climate for two years prior to running this model input.

6.1.3.4 Groundwater Discharge

Groundwater discharge occurred from drains, remediation systems, seeps, AET and through stream-saturated zone interaction. Appendix E shows the spatial distribution of drain discharge to streams. These occurred within the Industrial Area and the Present Landfill areas. The color distributions reflect different amounts of flow discharged. Footing drains extract the highest amounts of flow.

Appendix E shows the spatial distribution of groundwater discharge to modeled stream branches. The distribution represents annual accumulated flow contributions during the

year. Short-term events can reverse these general annual trends. The distribution along Woman Creek generally correlates well with the gaining/losing stream segments identified in the Fedors and Warner (1993) study. Conceptually the distribution also makes sense, where gaining stream segments occur in steeper hillslope areas, and losing segments occur in flatter, less steep hillslope areas (to the east). The losing segment on eastern Walnut below the A- and B- series ponds is affected to a large extent by the pond operations. The Western Diversion structure located to the northwest of the Industrial Area shows ponding year-round. The western part of North Walnut Creek is a gaining stretch, probably due to steeper hillslope conditions.

Simulated saturated zone discharges to the ground surface are shown in Appendix E. The plot shows the annual accumulated saturated zone discharges to the ground surface, regardless of when the discharge occurred. These represent areas where seep flow occurred. The highest discharge occurred in the Antelope Springs area. In the area to the north of the Industrial Area, some seep areas may occur; however, simulated surface discharge is probably incorrectly simulated due to over-prediction of groundwater levels in this area at some point during the year. Simulated seep discharge volumes were not significant in the overall model water balance.

Horizontal groundwater flows at the eastern model boundary are small compared to surface flows (1:100), but are important as potential pathways for off-Site migration. Appendix E shows a sectional profile just west of the boundary at Indiana, with the four model layers and initial groundwater table. Simulated water balance time-series results for major processes are also graphed in Appendix E. Results show that groundwater discharge along the eastern boundary occurs mostly through the upper model layer representing unconsolidated material. A significant amount of infiltration to the cells along this boundary occurs from stream infiltration (losing stream segments) compared to horizontal discharge through the relatively thin model layers. By comparison actual ET dominated the mass balance along the eastern boundary, accounting for most of the discharge of precipitation and stream recharge.

6.1.3.5 Simulated Numerical Error

The total combined numerical error for MIKE SHE model processes (overland flow, unsaturated zone flow, saturated zone flow, channel flow and snowmelt) is shown in Appendix E. In general errors were small compared to the total mass balance. Locally, errors were higher. For example, errors increased along stream channels, where the numerical solution became more dynamic (non-linear). These errors were still small compared to the total water balance in these cells. Some footing drains imposed greater stress on the local groundwater conditions and caused more numerical errors.

6.2 MODEL SENSITIVITY ANALYSIS

A sensitivity analysis was conducted using the calibrated SWWB model to establish which model parameters control the major RFETS system hydrologic flows. The three most sensitive parameters were used as the basis for conducting the uncertainty analysis for the Land Configuration Scenario. In addition, general simulated system response was assessed mainly in the focus areas through this analysis to demonstrate model performance. The sensitivity of different model outputs to different model input parameters were evaluated within focus areas. A brief summary of the approach and results of the sensitivity analysis are presented in the following sections; and a more detailed discussion is presented in Appendix C.

6.2.1 Approach

Many model parameters and input stresses are used to simulate flow in the RFETS system. Input stresses, like precipitation or PET, were not considered to be calibration parameters. Only calibration model parameters were considered in the sensitivity analysis (see Figure E-1). Of these, only a subset was selected for the sensitivity analyses based on results of calibration simulations. Combinations of these model parameters were not considered because the number of simulations would have been too great, and the integrated response too complex to attribute to a specific parameter. Instead parameters were changed individually for each simulation to show system-specific response attributable to a given parameter change. All other parameters remained

unchanged, corresponding to the calibrated model parameter set. The sensitivity analysis showed non-calibrated conditions.

Sensitivity parameters considered included:

- K_h - saturated zone hydraulic conductivity;
- K_{sat} - unsaturated zone saturated hydraulic conductivity;
- ret - unsaturated zone moisture retention function;
- n - unsaturated zone hydraulic conductivity curve ('n'-exponent);
- LAI - (ET parameter);
- RDF - root distribution function (ET parameter);
- Kc - (ET parameter); and
- L - stream-saturated zone leakage coefficient.

Parameters selection was based on simulations performed during calibration. For example, parameter changes in channel resistance affected the flow rates in streams, but they did not affect total annual system flow volumes. Other parameters, however, caused notable changes in system flows and dynamics over a relatively small range of values. For example, if groundwater levels rose too high in the Industrial Area by reducing vertical saturated hydraulic conductivity values, a significant increase in drain discharges would occur and streamflows would change notably. Another example, is if soil hydraulic conductivities were reduced to values below average precipitation intensities, a substantial increase in overland flow would be generated, and streamflows would increase dramatically. Both of these examples clearly would have simulated unrealistic system flows. As a result, the eight sensitivity parameters were adjusted within a range that would not cause physically unrealistic system responses.

The ranges of parameter values considered in the sensitivity analysis were selected based on observed Site data ranges and published information. An attempt was made to adjust each parameter by about the same ratio defined by the parameter change divided by the total parameter range. These parameter ranges were assumed physically realistic, and the analysis was intended to describe model sensitivities only in this part of the parameter space.

A number of absolute, relative and comparative measures were applied to evaluate the sensitivity at points of importance namely:

- Surface water flow sensitivity (changes in discharge at GS01, GS03, GS10, SW093 and SW027);
- Water balance sensitivity (changes in major water balance variables for the entire RFETS model area, GS01, GS03, GS10, SW093, SW027, Mound Plume Remediation System, Solar Pond Plume Remediation System, Industrial Area storm drain cells, Industrial Area sanitary drain cells, Industrial Area footing drain cells, East Trenches Plume Remediation System and 881-Hillside French Drain);
- Groundwater level sensitivity (changes in mean groundwater levels at Industrial Area - north, Industrial Area - south, Mesa East, Mesa North, 881-Hillside French Drain, Solar Pond Plume Remediation System, GS01 and GS03 [near-stream]; and
- Pond water-level sensitivity (changes in pond water depths in A-3, A-4, B-3, B-5 and C-2).

6.2.2 Results

The results from the sensitivity analysis are presented in detail in Appendix E. The following sections present a summary of the results in terms of surface water discharges, pond water levels, groundwater levels, and water balance.

6.2.2.1 Surface Water Discharges

GS01 discharge was very sensitive to the hydraulic conductivity values applied for the UHSU system and the leakage coefficients controlling the stream-saturated zone interaction. Moderate responses in discharge were observed for reductions in LAI and RDF ET parameters. Unsaturated zone parameter changes had relatively little effect on the simulated discharge at GS01.

The GS03 discharge is dominated by pond releases at GS11 and GS08. Consequently, it is much less sensitive to parameter changes than GS01.

With a few exceptions, the responses of the two Industrial Area gages (GS10 and SW093) were very similar. The pavement and subsurface drainage systems control their hydrological responses. The Industrial Area discharges were generally less sensitive than those for the Buffer Zone areas. These surface water discharges are moderately sensitive to changes in K_{sat}, K_c and L.

Estimated from the relative discharge response, SW027 was the most sensitive of the surface water gages. Large relative increases in surface water runoff are seen for all of the eight sensitivity runs (40 –76 percent).

Estimated from the relative discharge response, SW027 was the most sensitive of the surface water gages. Large relative changes in surface water runoff are seen for all of the eight sensitivity runs (40 –76 percent).

6.2.2.2 Pond Water Levels

Pond A-3 water levels were the most sensitive to increasing groundwater hydraulic conductivities and secondly to changes in stream leakance coefficients. With the exception of changes in saturated zone conductivities, Pond A-4 water levels were insensitive to all parameter changes. Pond B-3 water levels were affected less than 0.04 m (< 2 in) during the simulation period for all of the parameter changes investigated with the exception of increased conductivity of the UHSU. Pond B-5 water levels were the least sensitive to changes in ET component parameters and stream leakage coefficients,

but increasing saturated zone conductivity caused a significant change in water depth. Groundwater and unsaturated zone soil properties were of primary importance to the simulated Pond B-3 water levels.

The largest effect on Pond C-2 water levels occurred from changes in stream leakage coefficients. A larger volume was lost from the SID to the saturated zone, and the discharge to Pond C-2 was reduced. For all other sensitivity runs, water-level changes were less than 10 percent by the end of the simulation.

6.2.2.3 Groundwater Levels

By increasing the saturated zone hydraulic conductivities, a significant groundwater level decrease was seen in the Industrial Area. After one year, the mean water-level differences were 0.42 m (1.42 ft) for the northern part of the Industrial Area and 0.86 m (2.8 ft) for the southern. The entire Industrial Area was insensitive to the unsaturated zone parameter changes.

Mesa East groundwater levels were characterized by very low sensitivity. A maximum groundwater level change of 0.06 m (0.20 ft) was observed when changing the saturated hydraulic conductivities. Mesa North, on the other hand, was only insensitive to retention curve changes. High sensitivity is observed for saturated zone hydraulic conductivity and K_c and less sensitivity for the remaining cases.

The 881 Hillside and Solar Ponds Plume Hillside (hillside near corresponding to the location of the Solar Ponds Plume) groundwater levels were both highly sensitive to changes in saturated zone conductivities, and crop coefficients. Water levels in the vicinity of 881 Hillside dropped by 0.51 -0.74 m (1.7 – 2.4 ft) and those of Solar Pond Plume Hillside increased 0.22-0.26 m (0.72 – 0.85 ft). The remaining sensitivity runs only provoked minor changes in the water table.

The near-stream groundwater levels in the GS01 and GS03 drainages were relatively unaffected by changes in sub-surface conductivities, but to a higher degree influenced by changes in unsaturated zone and ET parameters.

6.2.2.4 Water balance

For the entire model area, changes to the hydraulic conductivity of the saturated zone led to large changes in the Site water balance, but most changes were temporary because the water volume initially stored was discharged. Unsaturated zone parameter changes had little effect on the surface water and groundwater flow and mostly affected the balance between water stored in the unsaturated zone and ET losses. A similar effect was seen of the ET parameter changes. Increased leakage coefficients lead to significantly higher losses from the streams to the saturated zone (along Walnut and Woman).

The GS03 water balance sensitive parameters were the same as GS01, although the individual responses of water balance variables were different. The most pronounced water balance response was attributed to hydraulic conductivity changes of the UHSU.

The GS10 and SW093 water balances were not as sensitive to parameter changes as GS01 and GS03. Changes in ET were mostly associated with changes in sub-surface storage, which impacted groundwater discharges to the streams only to a limited degree. Changes in saturated zone hydraulic conductivity, the unsaturated zone hydraulic conductivity curve, ET crop coefficient and stream leakage had the most significant effect on the simulated water balance.

The Mound Plume Remediation system was sensitive or highly sensitive to all of the parameter changes. The Solar Ponds Plume Remediation system area is highly sensitive to saturated zone conductivity, non-sensitive to leakage coefficients and low to moderately sensitive to the remaining parameters.

The model grid cells representing storm, sanitary and footing drain systems were primarily sensitive to the saturated zone hydraulic conductivity, leakage coefficients and ET crop coefficients. Surface runoff from the storm and footing drains were generally more sensitive than sanitary drain runoff. All of the drains were sensitive to changes in the parameters.

The East Trench Plume Remediation system water balance was sensitive to all parameters with the exception of stream leakage coefficients. The 881 Hillside French Drain was highly sensitive to the leakage coefficients and low to moderately sensitive to the remaining parameters.

In summary, the magnitude of the SWWB-simulated hydrological variable responses to parameter changes varied between the evaluation points. Despite these differences, it was possible to identify the primary model sensitive parameters. Saturated zone hydraulic conductivities, unsaturated zone hydraulic conductivities, LAI and K_c are the parameters affecting key model outputs the most. These parameters were used to assess the range of uncertainty in the Land Configuration Scenario (Section 7.3). Sensitivity analyses showed that the system hydrology not only responded most to similar changes in these parameters, but it also responded in an expected way.

6.3 MODEL VALIDATION

The calibration effort considered model performance only for the range of conditions observed for WY2000. Model validation consisted of testing the model against two additional periods of climatic record. As such, the validation was essentially an additional evaluation of the numerical model performance. The approach and findings of the validation simulations are presented briefly below and discussed in detail in Appendix E.

6.3.1 Approach

The two validation simulation periods consisted of the large spring event of 1995 and the entire WY2001. These two periods were chosen primarily based on the range of climatic conditions represented, relative to the calibration period of WY2000. This section briefly discusses the validation period climates, validation model development, and the data limitations.

The May 17, 1995 event corresponded to roughly a 15-year return-frequency precipitation event at the Site (EG&G, 1992a). Further, the 1995 months of April and

May were exceptionally wet; 12.1 inches (307 mm) of precipitation fell, compared to 13.8 inches (350 mm) for all of WY2000. These precipitation events of 1995 were long-duration, low-intensity storms. WY2001 (15.6 inches (396 mm) of precipitation) was also wetter than average (14.8 inches or 376 mm). In contrast with the 1995 event, WY2001 had several high intensity events. The climate of the validation simulation periods is discussed in greater detail in Appendix E.

The calibration model structure was modified to represent the conditions of each simulation period. This included a number of surface water routing and control structure changes for 1995; but very few changes were required for WY2001. Climatic input, boundary inflows and internal transfers and discharges were all updated to reflect the period of record. More information on changes made to create the validation models is presented in Appendix E.

The data quality and quantity for WY2001 were as complete as that for WY2000. The data set for the 1995 simulation, however, had limitations:

- Missing inflow data (no records for inflows from McKay Ditch to GS03 and Smart Ditch to GS01);
- Estimated comparison data for most peak flows (peak flows exceeded flume capacity at most locations);
- No spatial distribution of precipitation (single precipitation gage available);
- Limited resolution for comparison data (only mean daily flow rates available for GS01, GS02 and GS03); and
- Uncertainty of initial conditions (see Appendix E).

These data limitations were taken into consideration when assessing results. See Appendix E for more detail on data limitations.

6.3.2 Results

In general, the model performed well for both validation periods. Findings from comparison of simulated results and observed results were similar to findings for the

calibration model. Simulated and observed channel flow volumes and flow rates compared well, for Buffer Zone and Industrial Area subdrainages. The effects of grid resolution limitations along Woman Creek and the SID, identified in the calibration year model, were also observed in these validation models. (See Section 5.2.1.1 for more discussion of grid resolution issues.) Simulated groundwater levels compared well to observed quarterly data, especially in near-stream areas. These results are presented in greater detail in Appendix E. The validation effort, thus, provides confidence in the calibrated model.

6.4 SECTION 6 SUMMARY

The integrated model performance was described in this Section. The approach and results for model calibration, sensitivity analysis and model validation were used to demonstrate performance. Although, a substantial amount of information was produced by the integrated model, the discussion was limited to model performance in the focus areas (defined in Section 1.6).

The model calibration required a Site-specific approach. The Site-specific approach was developed because available modeling protocols are too general or inadequate for developing a fully integrated hydrologic model capable of simulating the complex, dynamic and integrated RFETS semi-arid flow system. Calibration parameters and targets were identified and prioritized to focus the calibration process and overall model development in the focus areas. The calibration followed an iterative and prioritized approach. Spatially, calibration targets were prioritized, giving focus areas and near-stream hydrologic areas the highest priority because a larger percentage of the off-Site discharge occurs as surface flow.

Simulated system response was compared to observed hydrologic response at different time scales to demonstrate performance. In general, the integrated model reproduced the regional system response well. Simulating surface flows accurately was given the highest priority; and observed annual, seasonal and event level surface flow responses were simulated well with the integrated model.

In the approach, more accurate calibration of groundwater levels was required in the Industrial Area and near-stream areas. Results showed that simulated and observed levels compared better in these areas. Simulated levels in local mesa and hillslope areas were not captured as well. For the purposes of the SWWB model, the calibration was considered reasonable. Simulated results support the conceptual model that suggests mesa and hillslope areas have limited effects on stream-saturated zone flow dynamics. This is largely due to the strong local effects of ET combined with the relatively slow groundwater flow velocities from hillslopes to streams throughout the system.

Calibration of the subsurface flow system was more challenging than the surface flow system because of the greater degree of uncertainty associated with available data. Local variations in subsurface hydraulic properties were effectively averaged over each model cell.

Sensitivity analyses were also conducted on the calibrated integrated model. Results support the general understanding of which parameters control the system hydrology. Outside of external driving stresses, like precipitation, the saturated zone hydraulic conductivity had the greatest effect on system flows. These results were used in the uncertainty analysis conducted as part of the hypothetical Site configuration scenario simulations.

The performance of the integrated model was further tested for pre- and post-calibration time periods (1995 and WY2001). This required specifying different climate input datasets (precipitation, temperature and PET) and adjusting some features of the model to reflect flow conditions during these time periods. Limitations on available climate data, flow configuration details and response data prevented a full comparison for the pre-calibration period, 1995. However, simulated results generally compared well with observed responses. Simulated results from the post-calibration period (WY2001) were not affected by lack of data, allowing for a more thorough assessment. WY2001 simulation result compared very well with observed responses in both the Industrial Area and Buffer Zone, showing an improvement over even the calibration year simulation.

7.0 HYPOTHETICAL SCENARIOS

The calibration model (WY2000 Site configuration) was modified to create two hypothetical scenarios, simulating progress toward Site closure. The scenarios were based on the best available information as of January, 2002 (Scheck, 2002), and do not represent specific or finalized plans or designs for Site closure. The scenarios were simulated only as a preliminary application of the SWWB. Conclusions and implication generated from these scenarios should be considered accordingly, but they do provide insight for RFETS closure strategy and long-term stewardship.

The two hypothetical scenarios included: (1) the No Imported Water Scenario, and (2) the Land Configuration Scenario. The No Imported Water Scenario simulated the discontinuation of imported water from the DWB. The Land Configuration Scenario simulated surface and subsurface modifications to the Industrial Area, the Original Landfill and the Present Landfill (based on Scheck [2002]). Import of water was also discontinued in the Land Configuration Scenario. The scenarios were evaluated for WY2000 climate conditions as well as hypothetical dry and wet years.

The matrix shown on Figure 7-1 summarizes the scenario simulations performed for this report. In the matrix, the term "Pond Algorithm" refers to the algorithm applied to the model which determined pond transfers and discharges, based on simulated pond levels and inflows. The pond algorithm was developed to simulate water routing through the ponds where observed data were not available (i.e., hypothetical scenarios and climates). As shown on the matrix, the WY2000 configuration was also simulated with the pond algorithm to assess the algorithm performance and to generate a baseline for comparison of scenario results.

The setup and results of scenario simulations are presented and discussed in the following sections. The uncertainty analysis is presented in Section 7.3. The uncertainty analysis was conducted only for the Land Configuration Scenario using calibration year climate.

Figure 7-1. Scenario Simulations Matrix

	Calibration Year (WY2000)	Wet Year	Dry Year
WY2000 Configuration (Calibration)	x		
WY2000 Configuration (Pond Algorithm)	x	x	x
No Imported Water (Pond Algorithm)	x	x	x
Land Configuration (Pond Algorithm)	x	x	x

Uncertainty Analysis

7.1 MODEL SETUP

The following sections describe steps taken to construct the scenario models, using the calibrated model as the basis. Structural modifications, climate generation and initial/boundary conditions are described.

7.1.1 Structural Modifications

7.1.1.1 Pond Algorithm

For the calibration and validation models, pond transfers and discharges were pre-specified to match the observed records. In other words, pond discharges were forced in the model to occur in accordance with the record of operations for WY2000 (as opposed to programming the model to determine discharge timing in response to simulated pond levels and inflows). This approach was appropriate for calibration and validation runs, where the model was being run to reproduce observed results. Applying the actual start times and flow rates for discharges allowed the system to respond as observed,

facilitating calibration of pond levels and downstreamflow records. In contrast, no observed pond transfer and discharge records could be applied to the hypothetical scenarios and climates. Therefore, for these simulations, an algorithm was applied in the model which determined pond transfers and discharges in response to simulated pond levels and inflows.

This algorithm for pond operations was developed with control structures in MIKE 11. Control structures were defined with of a series of logical programming statements, designed to simulate the Site protocols described in the Pond Operations Plan (RMRS, 1995). The control structures dictated the following actions:

- Initiate a discharge at the appropriate pond level;
- Discharge at a rate corresponding to 1 ft (~0.3 m) of draw-down per day for the given pond;
- End the discharge when the pond level reaches 10 percent capacity;
- Increase the discharge rate to account for inflow; and
- Set the maximum discharge flow rate based on outlet structure or pumping limitations.

The applied control structures are described in greater detail in Appendix F.

The pond algorithm in the model did not simulate all variables of the actual decision-making process applied at the Site; delays and scheduling often vary depending on timing of weekends, holidays, weather forecasts and water quality testing. However, when the pond algorithm was applied to the calibration year, simulation results compared well to the observed record for both discharge frequency and timing for all ponds. These results are discussed in greater detail in Appendix F.

The pond algorithm was applied to all scenario runs, as well as the calibration year run used for comparison.

7.1.1.2 No Imported Water Scenario

The first scenario simulated by the SWWB model was the No Imported Water Scenario. This scenario represented a hypothetical situation where all conditions were identical to the calibration year except, import of water from the DWB was discontinued. In the model, this situation was simulated by discontinuing water leakage from domestic distribution pipes and removing WWTP discharge to Pond B-3. These modifications effectively removed the influence of imported water from the model.

7.1.1.3 Land Configuration Scenario

The second scenario simulated by the SWWB model was the Land Configuration Scenario. Several modifications were made to the surface and subsurface flow system to simulate the Land Configuration Scenario (based on Scheck [2002]). Technical details specified in the design of the Land Configuration Scenario were obtained from D.B. Stephens (2001), and from discussions and other data provided by the Site Environmental Restoration personnel (Scheck, 2002). Modified areas (shown on Figure 7-2) included: (1) the Industrial Area; (2) the Present Landfill; and (3) the Original Landfill.

Hypothetical changes made to the Site for the Land Configuration Scenario are described in the following sections in terms of changes to the calibrated model for the surface and subsurface systems.

7.1.1.3.1 Surface Flow System

The following changes were made in the model representation of the physical system to simulate changes to the surface flow system for the Land Configuration Scenario:

- The network of Industrial Area channels was replace with two channels that route water to the A and B-series ponds;
- WWTP discharge to Pond B-3 was discontinued to simulate discontinuation of imported water;

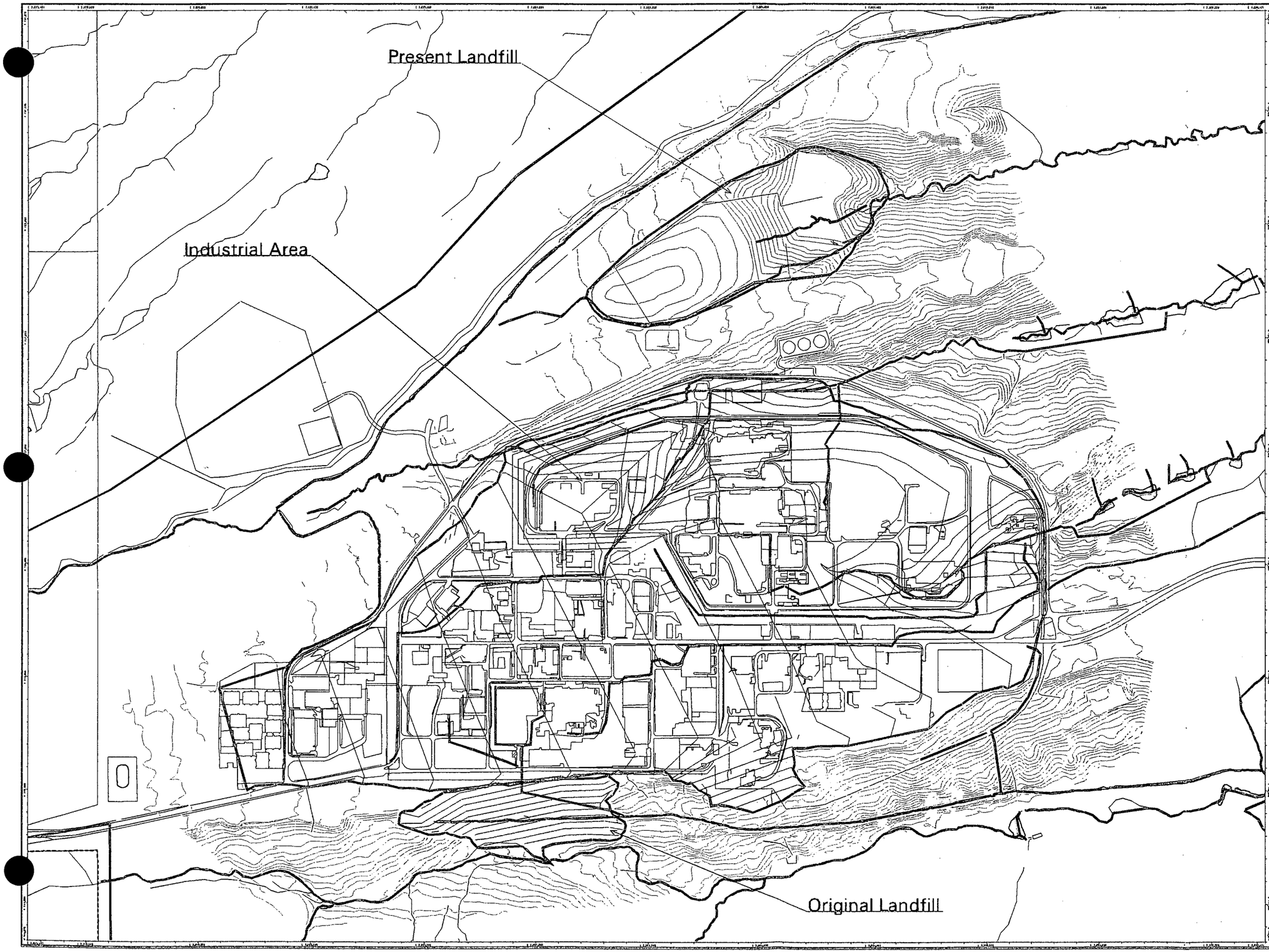


Figure 7-2

Site-Wide Water Balance Report

Land Configuration Scenario - Changed Areas

EXPLANATION

- Surface Channel Network
- Regraded Areas
- Industrial Area Contours (5' Interval)
- Original Landfill Contours (5' Interval)
- Present Landfill Contours (5' Interval)
- Unchanged 5' Topographic Contours

Standard Map Features

- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:
Regraded area topography obtained from (Scheck, 2002).

40 0 80 160m
100 0 200 300ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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- The upper reach of the SID was removed, and
- The Landfill Pond was removed.

Details about modifications to the surface channels are presented in Appendix F.

7.1.1.3.2 Subsurface Flow System

Most of the Land Configuration Scenario modifications to the calibrated model were made to the subsurface system. Table 7-1 summarizes the modifications associated with different physical configuration changes shown on the left of the table. Changes are also specified in the summary table for each changed area defined on Figure 7-2.

Subsurface drains, including storm sewers, sanitary sewers and footing drains, were deactivated in the Land Configuration Scenario so that they no longer discharged groundwater into nearby surface streams or routed flow to the WWTP. This was done by adjusting drain codes in the MIKE SHE model. The adjustment to these model components did not affect the current operation of the five groundwater remediation or collection systems that discharge to the surface flow system.

The effect of removing subsurface utilities and trench material in local process waste line areas was simulated in the Land Configuration Scenario model. Environmental Restoration personnel (Demos, 2002) specified areas where trench material would be removed. In the model, the hydraulic conductivities associated with those trench areas were modified to reflect backfill with Rocky Flats Alluvium material (Lindsay, 2002).

Table 7-1. Subsurface Modifications to the Land Configuration Scenario

Physical Change	Model Input	Proposed Modification Areas: Industrial Area	Present Landfill	Original Landfill
1 Discontinued DWB imported water.	Water Supply (abstractions in MIKE SHE)	Turned off	no change	no change
2 Deactive Drains (footing, sanitary, storm)	Draincodes	No WWTP inflow at B3 All utility drain codes modified	No change. Keep existing GW interceptor drain	no change
2 Utility trench removal - Only NWPL/OPWL areas defined by Nick Demos.	Layer 1 Kh	Remediation system drain codes left as is. Assign backfill Qrf material to cells where utility trenches are removed. Use typical calibrated Qrf borrow material Kh value.	no change Flow in landfill assumed isolated from regional system. Parameter change not important here.	no change. Kh changed to Qrf fill material - Use mean calibrated value typical of Qrf material
3 Footing Drain removal.	Layer 1 Kh	Borrow material replaces cells where footing drains removed. Use typical calibrated Kh value for Qrf borrow material.	no change	no change
4 Leave basement walls/slabs in place, except bldg 771.	Saturated zone vertical hydraulic conductivity.	Building 771 same as typical calibrated Qrf Kv. All other buidling-basement cells use Kv = 1e-7 m/s (this is lower than typical calibrated Qrf Kv to simulate effects on vertical flow due to basement slabs left in place.	no change	no change

Physical Change	Model Input	Industrial Area	Proposed Modification Areas Present Landfill	Original Landfill
		Slurry wall feature in MIKE SHE used to simulate reduced horizontal flow through each building's basement walls left in place.	no change	no change
5 Pavement and Building Removal	Soil Distribution	Pavement and building cells converted to Qrf borrow material.	no change	no change
6 Regrade and ET Cover on Present and Original Landfills.	Soil Distribution	no change	Uses Present Landfill ET cover specifications as per D.B.Stephens Report	Same ET cover specifications as present landfill. Specified over entire regrade area
	UZ vertical discretization	no change	ET cover specifications. Use 1 cm at ground surface and soil layer contacts	ET cover specifications. Use 1 cm at ground surface and soil layer contacts
	UZ Saturated Vertical Hydraulic Conductivity	At buildings w/inplace slabs, adjust to rubble. Change pavement areas to Qrf.	(Scheck, 2002)	(Scheck, 2002)
	UZ moisture retention function	no change	ET cover specifications. Varies for 4 different layers.	(Scheck, 2002)
	UZ Unsaturated hydraulic conductivity function	no change	Determined exponent value by curve matching with van Genuchten parameters provided in D.B. Stephens report. Parameter value selected is similar and prevents recharge and ponding	Same as ET cover speciciations for present landfill.
	UZ Residual moisture content	no change	Specified as per D.B.Stephens report.	Specified as per D.B.Stephens report.
	UZ Saturated moisture content	no change	Specified as per D.B.Stephens report.	Specified as per D.B.Stephens report.

Physical Change	Model Input	Industrial Area	Proposed Modification Areas Present Landfill	Original Landfill
	Leaf Area Index	Specified as per D.B.Stephens report.	Specified as per D.B.Stephens report.	Specified as per D.B.Stephens report.
	Root depth function (describes root density with depth)	Specified as per D.B.Stephens report.	Specified as per D.B.Stephens report.	Specified as per D.B.Stephens report.
	Crop Coefficient (Kc) specified in vegetation database.	assume 5% bare soil - (Scheck, 2002)	assume 5% bare soil - (Scheck, 2002)	assume 5% bare soil - (Scheck, 2002)
	Vegetation distribution - type	Assume ET cover vegetation is placed over entire regraded area	Assume ET cover vegetation is placed over entire regraded area	Assume ET cover vegetation is placed over entire regraded area
7 Regraded surface topography	Topography	As per initial (Scheck, 2002) regrading and drainage plan (1/22/02). Some assumptions required for local regrade topography merge with existing adjacent topography.	As per (Scheck, 2002) regrading and drainage plan (1/22/02)	As per regrade diagram provided by (Scheck, 2002). Five feet of additional fill added as per Scheck.
8 Slurry Wall to the north of the Original Landfill				A slurry wall, or impermeable horizontal flow barrier is placed along the entire upgradient length of the landfill.

Trench material associated with building footing drains were removed, but the building basement walls and slabs were left in place. In the calibrated model, relatively high drain leakance values were used to simulate effects of footing drains on groundwater. In addition, relatively high hydraulic conductivity values were also assigned to the upper saturated model layer, where footing drain cells are present, to improve simulation of basement de-watering. In the Land Configuration Scenario model, horizontal saturated hydraulic conductivity values for the Rocky Flats Alluvium borrow material replaced the high footing drain/basement model cell conductivities (Lindsay, 2002).

Building basement walls and slabs were left in place, except for Building 771, where the slab was assumed to be rubblized, resulting in a more permeable material. Leaving the slabs in place and removing footing drains will cause surrounding groundwater to inflow until the local groundwater table equilibrates. The rate at which groundwater levels within the former building basements will equilibrate with surrounding groundwater levels depends on effective permeabilities of cracks or joints between the concrete walls and slabs. It was assumed that the rate of inflow would be significantly lower than through the natural Rocky Flats Alluvium. A MIKE SHE slurry wall feature was used to simulate the increase in groundwater levels in basements and slow inflows/outflows. The inflow/outflow rate was controlled by a slurry-wall leakance. Vertical hydraulic conductivities were reduced to 1.0×10^{-7} m/s (3.3×10^{-7} ft/s) to simulate slower flow rates across basement slabs.

Areas with removed pavement and buildings were back-filled with a Rocky Flats Alluvium material. As a result, these areas were subject to the infiltration characteristics of this material. In the Land Configuration Scenario model, unsaturated zone material was specified in these areas as Qrf.

The surface topographies in the three key regrade areas (shown on Figure 7-2) were modified in the Land Configuration Scenario model based on information from (Scheck, 2002). Several assumptions were required in merging the proposed main Industrial Area regrade area topography with adjacent ground surface contours, though major drainage routes and general overland flow directions were unchanged.

ET covers (described in D.B. Stephens [2001]) were specified for the Present and Original Landfills. The covers assumed the configuration and vertical layer dimensions shown on Figure 7-3. An Erosion Protection Layer (EPL), Soil Rooting Medium (SRM), Venting Layer (VL) and Interim Cover (IC) overlay the waste material. Several simulations were performed for this ET cover to verify that the SWWB model adequately reproduced the lack of recharge and ponding as simulated by the UnsatH code (Fayer, 1996).

Vegetation parameter values over each regrade area (on Figure 7-2) assume an LAI, RDF and growth cycle specified for the ET cover design. K_c values were defined assuming that 5 percent of the vegetated area is bare soil.

A single slurry wall was defined for the entire area north of the Original Landfill. The MIKE SHE slurry wall feature was used to simulate this feature. Low leakance values were assigned to prevent flow across the slurry wall.

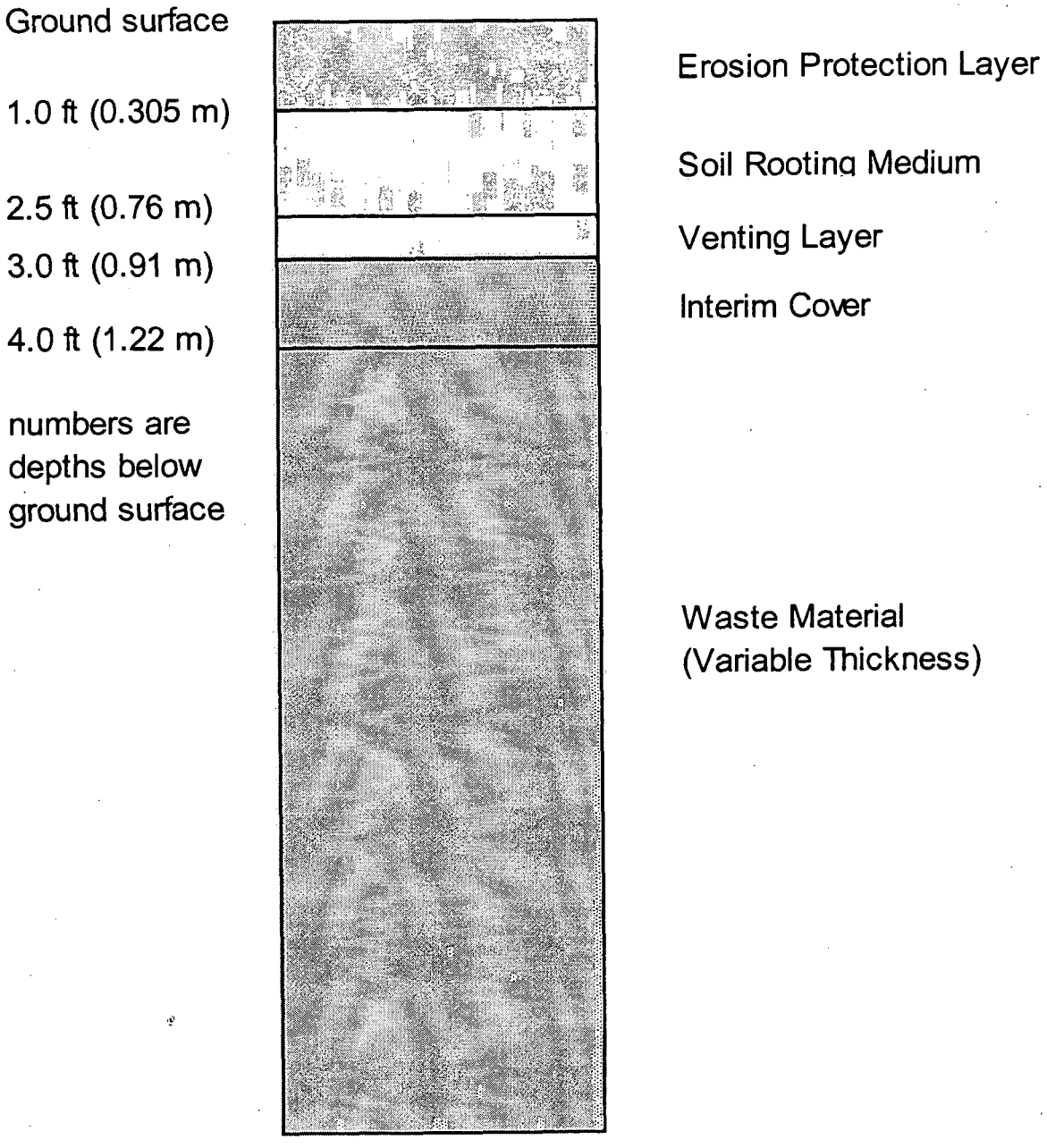
7.1.2 Climatic Conditions

Climate within the model is defined by precipitation, PET, and temperature. As described above, three climate conditions were applied to each scenario to develop a range of simulated responses. The three conditions represent average, wet and dry years of precipitation for the Site.

The first climatic condition was the WY2000 climate prepared from observed data for the calibration year. This condition represented average conditions. PET, temperature and precipitation were all determined from the Site metrology record and distributed precipitation gages (as described in Section 5.2.1).

Climate input sets for the wet and dry years were synthesized. Site data required to generate PET input were available only back through 1996. During these five years, no extremely dry or extremely wet years were observed. Consequently, the wet and dry years could not be defined directly from the Site record.

Figure 7-3. ET Cover – Present and Original Landfills



Note: Source D.B. Stevens, 2001.

Recognizing the need to correlate input PET with cloud cover (associated with precipitation), snow albedo effects, and humidity, the following solution was reached. The wet and dry years applied the WY2000 PET time series and temperature, and the WY2000 precipitation was multiplied by a factor to generate wet and dry years of precipitation.

The result of this approach was to increase or decrease the intensity of precipitation events throughout WY2000 to create total precipitation values corresponding to wet and dry years. Wet and dry years were defined for the purpose of this project as one standard deviation above and below the mean annual precipitation. The mean and standard deviation of the annual precipitation were determined to be 15.2 inches (386 mm) and 4.2 inches (107 mm), respectively. The resulting total annual precipitation applied to the scenarios were 19.4 inches (493 mm) for the wet year and 11 inches (279 mm) for the dry year. Details of this calculation (estimation) and a discussion of resulting intensities are presented in Appendix F.

7.1.3 Initial/Boundary Conditions

Results of the sensitivity analysis using WY2000 climate data showed that the near-streamflow system reached a state of dynamic equilibrium after simulating one to two years. Hillslope and mesa areas have a greater unsaturated zone depth and consequently took longer to equilibrate than the stream areas, but do not affect near-stream hydrology significantly. Furthermore, groundwater flow gradients and velocities do not change significantly, even if groundwater levels have not fully adjusted to initial conditions. Therefore, initial groundwater levels, developed by simulating a full year, were used in a second simulated year to stabilize unsaturated zone conditions. This provided assurance that the more important near-stream areas were stable prior to running the scenario runs. Because the calibration and Land Configuration Scenario models were simulated using the same initial conditions, simulated differences between the two models reflect only the effects of the modifications, rather than the initial conditions.

The boundary conditions for surface and groundwater flow systems are the same as the calibration model. Constant groundwater levels were specified on the west and east model boundaries, while time-varying upstream inflows were specified for the western boundary along Woman Creek, Owl Creek, and McKay Ditch. Constant stream stage heights are used for downstream Woman and Walnut Creeks along the eastern boundary. External stresses included precipitation, temperature and PET (the same as the calibration model). For different climate conditions, only the temporal precipitation amounts were changed.

7.2 SCENARIO SIMULATION RESULTS

In this section, simulated results from the scenario simulations are presented in several ways to depict hydrologic response to the closure modifications and climate conditions. The model was designed to predict the hydrologic changes to the system due to hypothetical Site configuration changes. Therefore, emphasis was placed on predicting changes to the hydrologic system, rather than model-predicted flow rates, or state of the system (i.e., pressure) at a given point in the model. The change in simulated hydrologic conditions were considered the most reasonable model predictions because flow conditions were not subject to errors in input stresses, initial conditions and the calibration parameter values used in the model. The predicted change in system response is calculated as the difference between Scenario and WY2000 configuration results.

The substantial amount of temporal and spatial model output data required consideration of more focused output. Drainage basin-scale results over the entire model are described first to give an idea of the relative effects that both scenarios have on the entire system hydrology. Model output is then described for key focus areas (defined on Figure 1-2 and Figure 1-3), because key decisions or significant hydrologic changes are expected in these areas.

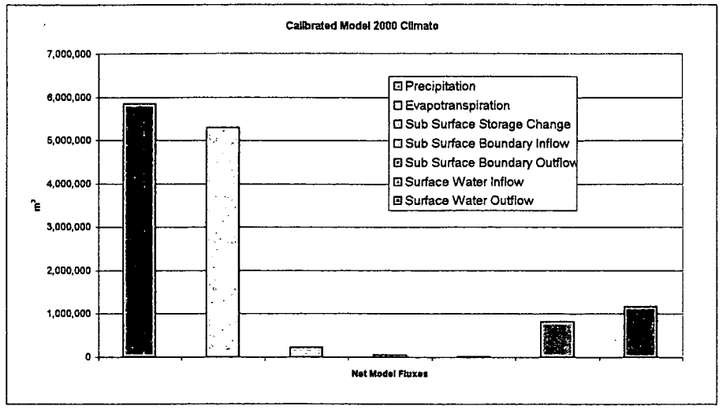
7.2.1 Regional (Drainage Basin-Scale)

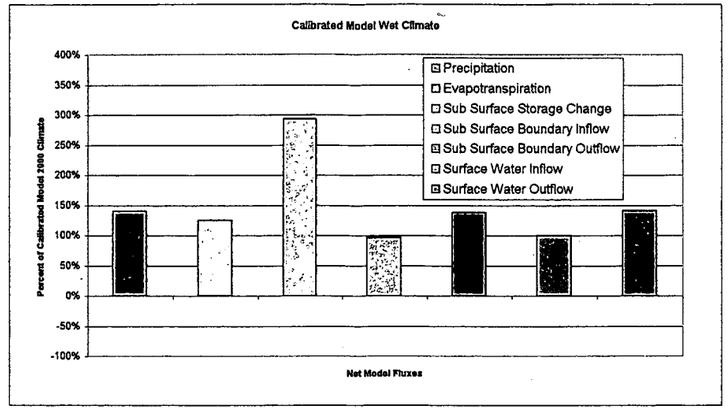
Simulated regional hydrologic response to changes in the hypothetical Land Configuration Scenario, is summarized through a regional water balance shown on Figure 7-4 and through groundwater levels shown on Figure 7-5. The graph in the upper left area of the plot illustrates simulated annual flows for key calibrated model water balance components for the entire model area. Other graphs show water balance flow components for other scenario simulations (No Imported Water Scenario, Land Configuration Scenario and wet/dry climates) that have been normalized against the calibrated model results.

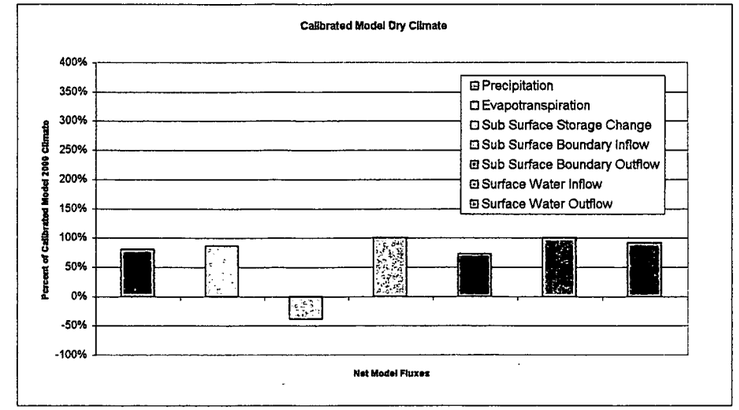
There are two key points to note about the calibrated model regional water balance. First, the annual precipitation and ET were significantly larger than the subsurface storage changes, groundwater inflow/outflow and surface water inflow/outflow. Secondly, the total annual groundwater outflow from the model is less than 1 percent of the total annual surface water outflow from the system. Furthermore, the ratio of groundwater inflow to surface inflow was low. Both observations support the conceptual flow model and calibration priority for the surface flow. About 90 percent of the total annual precipitation that enters the system leaves, as ET, which is typical of a semi-arid flow system.

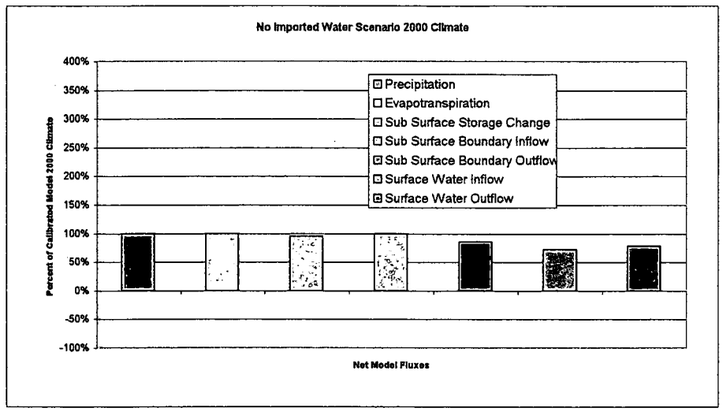
Within the Buffer Zone, groundwater levels decreased along the eastern portion of Walnut Creek (downstream of the A- and B-pond series) for both scenarios. This was the result of the decreased number of pond discharges. In the case of the No Imported Water Scenario, the decrease is directly related to the removal of WWTP effluent to Pond B-3. For the Land Configuration Scenario, the decrease is caused by the combined effects of the removal of WWTP effluent to Pond B-3 and the decrease in fast runoff from the Industrial Area (from pavement removal). The average decrease in groundwater level in cells adjacent to the stream along lower Walnut Creek was about 0.5 m (1.6 ft) (calibration year climate) for the Land Configuration Scenario. The decrease was less than 0.5 m for the No Imported Water Scenario.

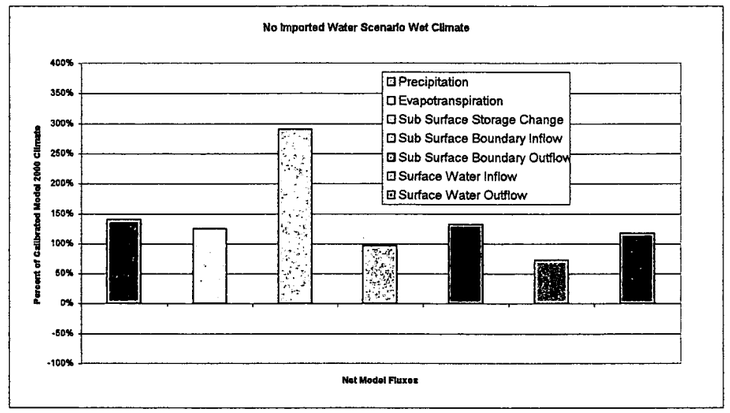
Figure 7-4. Scenarios - Regional Water Balance

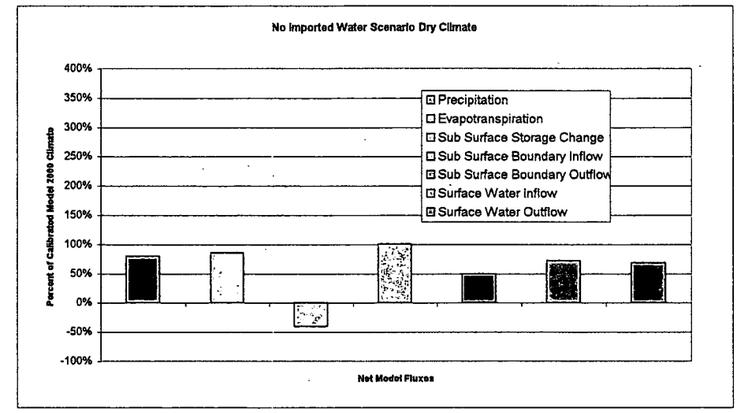


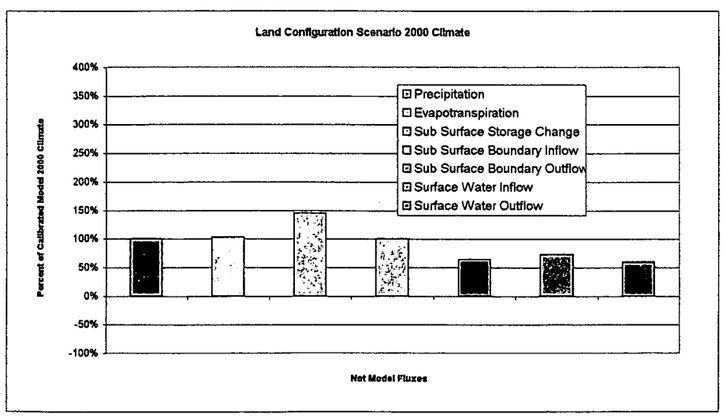


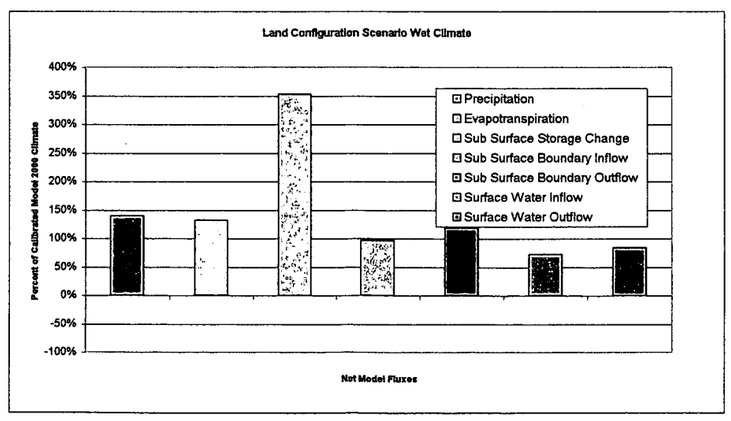


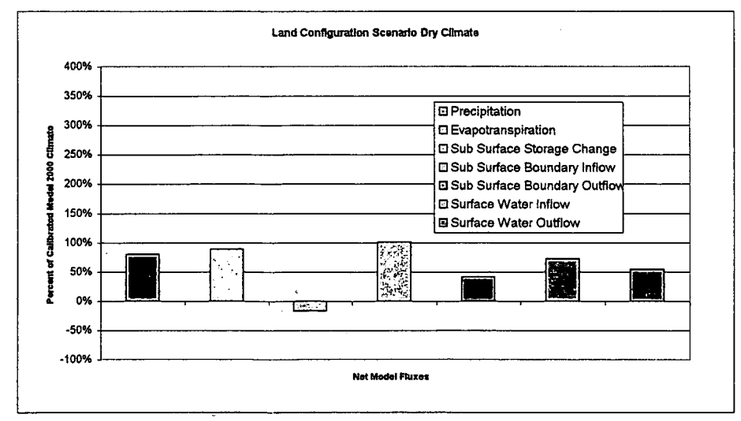












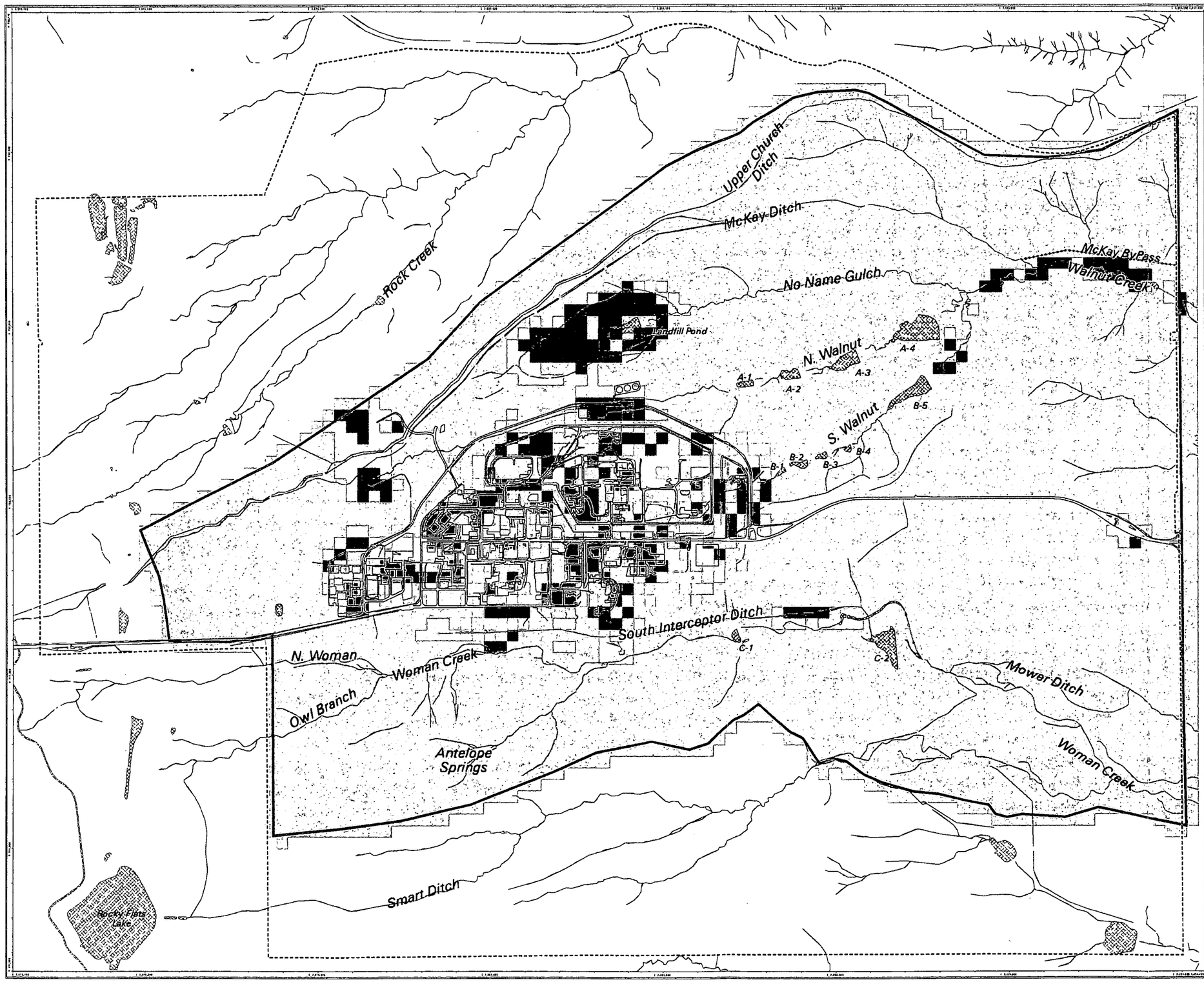


Figure 7-5

Site-Wide Water Balance Report

Distributed Change in Annual Groundwater Levels (Numerical Model Grid)

EXPLANATION

Mean Groundwater Elevation Difference (m)

- < -1
- -1 to -0.5
- -0.5 to -0.2
- -0.2 to 0.2
- 0.2 to 0.5
- 0.5 to 1
- 1 to 2
- 2 to 4
- > 4
- Outside of Model Boundary

Standard Map Features

- Lakes and ponds
- Streams, ditches, or other drainage features
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:

Positive difference denotes increase in groundwater levels.

Negative difference denotes decrease in groundwater levels.

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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Prepared for: KAISER-HILL

May 13, 2003

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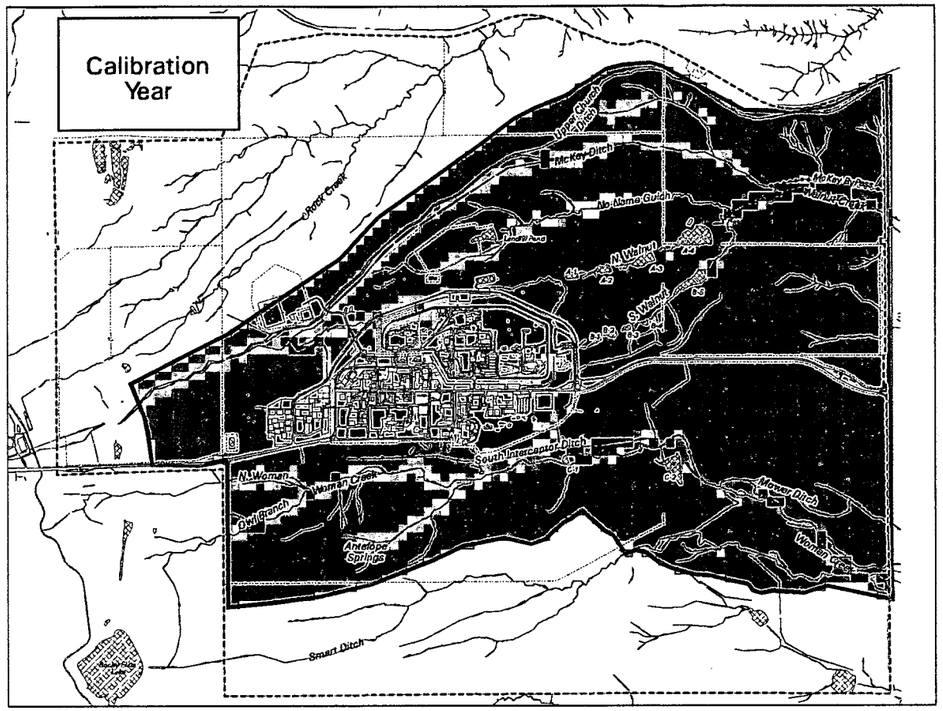
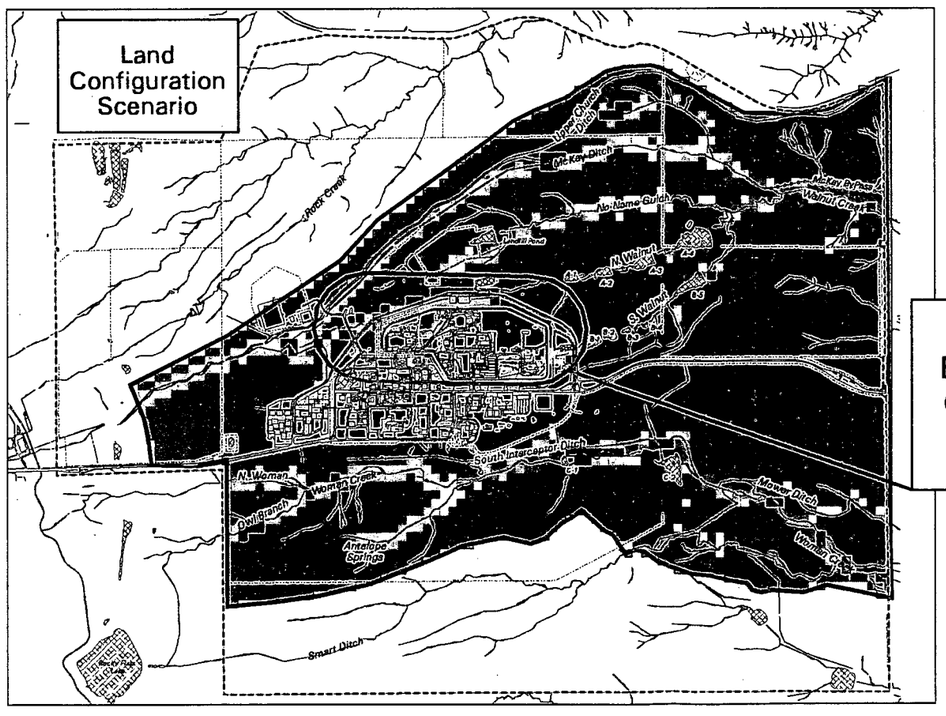
Figure 7-6 shows that annual baseflow occurred in the Industrial Area streams (GS10 and SW093) in the Land Configuration Scenario simulation, but not in the calibrated model. This figure illustrates that surface water within the reconfigured Industrial Area was impacted by groundwater within the Industrial Area. Actual discharge rates may be different than simulated by the Land Configuration Scenario model because stream leakance values were assumed equal to calibration values. It is important to note that land configuration changes may require different leakance values that will affect leakage. Also shown in Figure 7-6, the baseflow decreased slightly for the No Imported Water Scenario at GS10 and SW093. This small effect can be attributed to the removal of leaking water distribution pipes as part of the scenario.

Simulated groundwater discharges at the eastern model boundary are summarized on Figure 7-7. Boundary discharges for the near-stream Walnut Creek, Mower Ditch and Woman Creek and for the entire eastern boundary are included in the graph. Results show that groundwater discharge was reduced along Walnut Creek and the eastern boundary for each scenario, while flows at Mower Ditch were absent except for a small amount generated for the wet climate. The total groundwater discharged along the eastern boundary changed by nearly the same ratio (ratio of calibration year to wet, or dry year precipitation). This suggests that the Land Configuration Scenario changes affected eastern boundary discharges more than either climate regimes. The No Imported Water Scenario had much smaller effects of GW discharge.

To verify the conclusions made about scenario predictions (based on a two-year initialization period) the Land Configuration Scenario simulations were extended to ten years. The ten-year simulation was completed for both the WY2000 configuration and the Land Configuration Scenario, using the WY2000 climate. The Land Configuration Scenario was used because it represented more drastic configuration changes than the No Imported Water Scenario. Results showed that, although some individual model cell groundwater levels within the Industrial Area continued to adjust from their initial conditions, the predicted average levels increased only slightly in the years following the second year. At the end of the ten-year simulation, the average Industrial Area groundwater levels had increased only by a total of about 0.5 m (~1.6 ft) as compared to





Baseflow develops here

Figure 7-6

Site-Wide Water Balance Report

Simulated Change in Baseflow * (Numerical Model Grid)

EXPLANATION

Baseflow to Streams (m^3/yr)

- -5000 to -1000
- -1000 to -100
- -100 to -10
- -10 to 10
- 10 to 100
- 100 to 1000
- 1000 to 5000
- Outside of Model Boundary

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:

* 1. Positive = gaining stream
2. Negative = losing stream

To convert indicated flow rate to length per time, divide rate by model grid cell area (40,000 square ft).

200 0 400 800m

500 0 1000 2000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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Prepared for: KAISER-HILL COMPANY

May 31, 2002

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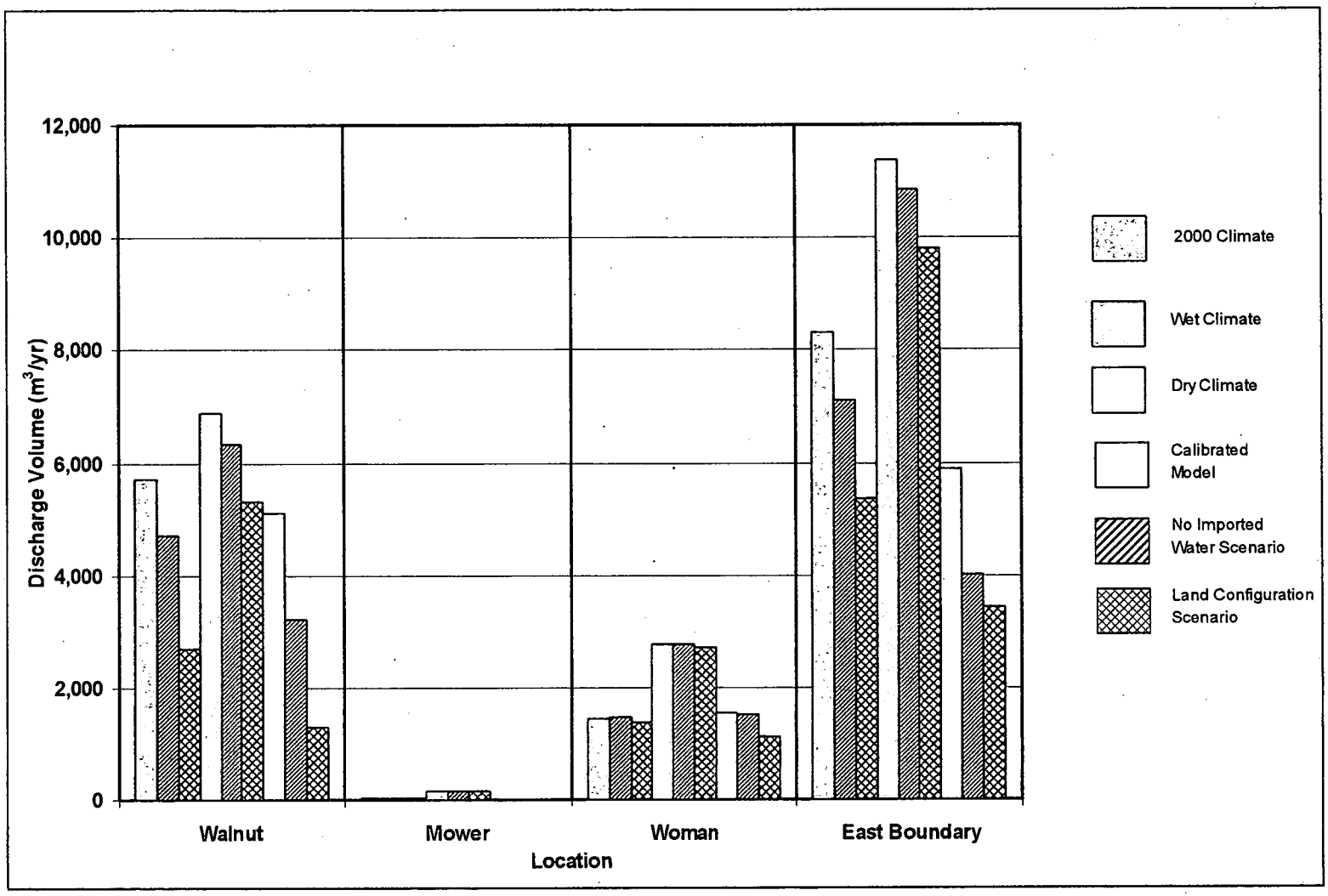
Figure 7-7. Simulated Eastern Model Boundary Groundwater Outflow



the two-year simulation levels. This observation suggests that conclusions drawn from the two-year simulation were appropriate for predicting general system response from scenarios.

7.2.2 Major SW Drainages

Model-predicted responses to scenarios for the major surface water drainages of Woman (GS01) and Walnut (GS03) Creeks are presented in this section. The simulated annual volume of surface water for each scenario climate condition is presented in Figure 7-8. Simulated volumes are presented for the major drainages of GS01 and GS03, as well as the major Industrial Area subdrainages of GS10, SW093 and SW027.

7.2.2.1 Woman and Walnut Creeks

The simulation results predicted little change in surface flow response at GS01 for the scenarios relative to the WY2000 Site configuration. The simulated annual hydrographs for the calibrated model, the No Imported Water Scenario, and the Land Configuration Scenario are presented in Figure 7-9 for the WY2000 climate.

This result was expected considering the GS01 drainage is primarily non-industrial. As shown in Figure 7-8, the scenarios did not predict significantly changes in annual GS01 discharge volumes during wet or dry climate periods.

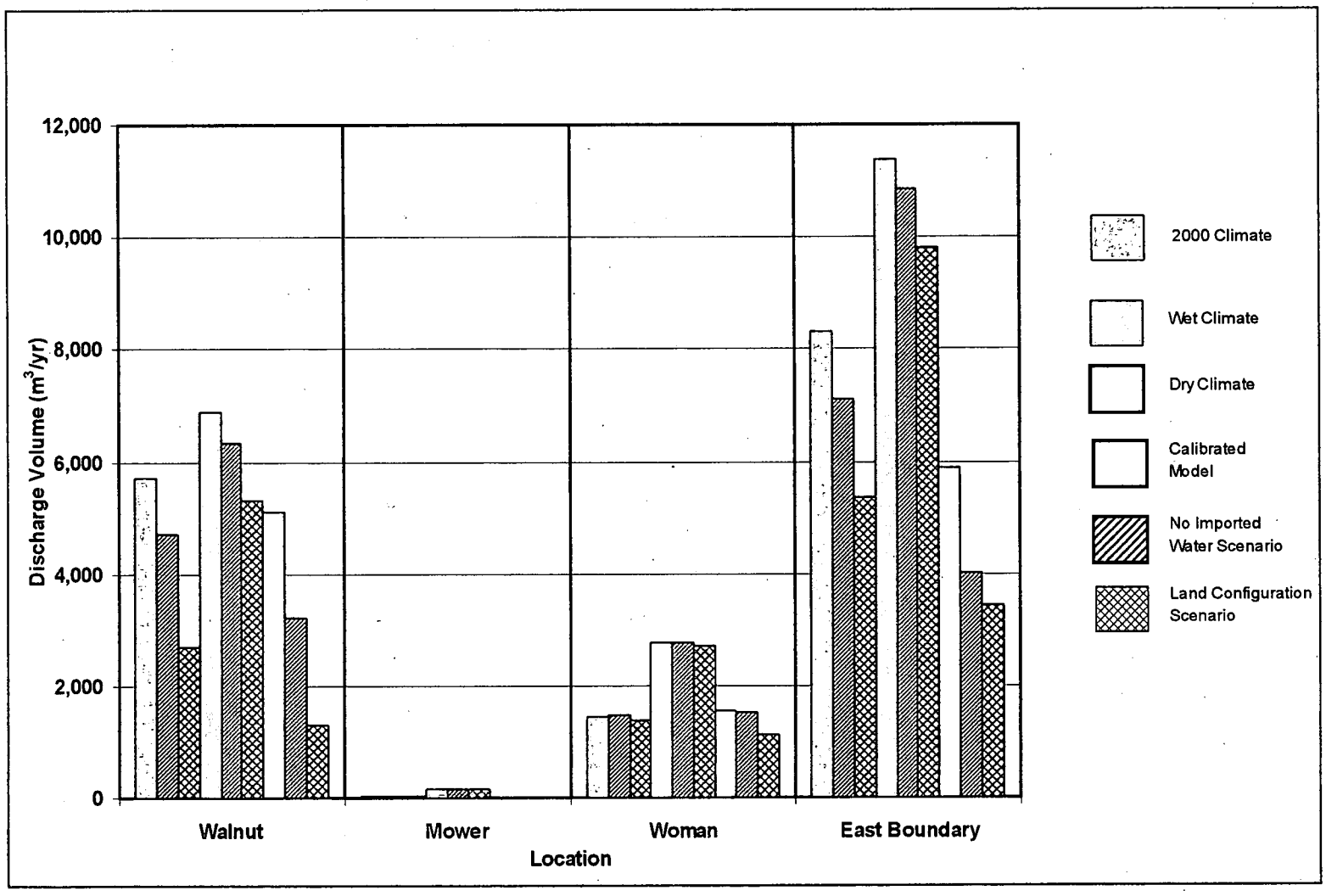
The only area within the Woman Creek drainage that was influenced by the scenarios was the SW027 subdrainage. As discussed previously, this subdrainage contains a small portion of the Industrial Area and drains to Pond C-2. (Pond C-2 did not meet the volume requirements for discharge to GS01 during any of the scenarios; however, the inflow to Pond C-2 from the SW027 drainage did vary with the scenarios and climates.)

Figure 7-6 shows that annual baseflow occurred in the Industrial Area streams (GS10 and SW093) in the Land Configuration Scenario simulation, but not in the calibrated model. This figure illustrates that surface water within the reconfigured Industrial Area was impacted by groundwater within the Industrial Area. Actual discharge rates may be different than simulated by the Land Configuration Scenario model because stream leakance values were assumed equal to calibration values. It is important to note that land configuration changes may require different leakance values that will affect leakage. Also shown in Figure 7-6, the baseflow decreased slightly for the No Imported Water Scenario at GS10 and SW093. This small effect can be attributed to the removal of leaking water distribution pipes as part of the scenario.

Simulated groundwater discharges at the eastern model boundary are summarized on Figure 7-7. Boundary discharges for the near-stream Walnut Creek, Mower Ditch and Woman Creek and for the entire eastern boundary are included in the graph. Results show that groundwater discharge was reduced along Walnut Creek and the eastern boundary for each scenario, while flows at Mower Ditch were absent except for a small amount generated for the wet climate. The total groundwater discharged along the eastern boundary changed by nearly the same ratio (ratio of calibration year to wet, or dry year precipitation). This suggests that the Land Configuration Scenario changes affected eastern boundary discharges more than either climate regimes. The No Imported Water Scenario had much smaller effects of GW discharge.

To verify the conclusions made about scenario predictions (based on a two-year initialization period) the Land Configuration Scenario simulations were extended to ten years. The ten-year simulation was completed for both the WY2000 configuration and the Land Configuration Scenario, using the WY2000 climate. The Land Configuration Scenario was used because it represented more drastic configuration changes than the No Imported Water Scenario. Results showed that, although some individual model cell groundwater levels within the Industrial Area continued to adjust from their initial conditions, the predicted average levels increased only slightly in the years following the second year. At the end of the ten-year simulation, the average Industrial Area groundwater levels had increased only by a total of about 0.5 m (~1.6 ft) as compared to

Figure 7-7. Simulated Eastern Model Boundary Groundwater Outflow



the two-year simulation levels. This observation suggests that conclusions drawn from the two-year simulation were appropriate for predicting general system response from scenarios.

7.2.2 Major SW Drainages

Model-predicted responses to scenarios for the major surface water drainages of Woman (GS01) and Walnut (GS03) Creeks are presented in this section. The simulated annual volume of surface water for each scenario climate condition is presented in Figure 7-8. Simulated volumes are presented for the major drainages of GS01 and GS03, as well as the major Industrial Area subdrainages of GS10, SW093 and SW027.

7.2.2.1 Woman and Walnut Creeks

The simulation results predicted little change in surface flow response at GS01 for the scenarios relative to the WY2000 Site configuration. The simulated annual hydrographs for the calibrated model, the No Imported Water Scenario, and the Land Configuration Scenario are presented in Figure 7-9 for the WY2000 climate.

This result was expected considering the GS01 drainage is primarily non-industrial. As shown in Figure 7-8, the scenarios did not predict significantly changes in annual GS01 discharge volumes during wet or dry climate periods.

The only area within the Woman Creek drainage that was influenced by the scenarios was the SW027 subdrainage. As discussed previously, this subdrainage contains a small portion of the Industrial Area and drains to Pond C-2. (Pond C-2 did not meet the volume requirements for discharge to GS01 during any of the scenarios; however, the inflow to Pond C-2 from the SW027 drainage did vary with the scenarios and climates.)

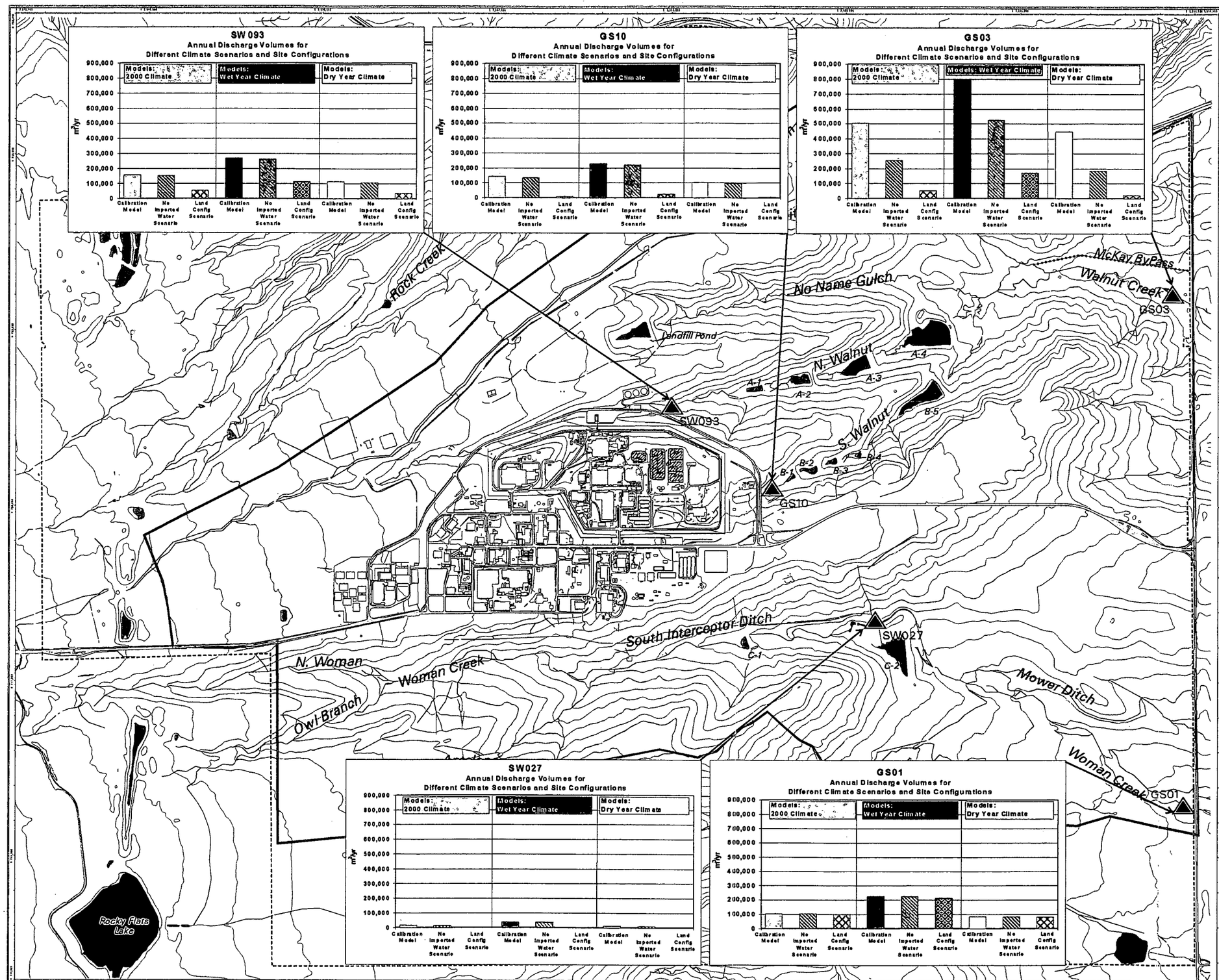


Figure 7-8

Site-Wide Water Balance Report

Simulated Surface Flow Volumes for Scenarios

EXPLANATION

- Gaging Station

Standard Map Features

- Buildings and other structures
- Paved roads fill
- Solar Evaporation Ponds (SEPs)
- Lakes and ponds
- Streams, ditches, or other drainage features
- Topographic Contour (20-Foot)
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95 Topographic contours were derived from digital elevation model (DEM) data by Morrison Knudson (MK) using ESRI Arc TIN and LATTICE to process the DEM data to create 5-foot contours. The DEM data was captured by the Remote Sensing Lab, Las Vegas, NV, 1994 Aerial Flyover at ~ 10 meter resolution. DEM post-processing performed by MK, Winter 1997.

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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May 15, 2003

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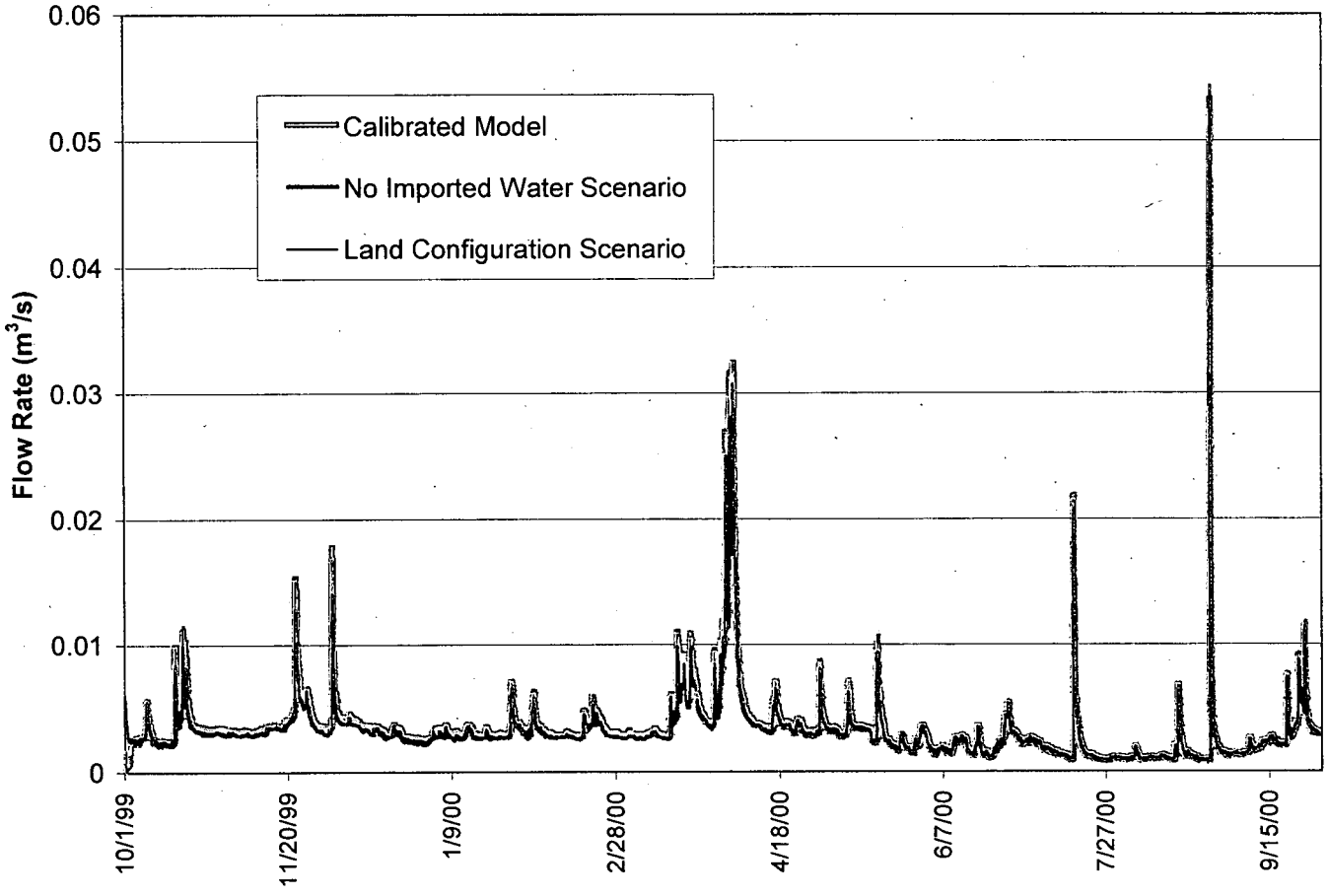
Figure 7-9. Simulated Annual GS01 Hydrographs for Scenarios (WY2000 Climate)



The predicted annual surface water flow volumes for SW027 were presented in Figure 7-10. The No Imported Water Scenario had little effect on the surface water flow volume at SW027. This is reasonable considering the routing of imported water through the system; imported water is ultimately discharged into the Walnut Creek drainage and does not route to Woman Creek. The only potential effect on the SW027 subdrainage for this scenario was from the removal of leaking distribution pipes in this small portion of the Industrial Area.

The Land Configuration Scenario predicted significant decreases in simulated surface water flow to SW027. In the conceptual and calibrated models, the primary sources of surface water flow to SW027 were drain flow and rapid runoff from paved areas. With paved surfaces removed and drain connections to surface water interrupted, these primary sources of flow were effectively removed. The result was a loss of sharp hydrograph peaks and a decrease in baseflow. This effect is shown in the detailed hydrographs of Figure 7-10.

The decrease in surface flows predicted at SW027 were not translated to decreases at GS01 because of detention by Pond C-2. Historically, however, flow measured at SW027 is less than 10 percent of the flow measured at GS01 (WY1996 through WY2001). Consequently, even if flow-through conditions were applied to Pond C-2, the net effect at GS01 would be small for both scenarios.

The simulated annual hydrographs for the calibrated model, the No Imported Water Scenario, and the Land Configuration Scenario are presented in Figure 7-11 for the WY2000 climate for Walnut Creek. As expected, pond discharge timing and frequency were affected by the change in inflows to the ponds. The decreasing number of pond discharges for both scenarios is apparent in the annual hydrographs (pond discharge numbers and volumes are discussed further in Section 7.2.3). To gain further insight into the predicted decrease in flow, consideration was given to the major industrial subdrainages in Walnut Creek, GS10 and SW093. Annual volume summaries for these gages are presented in Figure 7-8. Hydrograph details, presented in Figure 7-12 and Figure 7-13 depict a small, uniform decrease in baseflow.

Figure 7-10. Detail of Simulated Hydrograph Response for Scenarios at SW027 (WY2000 Climate)

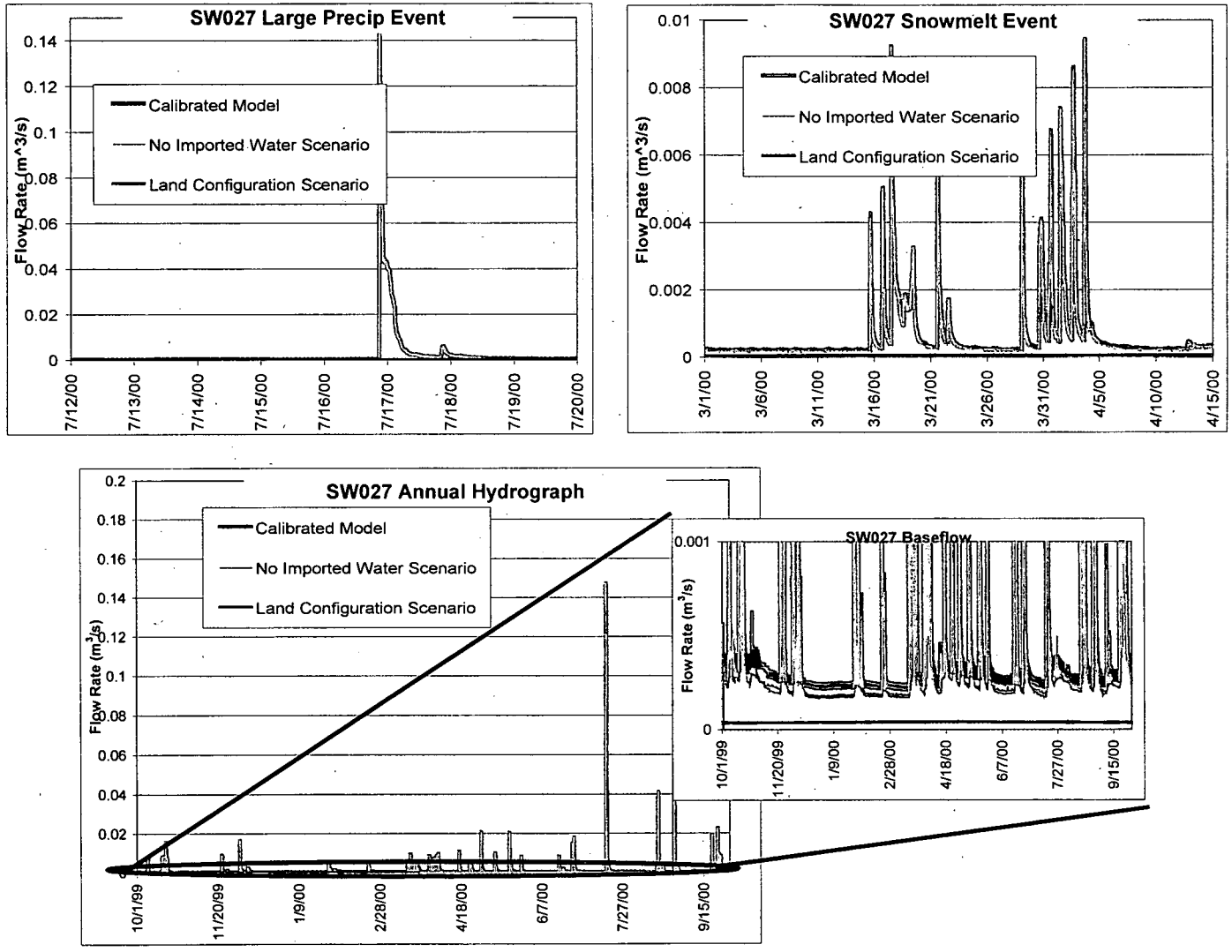


Figure 7-11. Simulated Annual GS03 Hydrographs for Scenarios (WY2000 Climate)

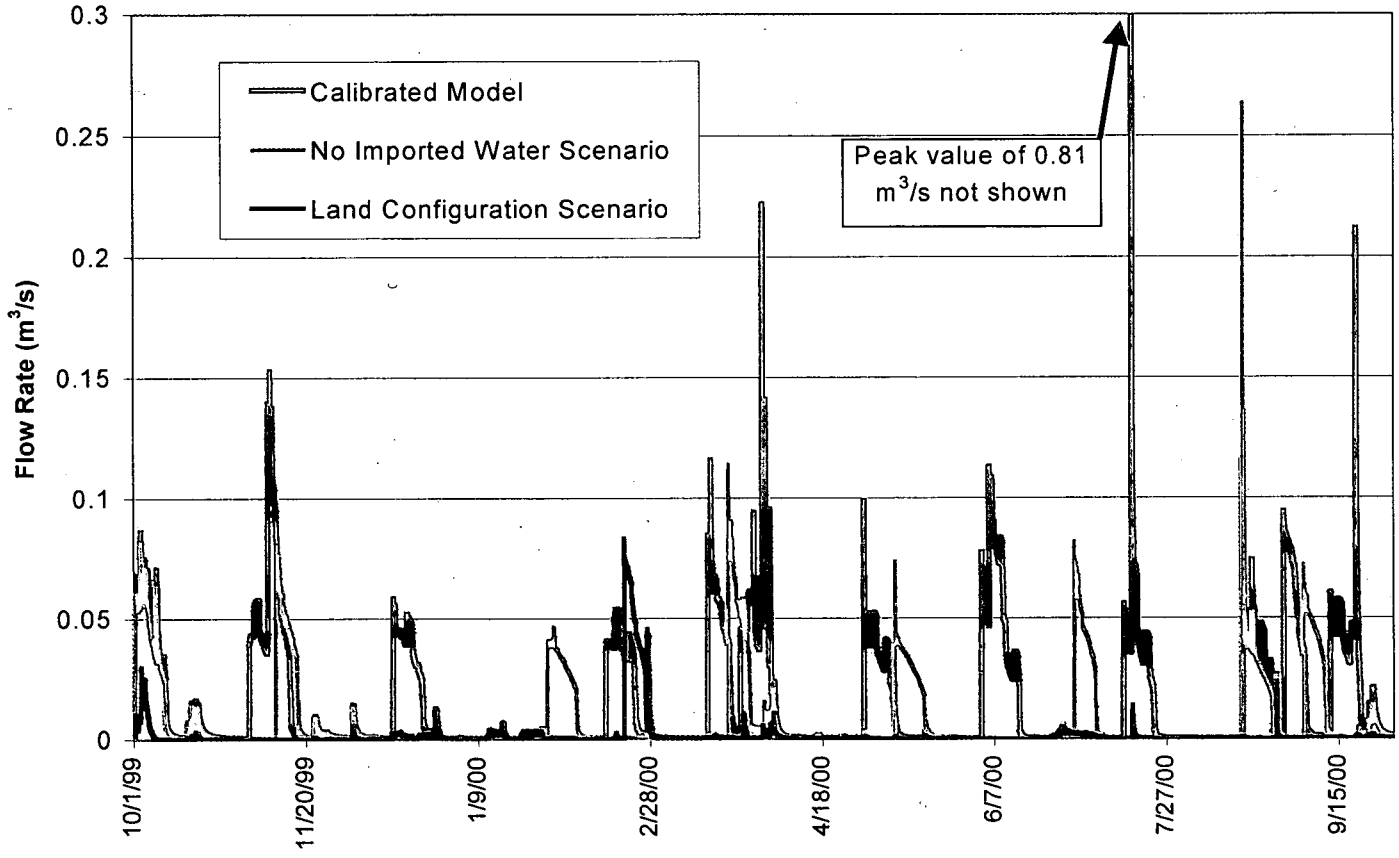


Figure 7-12. Detail of Simulated Hydrograph Response for Scenarios at GS10 (WY2000 Climate)

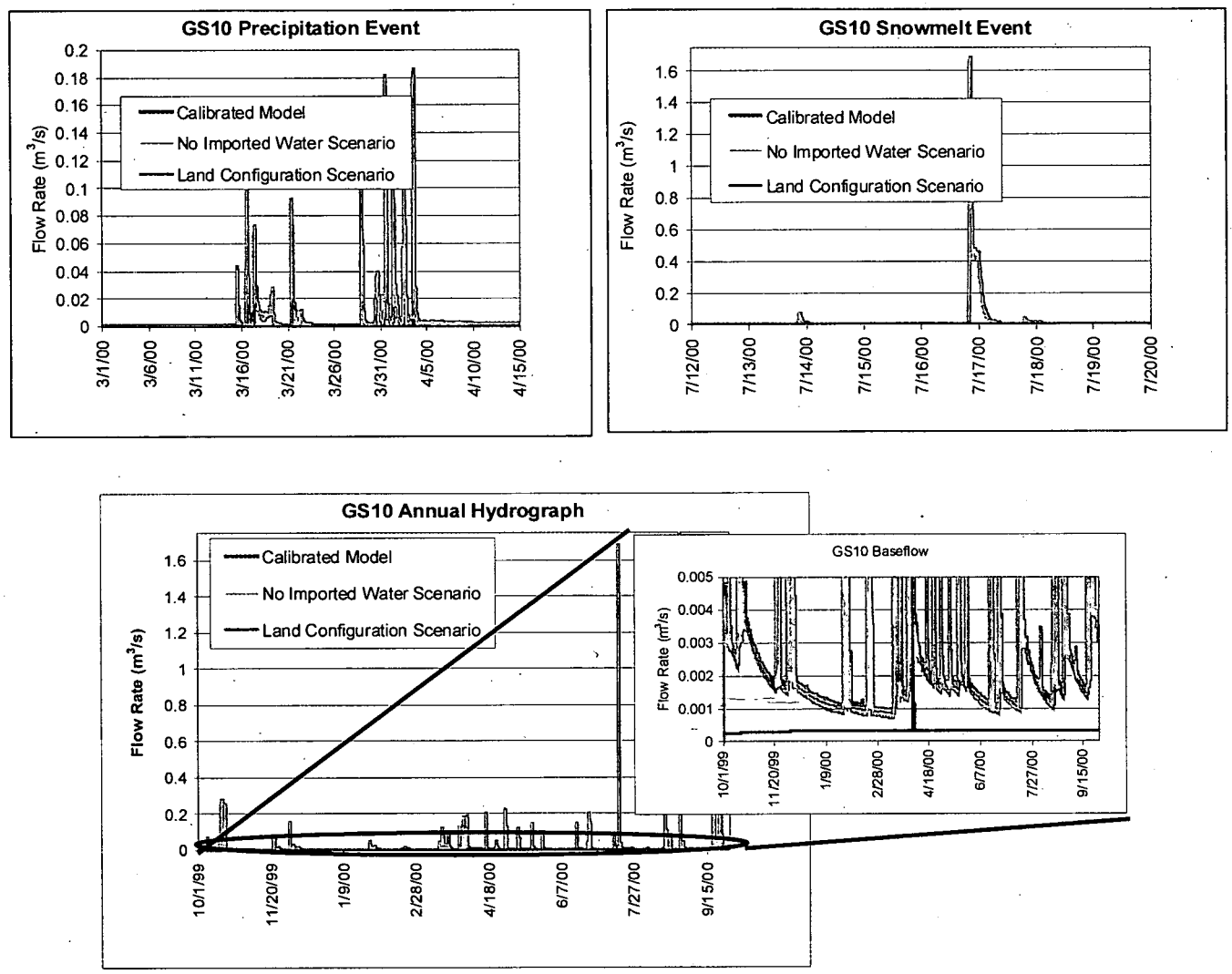
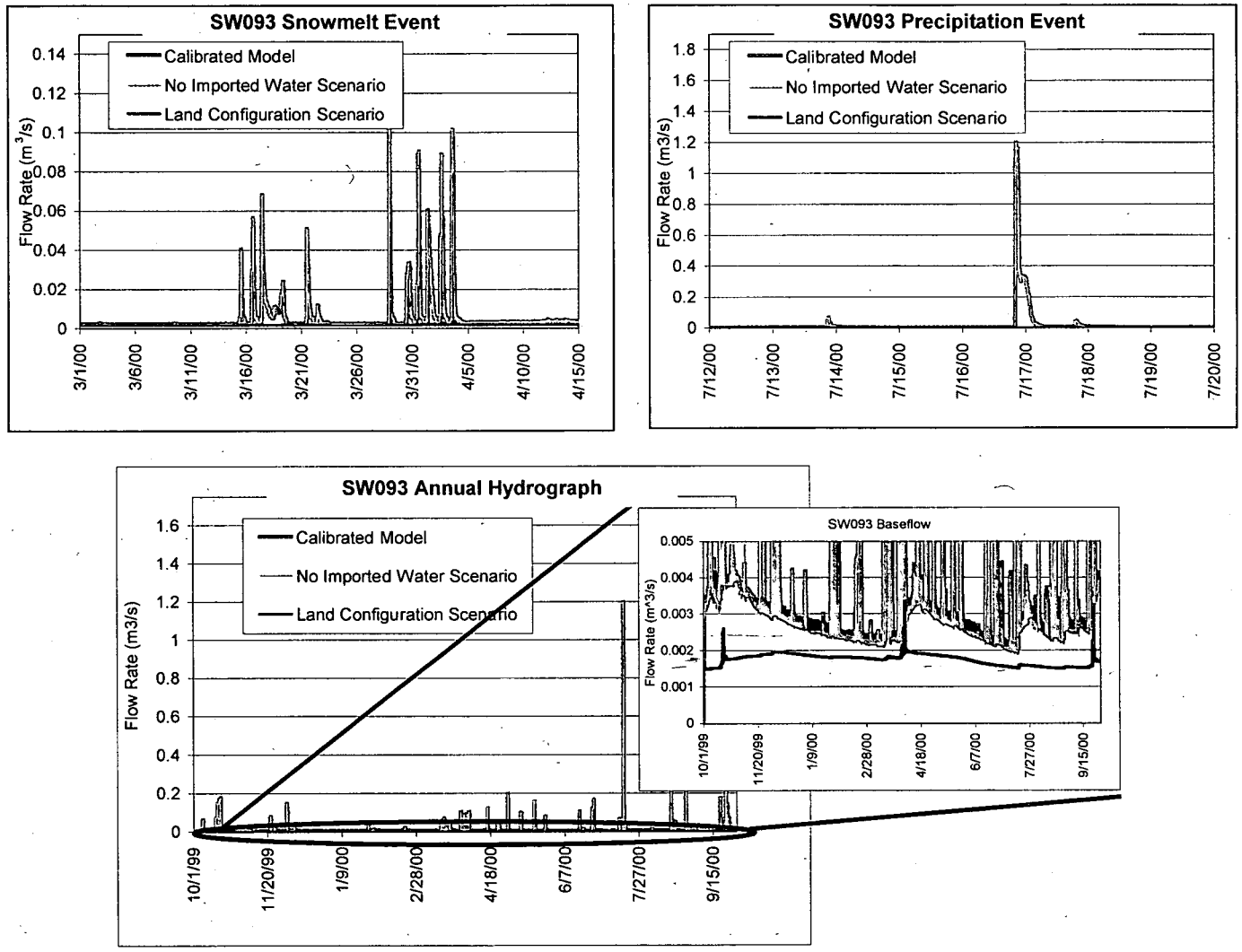


Figure 7-13. Detail of Simulated Hydrograph Response for Scenarios at SW093 (WY2000 Climate)



It should be noted that the drainage areas of the major subdrainages in the Industrial Area changed slightly with the regrading for the Land Configuration Scenario. This change in area was minor and is not expected to effect the conclusions based on comparisons of results.

For the No Imported Water Scenario, only a small (about 5 percent) annual decrease in flow was predicted at GS10 and SW093 (as shown in Figure 7-8). This is reasonable considering the routing of imported water through the system; treated domestic water is currently routed around the GS10 gage and discharged to Pond B-3. The only effect on the flow at GS10 and SW093 occurred as a result of the removal of leaking distribution pipes. The effect is apparent in Figure 7-10 and Figure 7-12.

More significant effects were predicted at GS10 and SW093 for the Land Configuration Scenario as compared to the No Imported Water Scenario. (Reminder: both scenarios include discontinuing imported water from the DWB). As shown in Figure 7-8, a 90 percent decrease in annual flow was predicted for GS10, and a 65 percent decrease in annual flow was predicted for SW093. Both gages showed a loss of the rapid runoff portion of the hydrograph (as shown in Figure 7-13). This was attributed to the removal of impervious surfaces, creating a system more similar to the Buffer Zone.

Additionally, a decrease in baseflow was predicted for both gages, due to the removal of the drain flow contribution. As shown in Figure 7-13, the Land Configuration Scenario model predicted roughly six times more baseflow at SW093 (0.0017 m^3/s or 0.06 cfs) than at GS10 (0.0003 m^3/s or 0.01 cfs). This result is reasonable considering the upstream sources of baseflow to SW093 which were not modified for the Land Configuration Scenario (e.g., North Walnut Creek, west of the Industrial Area).

7.2.3 Ponds

The simulated effects of the scenarios on the Site ponds are summarized in this section. Discharges/transfers (count and volume) and evaporative losses are discussed. These effects result primarily from the predicted decrease in inflow (described in the previous section).

As discussed in Section 7.1.1.1, the ponds were operated in the scenarios with the same transfer and discharge protocols applied to the current configuration using the pond algorithm. Alternative operating procedures may be applied to the model in the future. Varying the protocols would be expected to produce different results in terms of discharge frequency, average pond levels and evaporative losses. In short, it is important to note that these results represent only one alternative of operating protocols for the ponds.

7.2.3.1 Discharges/Transfers

The predicted effects of scenarios on pond discharge volumes are summarized in Figure 7-14. Predicted discharge volumes correspond directly to predicted inflow volumes. No discharges were predicted at the Landfill Pond or Pond C-2 for any of the scenarios or climates due to low inflows. Therefore, the discussion of discharges focuses on the A- and B- series ponds.

For the No Imported Water Scenario, only Ponds B-3, B-4 and B-5 were significantly impacted. With a less than 5 percent decrease in flow predicted at the inflow points to the pond series for this first scenario, the primary effect came from discontinuing WWTP discharge to Pond B-3. This effect is observed in the predicted reduction of discharge numbers and volumes for Pond B-5. As shown in Figure 7-14, the annual Pond B-5 discharge volume decreased by 70 percent for this scenario (for the WY2000 climate), with 5 fewer predicted discharges. This effect was slightly less for the wet year (55 percent decrease) and slightly more for a dry year (75 percent decrease).

For the Land Configuration Scenario, the large predicted decrease in flow from the Industrial Area to the ponds was reflected in the decrease in discharge volume and frequency for the A- and B-series ponds (see Figure 7-14). For the terminal pond in the A- series (Pond A-4), a discharge volume reduction of 75 percent was predicted for the WY2000 climate simulation (as compared to the current configuration simulation). The effect was less for the wet year (55 percent decrease) and more for the dry year (100 percent decrease).

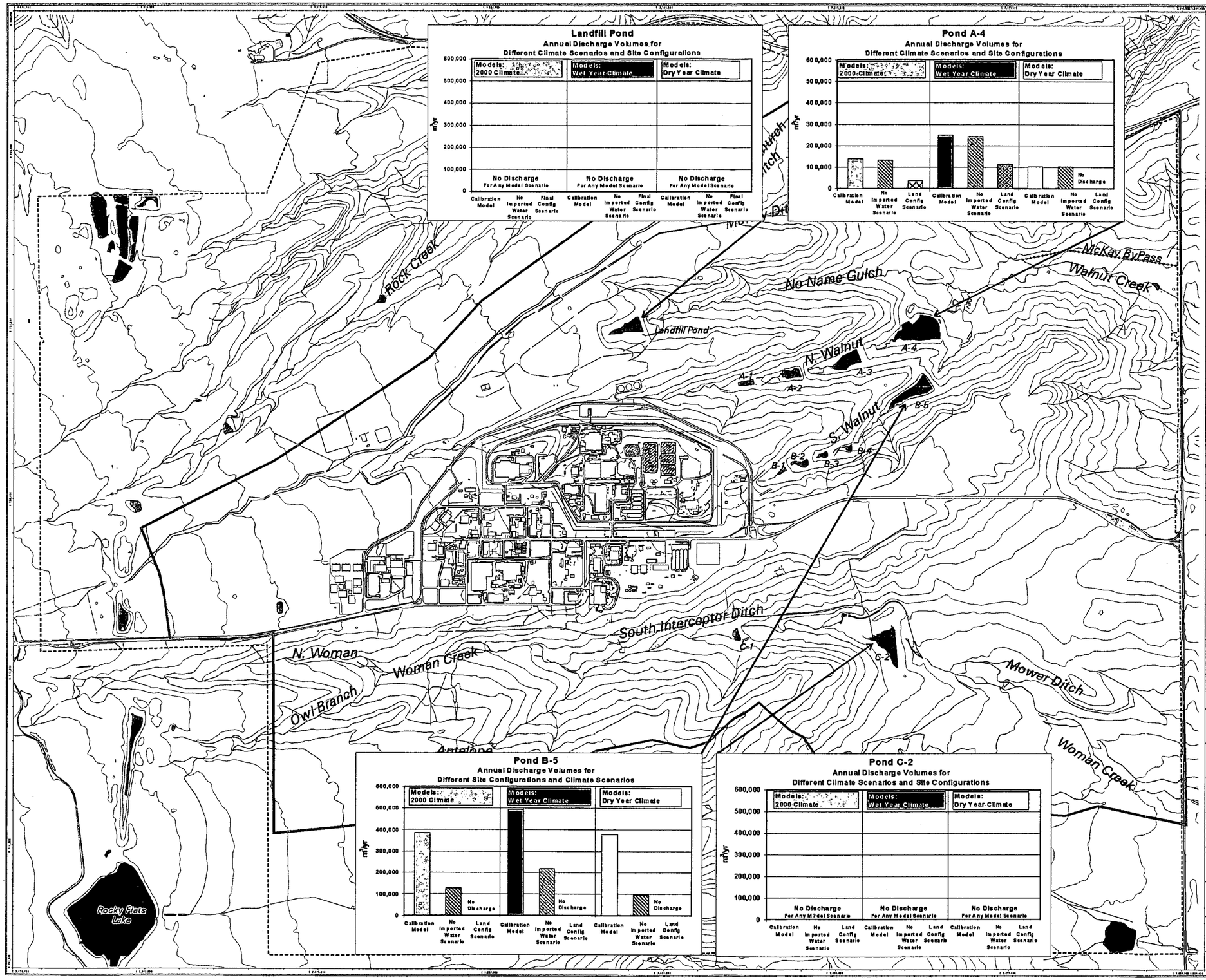


Figure 7-14

Site-Wide Water Balance Report

Simulated Pond Discharges for Scenarios

EXPLANATION

Standard Map Features

- Buildings and other structures
- Paved roads fill
- Solar Evaporation Ponds (SEPs)
- Lakes and ponds
- Streams, ditches, or other drainage features
- Topographic Contour (20-Foot)
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95 Topographic contours were derived from digital elevation model (DEM) data by Morrison Knudson (MK) using ESRI Arc TIN and LATTICE to process the DEM data to create 5-foot contours. The DEM data was captured by the Remote Sensing Lab, Las Vegas, NV, 1994 Aerial Flyover at ~ 10 meter resolution. DEM post-processing performed by MK, Winter 1997.

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May 15, 2002

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For the terminal pond in the B- series (Pond B-5), discharges were not simulated for any of the climate conditions of the Land Configuration Scenario, in response to the sharp decrease in inflows from GS10 and the WWTP.

In summary, the number and volume of discharges to the Site boundary at Walnut Creek were predicted to decrease for each scenario. This estimated decrease is summarized in Table 7-2 for the WY2000 climate.

No discharges were simulated for the Landfill Pond for any of the scenarios either; however, no effects were expected. The Landfill Pond was removed for the Land Configuration Scenario, and no changes were made to affect the Landfill Pond for the No Imported Water Scenario.

Table 7-2. Summary of Predicted Annual Pond Discharge to the Site Boundary

Scenario	Number of Pond A-4 Discharges	Number of Pond B-5 Discharges	Discharge Volume (m^3/year)
Current (WY2000) Configuration	4	9.5*	520,000
No Imported Water Scenario	4	3.5*	260,000
Land Configuration Scenario	1	0	36,000

*Discharges not completed by the end of the simulation period were assigned as half discharges (0.5).

Note: The effect of reduced inflows to Pond C-2 was not apparent when considering discharges because pond-level requirements for discharge were not met in any of the scenarios/climates. The difference in simulated annual pond levels (discussed in the following section), however, does show the effect of the decrease in inflow predicted for SW027.

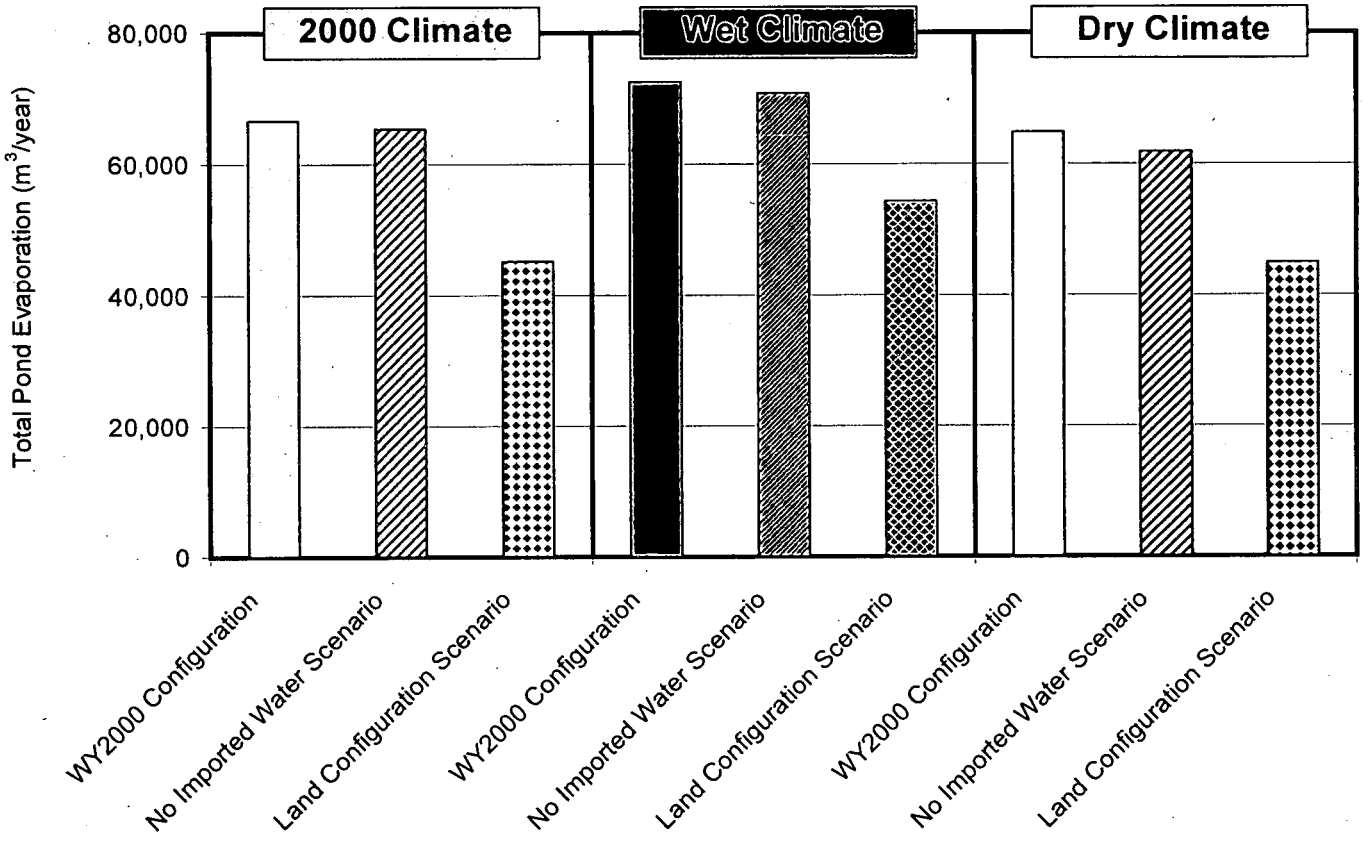
7.2.3.2 Evaporative Losses

Changes in inflow volumes to the ponds affect the average pond levels, which, in turn, affect the evaporative losses from the ponds. Evaporative losses from man-made ponds are a concern because they represent depletions of water to downstream users. Predicted evaporative losses from the ponds are presented in Figure 7-15 for all scenarios and climates.

As shown in Figure 7-15, only a slight decrease in evaporative losses is predicted from the No Imported Water Scenario (less than 5 percent decrease for all climates). This change reflected the lower average pond levels in Pond B-3 (receiving pond for imported water discharged from WWTP) and Pond C-2. The annual average level in Pond B-3 (a small pond) dropped 0.7 m (~2.3 ft), while the annual average pond level in Pond C-2 (a large pond) dropped 0.1 m (~0.3 ft). The annual average levels in all other ponds remained roughly unchanged.

For the Land Configuration Scenario, a roughly 30 percent decrease in total evaporative losses was predicted for all climate conditions; this change was largely attributable to the predicted decrease in annual average pond level for Ponds C-2 and B-5. For the ponds where enough inflow was predicted to allow for discharges, the operating protocols maintained the average water levels. For Ponds C-2 and B-5, however, the operating protocols could not maintain the annual average level because there was not enough inflow to provide a discharge. As a result, the average levels dropped roughly 1.5 m (~4.9 ft) each (as compared to the current configuration simulation). Decreases in average pond levels were also predicted for Ponds A-1, A-2, B-1, B-2 and B-3; however, the effect on the total evaporation was small for these smaller ponds.

Figure 7-15. Simulated Annual Evaporative Losses from Site Ponds



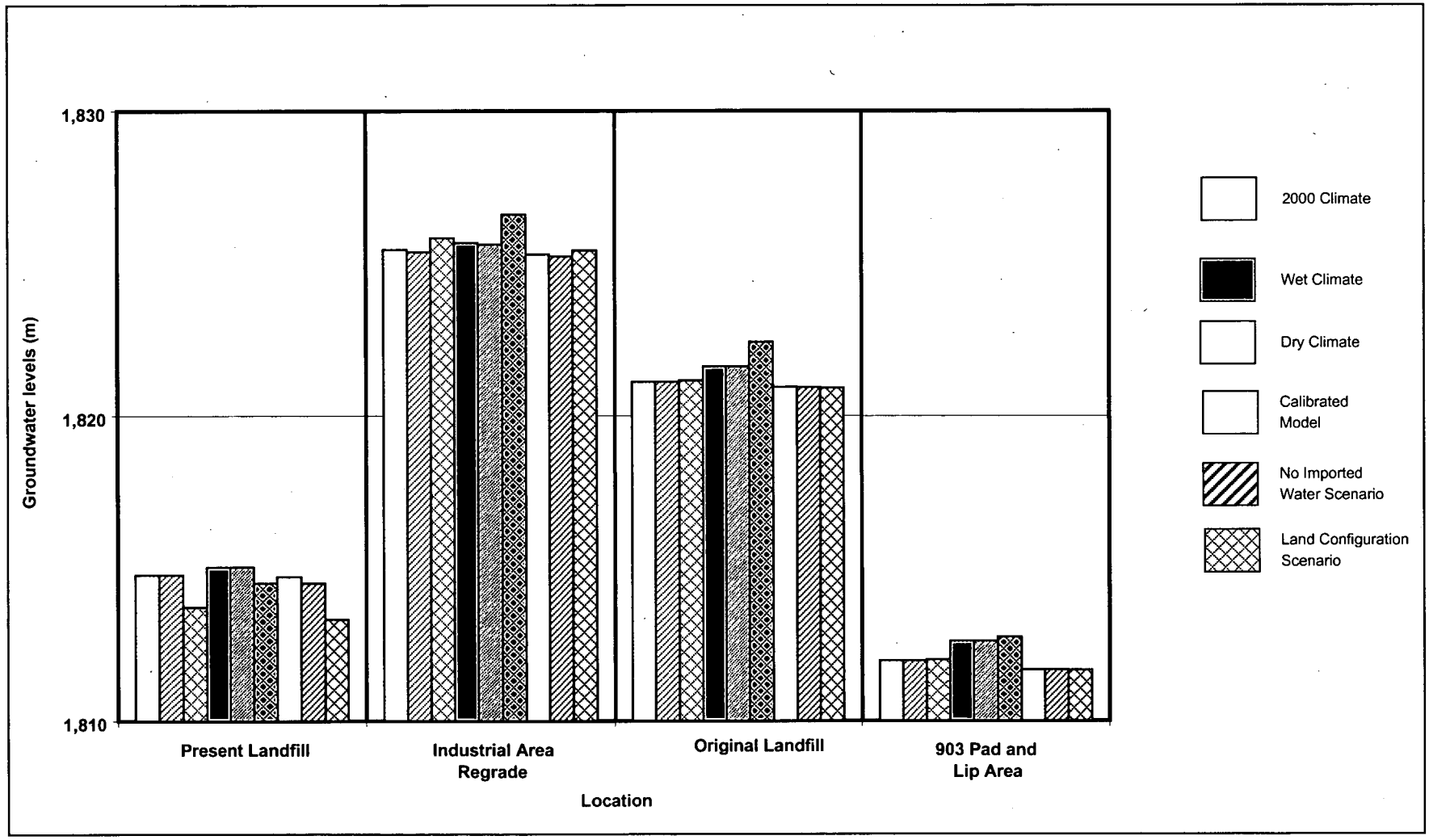
For information on evaporation rates, see Section 5.1.2.2.2.3 and Appendix B.

7.2.4 Contamination Focus Areas

Average annual predicted groundwater levels in four key areas where contaminants are present and of interest are summarized on Figure 7-16. These include: (1) the Present Landfill; (2) the Original Landfill; (3) the regraded Industrial Area; and (4) the 903 Pad/Lip area. Within the regraded Industrial Area, average annual groundwater levels increased for the Land Configuration Scenario relative to the calibrated model for each climate condition by about 0.13 m (~0.4 ft) to nearly 1 m (~3.3 ft) (dry and wet years, respectively). The dry and wet year climates only changed the average Industrial Area levels slightly. The No Imported Water Scenario resulted in a slight decrease in levels in response to removing leaking water supply pipes. Groundwater levels in the Original Landfill area and 903-Pad area both responded similarly to the Industrial Area for the Land Configuration Scenario. In the Present Landfill, however, average groundwater levels decreased. Levels decrease mostly in response to the lack of recharge simulated by the ET cover. The Original Landfill groundwater levels increased only slightly for the dry and calibration year climate, and more notably for the wet year climate.

Although, a hypothetical slurry (cuttoff) wall was placed upgradient of the Original Landfill, levels still increased, mostly in response to the increase in Industrial Area groundwater levels and no vertical flow barrier between the weathered bedrock. No significant changes were simulated for the No Imported Water Scenario in the landfills and 903 pad area.

Figure 7-16. Mean Groundwater Level Changes – Contamination Focus Areas



7.2.5 In-Situ Water Collection Systems

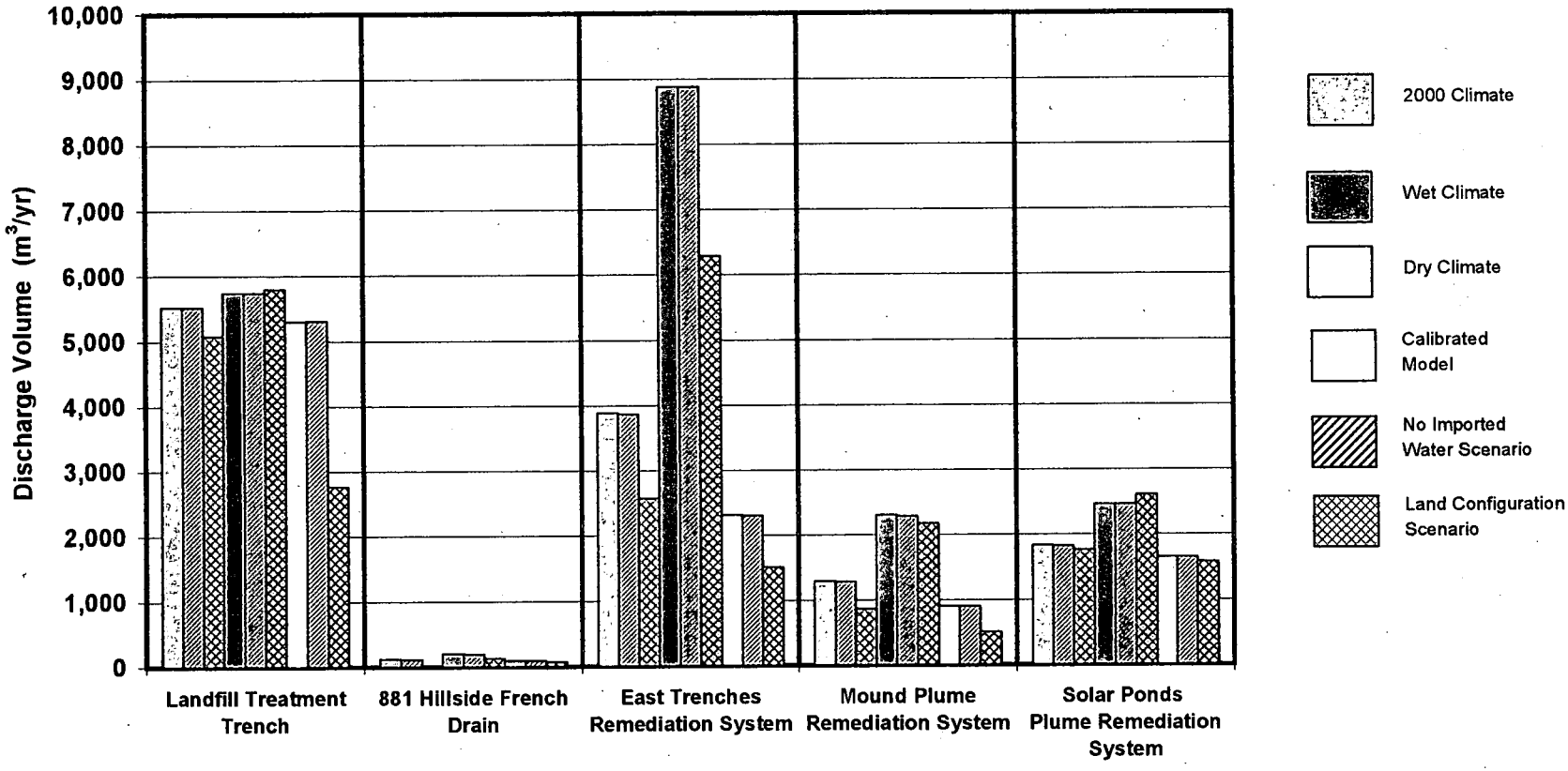
Simulated annual cumulative groundwater discharge from *in-situ* groundwater collection systems for scenarios are summarized on Figure 7-17. The Land Configuration Scenario decreased groundwater discharge from about 10 percent to 30 percent for the calibration and dry year climate conditions, except the 881-Hillside system. This was despite the average increase in groundwater levels in the regraded Industrial Area. Discharge from the 881-Hillside system, for the calibration year climate, dropped to zero. The Landfill Interception and Solar Pond Systems actually discharged slightly more water for the wet year (less than 5 percent). Discontinuing the imported water resulted in negligible changes to the remediation systems, suggesting that the other configuration changes had a greater impact on *in-situ* groundwater collection systems. Wet and dry climates affected discharge from the East Trenches and Mound systems more than other systems, for each simulation (about a 50 percent increase in discharge). This is probably due to their sensitivity to local saturated zone hydraulic properties.

7.2.6 Vegetation/Habitats

Scenario results were also assessed in the habitat focus areas. The vegetation/habitat areas (as shown in Figure 1-2) were defined as the combined area of riparian habitat and wetlands in the Walnut and Woman Creek drainages. These areas primarily trace the stream channels. Water availability in these areas is discussed in this section in terms of predicted annual changes in groundwater levels, frequency of channel flow and predicted changes in the saturated zone contribution to channel flow.

Reduced water availability is predicted in the Walnut Creek vegetation/habitat area for both scenarios. For the No Imported Water Scenario, average annual groundwater levels were predicted to decrease in the Walnut Creek vegetation/habitat area by about 0.2 m (~0.7 ft) in the reach between the terminal ponds and the east boundary. For the same reach, the model simulated a decrease in groundwater levels of 0.33 m (~1.1 ft) for the Land Configuration Scenario.

Figure 7-17. In-Situ Water Collection and Treatment Systems, Annual Simulated Response



This predicted decrease in groundwater levels was attributed to the decrease in discharge volumes and frequency from the terminal ponds to this reach, and the corresponding decrease in leakage of water from the channel to the saturated zone. Specifically, the model predicted an annual decrease in leakance from the Walnut Creek channel (in the vegetation/habitat area) to the saturated zone of 9,400 m^3 (330,000 cf) for the No Imported Water Scenario and 29,400 m^3 (1,040,000 cf) for the Land Configuration Scenario.

Model results for the vegetation/habitat area of Woman Creek did not indicate significant hydrologic changes in either scenario. Neither the predicted groundwater levels nor the saturated zone–channel interaction changed significantly, which is reasonable considering the related prediction of no significant change to surface flow in this drainage. The area south of the Original Landfill may experience localized diminished flow because of hypothetical covers and slurry walls. A more detailed analysis of this area could be performed when more design information is available.

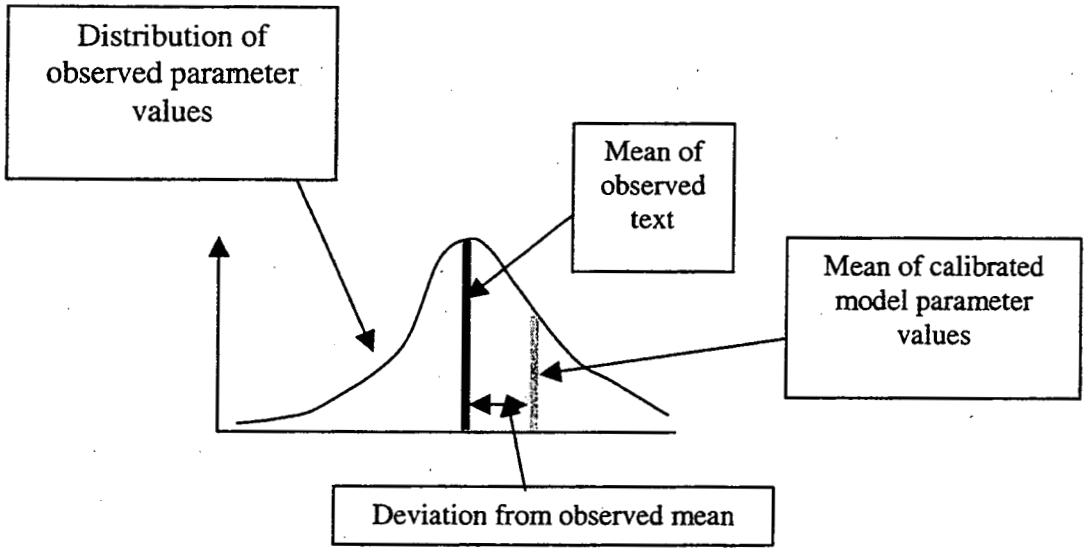
7.3 UNCERTAINTY ANALYSIS

The primary purpose of simulating the scenarios was to predict hydrologic responses that result from hypothetical land configuration changes (focusing on key decision areas). The objective of the uncertainty analysis was to determine the uncertainty of these model predictions given uncertainties in different model input. This was done by performing a simplified Monte-Carlo type uncertainty analysis (Melching, 1995) using the Land Configuration Scenario model.

When parameters are changed to conduct the uncertainty analysis, the model produces hydrologic responses that are not considered calibrated. Although, the output from these runs did not reproduce some observed response well, the results were only used to indicate a possible range of uncertainty in predicted response.

The approach used to conduct the uncertainty analysis and modeling results is presented in Appendix F and uncertainty range determination in Figure 7-18. Results are briefly summarized below.

Figure 7-18. Determination of Uncertainty Range



7.3.1 Results

Results of the analysis showed that the Land Configuration Scenario model predictions exhibit moderate levels of uncertainty. Predicted annual surface flows at the eastern boundary (GS03 and GS01) ranged from 80 percent to 120 percent. The range of predicted flows from the Industrial Area (SW093, GS10 and SW027) were variable. Flows at SW093 and GS10 are similar and range from 88 percent to 112 percent, while flows at SW027 range from 0 percent to 564 percent indicating that flow in the SID is strongly affected by specific model parameters. The flow rates and total discharge at SW027 is very low, which implies that small absolute changes entail large percent wise changes.

Other system responses changed less. Annual pond discharge at Ponds A-4 and B-5 did not change. Uncertainty in average annual pond levels, changed only slightly (less than 0.21 m [0.69 ft]). Predicted mean annual groundwater levels in locations like the vegetation/habitat or Industrial Area focus areas suggest that levels are reliable (changes less than 0.06 m [0.20 ft]). Of the water balance components for the Site, ET showed the greatest degree of uncertainty. However, this does not impact Site flows significantly

because the effects of model under-estimated ET rates are countered by increased groundwater storage in the subsurface.

7.4 SECTION 7 SUMMARY

Two hypothetical Site configuration scenarios were simulated as preliminary application of the model. The first scenario (the No Imported Water Scenario) simulated the effects of discontinuing imported water from the DWB. The second scenario (the Land Configuration Scenario) simulated the effects of modifications to the Present Landfill, the Original Landfill and the regraded Industrial Area, including removal of pavement, buildings, subsurface utilities and imported water. In addition, wet and dry year climates were simulated for both scenarios and the current configuration.

All simulations were performed with a two-year simulation. A ten-year simulation was also performed for the Land Configuration Scenario and the WY2000 configuration to confirm that two-year simulations were adequate for predicting most system long-term responses. Surface flow predictions remained largely constant for the runs extended for 10 years. The 10th-year results were compared to the second year results. Variations were observed in predicted annual volumes below the terminal ponds, depending on the discharge cycle timing; however, simulated inflow volumes to the ponds varied only slightly. Consequently, the model was considered adequately stable during the second year simulation to predicted trends in surface flow response.

Results of the scenario simulations were summarized regionally and by focus areas. Regionally, most changes to the system hydrology occur within the regraded Industrial Area, the two modified landfill areas, and the Walnut Creek drainage area east of these areas. Woman Creek was largely unaffected by changes made in the scenarios.

Along the eastern model boundary, simulated results showed that both streamflow and groundwater flow decreased for the Land Configuration Scenario, even when wet and dry annual climate conditions were considered. Specifically, flow across the eastern boundary decreased by 90 percent (for the WY2000 climate) within the Walnut Creek drainage basin as a result of discontinuing imported water discharge and eliminating fast

runoff generated in the Industrial Area. The No Imported Water Scenario caused a decreased in surface and groundwater discharge along the eastern boundary for Walnut Creek, though the fast runoff component from the Industrial Area was still present.

The effect of discontinuing the imported water was pronounced for the B-series ponds, due to routing of imported water. Specifically, the number of discharges decreased from 9.5 to 3.5, corresponding to a 50 percent decrease in discharge volume from Pond B-5 (for the WY2000 climate). The A-series ponds were largely unaffected.

Surface water from the three major subdrainages of the Industrial Area decreased significantly in the Land Configuration Scenario simulation, largely due to removal of the impervious surfaces. Based on this reduced inflow, pond discharges also decreased in both number and volume in the Land Configuration Scenario. Specifically, the terminal pond discharges decreased from 13.5 discharges per year to 1 discharge per year for the Land Configuration Scenario (given the WY2000 climate). This corresponded to a 75 percent decrease in discharge volume for Pond A-4 and 100 percent decrease for Pond B-5 (no discharges were predicted for any of the scenarios for Pond C-2, though inflow volumes to C-2 decreased for the Land Configuration Scenario).

Groundwater levels changed in the Land Configuration Scenario primarily in the three modified areas, and in the Walnut Creek drainage area downstream of the ponds. Flow directions did not change regionally, because these are controlled mainly by the ground surface topography and bedrock surfaces.

Average annual groundwater levels in the contaminant focus areas generally increased for the Land Configuration Scenario. Within the Industrial Area, average annual levels increased from about 0.13 to 1 m (0.43 to 3.28 ft). At a local scale, levels increased in response to increased recharge in former impervious areas and due to deactivation of subsurface drains. Groundwater levels decreased in response to removal of leaking water supply lines. Within these local areas, groundwater flow directions adjusted to reflect these groundwater level changes, but drainage basin-scale changes in flow direction were minimal.

Finally, a simplified Monte-Carlo type uncertainty analysis was conducted on the Land Configuration Scenario model to show an approximate range of uncertainty in model prediction given a range of uncertainty for key model parameter values. This analysis showed that the more sensitive model parameters produce significant uncertainty in model response. This level of predictive uncertainty must be considered in the context of assumptions used in the analysis, where an assumed uncertainty range of input parameter values was specified in the model to produce a response. Based on the uncertainty analysis, simulated responses are considered realistic, but the results should be interpreted considering the estimated ranges of output uncertainty.

8.0 CONCLUSIONS AND IMPLICATIONS TO SITE CLOSURE

8.1 SUMMARY

8.1.1 Background and Objective

Anticipated Site closure activities will involve reconfiguring portions of the existing Site. These changes may impact the current surface and subsurface hydrology. A comprehensive approach, incorporating mechanisms that govern the RFETS hydrology, was required to understand and predict the potential hydrologic changes caused by anticipated closure activities. The hydrologic system is strongly influenced by surface-groundwater interactions due to the Site's semi-arid climate. The hydrologic system is complicated by man-made modifications within the Industrial Area that impact both surface and subsurface flows.

The objective of the SWWB study was to create a hydrologic modeling management tool to quantitatively assess the current integrated hydrologic conditions for the RFETS flow system. Specifically, this integrated model was used to: (1) comprehend and simulate current Site hydrologic conditions; and (2) assess the hydrologic impacts caused by hypothetical changes to the current Site configuration.

8.1.2 General Approach

Developing a numerical model was considered the most suitable approach to quantitatively assess the hydrologic impacts of hypothetical Site scenarios. To achieve the project objectives, the following tasks were identified and conducted:

- Collected Site-specific data to support development of the conceptual and numerical hydrologic models (data included surface water and groundwater hydrology, surface and sub-surface Industrial Area structures, topography, geology, soils and vegetation);
- Developed the conceptual hydrologic model based on existing knowledge;

- Developed the modeling approach appropriate for the Site (including code selection and verification);
- Developed the numerical model based on a selected computer code;
- Evaluated model performance (including calibration, validation and sensitivity analysis);
- Applied the model to two hypothetical Site scenarios; and
- Assessed the model results for implications to Site closure.

8.1.3 Conceptual Flow Model

In order to develop the numerical model framework, a conceptual model was developed for the Site-wide flow system. The RFETS conceptual model considered the relevant surface and subsurface flow processes, their interactions and Site features affecting flows. The conceptual model development was comprehensive and supported by analyzing available Site information, including: (1) past studies; (2) hydrologic and geologic data; and (3) engineering plans and details.

Separate conceptual flow models were developed for the Industrial Area and Buffer Zone. This was necessary to assess the different observed flow responses in each area. The fully-integrated SWWB model simulates the combined flow characteristics of both areas.

8.1.4 Numerical Model Approach

The complex surface water-groundwater interactions within the RFETS hydrologic flow system required using a fully-integrated computer code to create a flexible, yet comprehensive, management tool. In a detailed comparison of available integrated models, the MIKE SHE computer code was selected for the SWWB modeling.

The complex semi-arid Site hydrology also required using a fully-integrated, transient modeling approach. Steady-state models could not reliably replicate the observed

conditions at the Site, nor could a combination of non-integrated, media-specific model codes. Sub-regional scale models of hydrologic processes were developed to understand basic flow processes prior to simulating the Site-wide model.

Model code verification results showed MIKE SHE was capable of simulating the important hydrologic processes and their complex interactions in the RFETS environment.

8.1.5 Calibration Strategy

Specific parameters and targets were identified and prioritized for the model calibration. Specific focus areas were specified where key decisions or Site hydrology would likely change in response to hypothetical Site scenarios. Focus areas included: (1) the regional flow system; (2) major surface water drainages; (3) detention ponds; (4) specific contamination areas including the 903 Pad and Lip Area, the Original Landfill and the Present Landfill; (5) *in-situ* groundwater treatment/collection systems; and (6) vegetation/habitat areas. Within each focus area, additional effort was expended to minimize the difference between model-simulated results and field measurements of the hydrologic system. The highest priority was given to accurately simulating surface water discharge from the Industrial Area to Woman and Walnut Creeks and from those drainages to the eastern Site boundary.

8.1.6 Numerical Model Design

The integrated numerical model consists of surface flow, unsaturated zone and saturated zone components at discrete points on a grid. A 200-x 200- ft (~ 61 x 61 m) regularly-spaced model grid was selected as the most suitable compromise between numerical efficiency versus solution accuracy required to meet regional project objectives. In addition, a range of time steps were used in the model to capture the rapid dynamics of the surface hydrologic system (0.5-minute time step) and comparatively much slower response of the groundwater flow system (6 hour maximum time step). Spatial precipitation distributions were specified from 10 stations every 15 minutes, while PET was specified every 2 hours.

The surface flow model was used to simulate two-dimensional overland flow and one-dimensional channel flow. The channel flow network included both Walnut and Woman Creeks and most tributary branches. The A-, B-, and C-series ponds and the Present Landfill Pond were also incorporated into the channel network. Both channel flow and pond water interacted directly with flow in the saturated zone. Drainage basin boundaries were used to define overland flow areas within the model, while detailed cross-sections defined the channel flow.

The subsurface model simulated one-dimensional unsaturated zone flow and three-dimensional saturated zone flow. The unsaturated zone model design accounted for spatially-distributed soils. Effects of the time-varying, spatially-distributed vegetation were simulated through the unsaturated zone as ET.

The saturated zone model used four model layers to describe flow within unconsolidated material and weathered bedrock units. Average hydraulic characteristics and properties of subsurface remediation systems, utility trenches and drains, water supply lines and building basements in the Industrial Area were incorporated into the saturated zone model.

8.1.7 Model Performance

After completing the numerical model design, the fully-integrated model was calibrated. Calibration was achieved by adjusting model parameters until the simulated model results compared well with observed data. The calibration used WY2000 data. Model results simulated observed Site-wide flow conditions at RFETS well. Key findings of the calibrated model include:

- ET dominated near-stream groundwater levels, which in turn strongly affected streamflows. During high ET, groundwater levels declined near Walnut and Woman Creeks at the eastern Site boundary. In Woman Creek, this effectively eliminated streamflow in late spring and summer. During times of the year with low ET, groundwater levels increased. This caused increased baseflow

contributions to Woman Creek with resulting increases in the total flow and peak flow rates in that drainage;

- In Walnut Creek, flows were dominated by pond releases. However, during non-pond discharge periods, precipitation events rarely caused streamflow in Walnut Creek because of high soil infiltration rates and low near-stream groundwater levels;

- Groundwater level changes were affected most by vertical processes, such as ET and direct recharge from precipitation, rather than lateral groundwater flow. Groundwater flow directions were strongly influenced by local topographic and bedrock surfaces; and

- Industrial Area surface flows were comprised of fast runoff, baseflow and drain inflows. The fast runoff causes rapid hydrograph peaks, while baseflow and drain inflows produced continuous low flow rates exiting the Industrial Area as surface water; and

- For the current Site configuration, the water balance differed greatly in the Industrial Area than the Buffer Zone. For the WY2000 climate, roughly 90 percent of the precipitation was lost through ET, with less than 1 percent running off to streams. In contrast, for the Industrial Area, roughly 60 percent of the precipitation was lost to ET, with 15 percent running off to streams.

The performance of the calibrated model was further assessed through a sensitivity analysis and model validation. The purpose of the sensitivity analysis was to identify key parameters to which the model was most responsive. The system hydrologic response was most sensitive to saturated hydraulic conductivity values. The model validation performance was demonstrated against pre- and post-calibration climatic conditions. These simulations showed that the model performed well in simulating hydrologic conditions of the Spring, 1995 and WY2001.

8.1.8 Model Scenario Evaluations

Model simulations were conducted for two hypothetical Site scenarios to evaluate changes in the WY2000 hydrologic conditions. In the first scenario, imported water is discontinued. The second scenario presented hypothetical regraded topography in the Present Landfill, the Original Landfill, and the Industrial Area, including removal of pavement, buildings, subsurface utilities, and imported water. These scenarios were evaluated for wet- and dry-year climate conditions as well as the WY2000 climate. Finally, a Monte Carlo-type uncertainty analysis was conducted on the second scenario to assess the range of uncertainty in predicted output given uncertainty in sensitive model input parameters.

Several key findings are made about the change in hydrologic conditions from the current configuration to the hypothetical Site scenarios were identified. These are summarized as follows:

- Regionally, most changes to the system occurred within the regraded Industrial Area, the two modified landfill areas (the Original Landfill and the Present Landfill) and to Walnut Creek, east of the Industrial Area;
- Surface discharge in Walnut Creek was substantially reduced, while flows in Woman Creek were largely unaffected;
- Walnut Creek discharges decreased for the following three reasons: (1) WWTP contributions to Walnut Creek were eliminated; (2) impervious surfaces in the Industrial Area were removed, thereby eliminating fast runoff; and (3) drain discharges to Industrial Area streams were eliminated;
- The number of required terminal pond discharges decreased in the Land Configuration Scenario because of decreased flow from the Industrial Area;
- Average groundwater levels in the Industrial Area increased. Removing drain discharges and impervious areas caused groundwater to rise, whereas removing

leaky water supply lines caused groundwater levels to decrease. The net effect of these changes was an increase in Industrial Area groundwater levels; and

- Simulated discharges from groundwater remediation systems slightly decreased by nearly 30 percent.

8.2 IMPLICATIONS FOR SITE CLOSURE

Modeling results suggest that significant impacts to the Site's hydrologic system are expected to occur for the scenarios modeled. These modeling results provide valuable insight into Site hydrology that will impact the RFETS closure strategy and long-term stewardship. Implications based on the simulated scenario results are summarized in the following sub-sections.

8.2.1 Regional Impacts

On a Site-wide basis, the greatest hydrologic changes at the eastern Site boundary are predicted in the Walnut Creek basin. Significantly less surface water is predicted in Walnut Creek after Site closure, whereas impacts to the Woman Creek basin are predicted to be minimal.

Annual off-Site discharge from Walnut Creek in the Land Configuration Scenario is projected to decrease by 80 to 95 percent in the wet year and dry year simulations, respectively. In addition, groundwater levels along lower Walnut Creek are predicted to decrease (by less than half a meter), based on the WY2000 climate. In contrast, Woman Creek at the Site boundary is predicted to remain largely unaffected by the simulated scenarios. This is an important concept for expected on-Site changes, such as potential impacts to vegetation, as well as anticipated impacts to downstream water users beyond the Site boundary. Walnut Creek should be a primary focus of attention in Closure design, based on these predicted changes to flow volumes and groundwater levels along the stream.

8.2.2 Pond Operations

The major hydrologic changes to the Site detention ponds, similar to the boundary impacts, are predicted to occur in the Walnut Creek basin. Decreased inflows are predicted for Pond C-2, but the impacts to Woman Creek are predicted to be minimal.

The reconfigured Industrial Area and elimination of WWTP effluent discharges will result in less flow in North and South Walnut Creeks and the SID. This translates to fewer pond discharges based on the current pond configuration and operating protocols. Specifically, the discharges from Pond A-4, the terminal pond on North Walnut Creek, are estimated for the WY2000 climate model to decrease by 75 percent in the Land Configuration Scenario. The magnitude of this predicted decrease varied slightly with the wet year and dry year climate simulations. Similarly, Pond B-5, the terminal pond on South Walnut Creek, was predicted to have the discharge volume decline by 70 percent annually for the No Imported Water Scenario and by even more for the Land Configuration Scenario.

Although runoff in the SID basin is expected to decrease in this scenario, no discharges were predicted for Pond C-2 in any of the scenarios. Regardless of how the managed ponds are ultimately configured, these predictions provide insight regarding the reduced volumes of water and changing requirements for pond management after Site closure.

8.2.3 Industrial Area Impacts

Based on the Land Configuration Scenario model results, there will be a decrease in surface water discharge volumes in all watersheds that receive runoff from the Industrial Area. The diminished surface flows are the result of removing pavement and other impervious surfaces that promote runoff. In addition to reduced surface flows, the modeling results indicate that groundwater levels generally increased throughout the Industrial Area, caused by increased infiltration in the Land Configuration Scenario. The model simulations showed that groundwater levels will continue to change for years after the hypothetical Site Configuration Scenario runs because of the low recharge rates and low sub-surface hydraulic conductivities.

In North Walnut Creek (SW093), which receives runoff from the northern Industrial Area, the annual discharge volume is predicted to decline by more than 65 percent for the Land Configuration Scenario. In South Walnut Creek (gaging station GS10), which receives runoff from the central Industrial Area, the annual discharge volume is predicted to decline by approximately an order of magnitude. The discharge volume is predicted to be less in the SID basin (SW027) as well.

Groundwater levels in the Industrial Area are predicted to increase in the Land Configuration Scenario. This predicted increase is the net result of several competing effects. Specifically, contributions to groundwater were reduced with removal of leaking water distribution pipes. Contributions to groundwater from recharge by precipitation increased with removal of the paved surfaces.

The Land Configuration Scenario predicted that the low flow (baseflow) rates at GS10 and SW093 would be reduced slightly. Though groundwater levels in the Industrial Area will increase, subsurface drains, which previously routed the water to the channels, will be removed, resulting in a net decrease of baseflow at these locations.

8.2.4 Groundwater Treatment Systems

Groundwater discharge is generally predicted to decrease for the *in-situ* groundwater treatment systems, although there were exceptions. This is based on the Land Configuration Scenario and different climate conditions. Exceptions to the decreased discharge are the Solar Ponds and the Present Landfill Interception Systems, which are predicted to have slightly increased discharge (less than 5 percent increase) for the wet climate scenario. It is noted that the trend in decreasing discharges for the groundwater treatment systems is based on simulation results using a model grid size that is relatively large compared to the size of the treatment systems.

8.3 POTENTIAL MODEL APPLICATIONS

A fully-integrated, hydrologic model has been developed for the Rocky Flats Environmental Technology Site. The model performance and sensitivity have been

demonstrated for a range of climatic conditions. Two hypothetical Site configuration scenarios have been simulated as a preliminary application of the model. Additional applications of the model may include local-scale modeling and contaminant transport evaluations.

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Site-Wide Water Balance Model Report

Appendix A

Site Background

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A APPENDIX: SITE BACKGROUND

A.1 SURFACE WATER HYDROLOGY

Streams and seeps at RFETS are largely ephemeral, with stream reaches gaining or losing flow depending on the season and precipitation amounts. Surface water flow across RFETS is primarily from west to east, with three major drainages traversing the Site. A total of 14 detention ponds (plus several small stock ponds) collect surface water runoff, although only 10 ponds are actively-managed. The Site drainages and detention ponds are described below.

A.1.1 Walnut Creek

Walnut Creek drains the central third of RFETS, including the majority of the Industrial Area. It consists of several tributaries (North Walnut Creek, South Walnut Creek, No Name Gulch and McKay Ditch [before July, 1999]) that join prior to Walnut Creek flowing off RFETS at the eastern boundary (Indiana Street). East of Indiana Street, Walnut Creek is diverted by the Broomfield Diversion Ditch to the south of Great Western Reservoir and into Big Dry Creek. The Walnut Creek tributaries, from north to south, are described below.

A.1.1.1 McKay Ditch

The McKay Ditch was formerly a tributary to Walnut Creek within the RFETS boundaries but was diverted in July, 1999 into a new pipeline to keep McKay Ditch water from co-mingling with RFETS water in Walnut Creek. Although no longer a contributor to Walnut Creek, the McKay Ditch drainage is described here to clarify water routing at the Site. The new configuration allows the City of Broomfield to transport water from the South Boulder Diversion Canal, across the northern Buffer Zone and directly into Great Western Reservoir (east of the Site) without contacting Walnut Creek water from the Site's stormwater detention ponds.

A.1.1.2 No-Name Gulch

This drainage is located downstream from the Present Lndfill. The Present Landfill Pond discharges, however, are not routed into No Name Gulch but instead are pumped over to Pond A-3. No Name Gulch does not receive runoff from the Industrial Area.

A.1.1.3 North Walnut Creek

Runoff from the northern portion of the Industrial Area flows into this drainage, which has four detention ponds (Ponds A-1, A-2, A-3 and A-4). The combined capacity of the A-series ponds is approximately 197,000 cubic meters (m^3) (52 million gallons [160 acre-feet]). Ponds A-1 and A-2 are kept off-line and maintained for emergency spill control, evaporation or transfer controls water levels in these ponds. North Walnut Creek flow is diverted around Ponds A-1 and A-2 to Pond A-3, where water is held and settling of solids occurs. Pond A-3 is transferred in batches to the A-series "terminal pond," Pond A-4. After filling to a predesignated level (typically approximately 50 percent of capacity), Pond A-4 water is isolated, sampled and released if water quality standards are met. These off-Site discharges, each averaging approximately 63,000 m^3 (16.6 million gallons [51 acre-feet]), typically occur two to four times per year.

The average annual discharge to North Walnut Creek at the east perimeter of the Industrial Area (at station SW093) is approximately 148,000 m^3 (39 million gallons [119 acre-feet]). The average mean daily flow rate at station SW093, from October, 1992 through April, 1997, was 0.005 cubic meters per second (m^3/s) (0.16 cubic feet per second [cfs]). The maximum mean daily flow rate during this period was approximately 0.25 m^3/s (9 cfs).

A.1.1.4 South Walnut Creek

Runoff from the central portion of the Industrial Area flows into this drainage, which has five detention ponds (Ponds B-1, B-2, B-3, B-4 and B-5). The combined capacity of the South Walnut Creek Detention Ponds (B-series Ponds) is approximately 102,000 m^3 (27 million gallons [83 acre-feet]). Ponds B-1 and B-2 are kept off-line and maintained for

emergency spill control, evaporation or transfer controls water levels in these ponds. Pond B-3 receives effluent from the Site's Wastewater Treatment Plant (WWTP) and flows into Pond B-4. South Walnut Creek flow is diverted around Ponds B-1, B-2 and B-3, into Pond B-4, which flows continuously into "terminal pond" Pond B-5. After filling to a pre-designated level, Pond B-5 is released in batches of approximately 54,000 m^3 (14.3 million gallons [44 acre-feet]) to South Walnut Creek. Pond B-5 discharges typically occur six to eight times per year.

The average annual discharge to South Walnut Creek, including effluent from the Site's WWTP, is approximately 318,000 m^3 (84 million gallons [258 acre-feet]). The average mean daily flow rate measured in South Walnut Creek (at station GS10), from October, 1992 through April, 1997, was 0.003 m^3/s (0.12 cfs), and the maximum mean daily flow rate during this period was approximately 0.142 m^3/s (5 cfs).

A.1.2 South Interceptor Ditch

South of the Industrial Area is the South Interceptor Ditch (SID)/Woman Creek system. Although it is tributary to Woman Creek, the SID warrants more thorough discussion than other comparable tributaries at the Site because it captures runoff from the southern portion of the Industrial Area, a drainage basin that includes the 903 Pad. The 903 Pad, located on the southeast corner of the Industrial Area, has some of the highest levels of actinides in surface soils on the Site.

Surface water runoff from the southern portion of the Industrial Area is captured by the SID, which flows from west to east into Pond C-2. Water from Pond C-2 is sampled and, if surface water quality criteria are met, pump discharged into Woman Creek (which flows to the Woman Creek Reservoir). Off-Site discharges from Pond C-2, averaging approximately 46,900 m^3 (12.4 million gallons [38 acre-feet]), typically occur once per year.

There is frequently no flow in the SID. The average mean daily flow rate (at station SW027), from October, 1994 through April, 1997 and including the periods of no flow,

was 0.001 m^3/s (0.05 cfs). The maximum mean daily flow rate during this period was approximately 0.170 m^3/s (6 cfs).

A.1.3 Woman Creek

South of the SID is Woman Creek, which flows through Pond C-1 and off-Site at Indiana Street. The Woman Creek drainage basin extends eastward from the base of the foothills, near Coal Creek Canyon, to Standley Lake. Woman Creek currently flows into the Woman Creek Reservoir, where it is held until it is pump transferred to Big Dry Creek. The average annual yield of the basin is approximately 420,000 m^3 (111 million gallons [341 acre-feet]). The average mean daily flow rate in Woman Creek (at Indiana Street) was 0.010 m^3/s (0.47 cfs), and the maximum mean daily flow rate during this period was approximately 2.150 m^3/s (76 cfs).

A.1.4 Other Drainages

The largest major drainage at the Site, other than Walnut and Woman Creeks, is Rock Creek. The Rock Creek drainage covers the northern portion of the Site's Buffer Zone. Flat areas to the west, several small stock ponds within the creek bed, and multiple steep gullies and stream channels to the east, characterize the drainage channel. This basin is hydrologically isolated from the Site Industrial Area. It receives no runoff from the Industrial Area and is not within the SWWB model boundaries.

Smart Ditch, located south of Woman Creek, is also hydrologically isolated from the RFETS Industrial Area. The D-series Ponds (D-1 and D-2) are located on Smart Ditch. This drainage and these ponds are not discussed in this report.

Upper Church Ditch conveys water from Coal Creek Canyon northeastward across the Site's northern Buffer Zone. This channel runs north of the Industrial Area and south of Rock Creek, before exiting RFETS at the Site's northeast corner. It is not linked with other surface water features at the Site.

A.2 SITE GEOLOGY

The Site is located along the western margin of the Denver Basin, an asymmetric basin with a steeply east-dipping western flank and a gentle eastern flank. The interpretation of the subsurface structure is generalized in the west-east generalized geological cross-section of the Site area presented in the Main Report. A monoclinal fold limb exposed west of the Site is the most significant surficial structural feature in the Site area. Along the west limb of the fold, an angular unconformity exists between the Upper Cretaceous bedrock and the base of the Quaternary Rocky Flats Alluvium.

No active faults have been identified at the Site. Several high-angle bedrock faults have been inferred to exist in the Industrial Area based on various stratigraphic and borehole correlation criteria. These faults appear to have only a limited hydrologic significance with regard to vertical groundwater movement and contaminant transport (RMRS, 1996b).

The following text provides additional details on geologic units at RFETS that were discussed in the Main Report Section 2.

A.2.1 Artificial Fill Materials

Artificial fill materials are present across the Site, including: (1) road and railroad embankments; (2) earth dams and other engineered fills; (3) compacted and uncompacted landfills; and (4) spoil piles along some of the irrigation ditches. The artificial deposits are commonly less than 3 meters (10 feet) thick, although some of the earth dams and landfills are greater than 9 meters (30 feet) thick. Most of these deposits are relatively impermeable and restrict groundwater flow (EG&G, 1995a and 1995b).

A.2.2 Colluvial Deposits

This material covers the steep hillslopes in the incised stream drainages (EG&G, 1995a and 1995b). These middle Pleistocene to Holocene deposits were derived from older alluvial units and bedrock and were deposited by sheet wash and soil creep. Colluvial deposits range in thickness from 0.9 to 4.6 meters (3 to 15 feet). Lithologically, the

Colluvium consists of silty sand, sandy silt, clayey silt and silty clay with pebbles and cobbles. These deposits are typically poorly-sorted and poorly-stratified. Colluvial deposits are variably saturated, and colluvial groundwater tends to flow downslope following paleogullies developed on the bedrock surface.

A.2.3 Landslide Deposits

These deposits are present along the steep hill slopes in the incised drainages (EG&G, 1995a and 1995b). These middle Pleistocene to Holocene deposits include earth flows, earth slumps, debris flows, debris slumps, rock-block slides and complex landslides. These deposits range in thickness from 3 to 30 meters (10 to 100 feet). Landslide scarps are present in all of the drainages in the map area and are most numerous in the Rock Creek drainage (EG&G, 1995a and 1995b). Landslides are commonly located downgradient from alluvial or bedrock groundwater discharge areas. Groundwater discharge increases the saturation within downgradient soils, leading to failure of the material.

A.2.4 Alluvial Deposits

Alluvial deposits have been mapped in floodplains, stream channels and terraces along the drainages across the Site, and they include the Valley-fill Alluvium, undifferentiated alluvium, and the Rocky Flats Alluvium. The Valley-fill Alluvium includes the Pleistocene Louviers, Broadway, and pre-Piney Creek Alluvium and the Holocene Piney Creek and post-Piney Creek alluvial units. Valley-fill Alluvium consists of channel and terrace deposits in and along most of the ephemeral streams that cross the Site (EG&G, 1995a).

Valley-fill Alluvium ranges in thickness from 3 to 12 meters (10 to 40 feet) and is variably saturated. The Valley-fill Alluvium is permeable and may provide preferential pathways for groundwater migration. Undifferentiated alluvial deposits include the Pleistocene Slocum Alluvium and Verdos Alluvium of Shroba and Carrara (1994). These units form small remnants of pediment or terrace deposits primarily in the southeastern portion of the RFETS. The undifferentiated alluvial deposits range in

thickness from 1.5 to 6 meters (5 to 20 feet), but this unit is not a significant component of the hydrologic system on the Site (EG&G, 1995a).

The Rocky Flats Alluvium caps the pediment at the Site. These Pleistocene sediments were deposited as alluvial fans along the eastern edge of the Front Range. The deposit diminishes from west to east with thicknesses ranging from approximately 30 meters to less than 0.3 meters (100 feet to less than 1 foot). In the central portion of the Site, the deposit is approximately 35 to 8 meters (115 feet to 25 feet) thick (RMRS, 1999a). Thicker deposits correspond to paleoscours and thinner deposits occur along the crests of paleoridges. Groundwater flow within the Rocky Flats Alluvium is influenced by the topography of the underlying bedrock surface (paleotopography), the geometry and lithology of alluvial lithofacies and the regional hydraulic gradient.

A.2.5 Arapahoe Formation

The Arapahoe Formation is composed of claystone and silty claystone with lenticular sandstone in the basal portion of the formation. The Arapahoe Formation is generally less than 8 meters (25 feet) thick at the Site, occurring as erosional remnants of fine-grained sandstone above the Laramie Formation at various locations on the Site (EG&G, 1995b). This basal Arapahoe Formation sandstone, which is currently defined as the No. 1 Sandstone, affects the local hydrology, especially where it subcrops beneath the alluvial/bedrock unconformity.

A.2.6 Laramie and Fox Hills Sandstone Formations

The Laramie Formation is approximately 183 to 244 meters (600 to 800 feet) thick and is composed of a lower sandstone/claystone/coal interval and an upper, thick claystone interval. Within the upper claystone interval, thin, lenticular sandstone lenses occur (EG&G, 1995b). The discontinuous nature of these sandstone lenses, coupled with the large claystone layer that encloses them, mitigates their potential for transmitting groundwater contamination in both horizontal and vertical directions.

The Fox Hills Sandstone is primarily fine-grained sandstone with thin siltstone and claystone interbeds and an approximate thickness of between 23 and 38 meters (75 and 125 feet) contamination. The Fox Hills sandstone crops out and subcrops along a narrow, north-south trending pattern in the extreme western part of the Site, upgradient from known sources of (EG&G, 1995b).

The Laramie-Fox Hills aquifer is composed of the permeable lower unit of the Laramie Formation and the underlying Fox Hills Sandstone (Robson, 1983). This aquifer system is an important water source in the South Platte River Basin and is the sole water supply for some residents in the Rocky Flats area (RMRS, 1999a). This aquifer lies approximately 183 to 274 meters (600 to 900 feet) below the Industrial Area and is protected from Site contamination by the intervening Laramie Formation claystones (EG&G, 1995b).

A.2.7 Pierre Formation

The Pierre Formation is a 7,500-foot thick, dark gray, silty bentonitic shale that acts as a lower confining layer for the Laramie-Fox Hills aquifer in the Denver Basin. This thick marine shale unit subcrops only in the extreme western part of the Site (RMRS, 1999a).

A.3 SITE VEGETATION

The uniqueness and diversity of the plant communities at the RFETS are documented by a number of studies. The topography and close proximity of the Site to the mountains has resulted in an interesting mixture of prairie and foothills plant communities at the Site. Six hundred species of plants have been reported present at the Site as of the 2001 field season. No threatened or endangered plant species are known to occur at the Site. Plant communities at the Site range from xeric (dry) grassland communities to more hydric (wet) communities such as wet meadows and marshes.

The Site vegetation distribution identifies 17 vegetation types within the study area. With the assistance of Site Ecology personnel (Murdock, 2001), these 17 types were grouped into four categories as described in Table A-1.

Table A-1. Designation of Broad Vegetation Group Categories

SWWB Vegetation Category	Detailed Vegetation Category
Wetland	Wet Meadow/ Marsh Ecotone
	Short Marsh
	Tall Marsh
Riparian Woodland	Riparian Woodland
	Leadplant Riparian Shrubland
	Willow Riparian Shrubland
	Tall Upland Shrubland
Mesic	Short Upland Shrubland
	Savannah Shrubland
	Mesic Mixed Grassland*
	Reclaimed Mixed Grassland
	Annual Grass/ Forb Community
Xeric	Ponderosa Woodland
	Tree Plantings
	Short Grassland
	Xeric Tallgrass Prairie
	Xeric Needle and Thread Grass

*Note: Reclaimed Mixed Grasslands designated as Mesic on hillsides and Xeric on mesas.

The plant communities of greatest ecological significance on Site are the xeric tallgrass prairie, the Great Plains riparian community, the tall upland shrubland community and wetlands. Other communities include mesic mixed grasslands (approximately 34 percent of Site acreage) found on moister hillsides and largely in the eastern half of the Site, and also small inclusions of needle-and-thread grass (3 percent of Site acreage) and shortgrass (0.2percent of Site acreage) prairie in the eastern portion of the Site. In the southeast portion of the Site and around ponds and industrialized locations, non-native revegetation communities (10 percent of Site acreage) are present. The "reclaimed grasslands" more resemble mesic mixed grassland in hill slope location and soil moisture conditions, and produce similar amounts of biomass.

The xeric tallgrass prairie occurs on the cobbly alluvium found on pediments (flat upland

areas) and ridges on the western half, and comprises about 28 percent of the total acreage of the Site. This prairie community type is distinguished by such tallgrass plant species as big bluestem, little bluestem, rice grass, prairie dropseed and switchgrass. These species are common and abundant in the tallgrass prairies hundreds of miles to the east of the Front Range, but their presence here is rare. Big bluestem and little bluestem are the most abundant of these prairie species found at the Site with the others occurring less commonly. In addition, common montane or foothills species such as mountain muhly, Fendler's sandwort and Porter's aster, also occur in the tallgrass prairie at the Site. These latter species are indicative of the unique mixing of mountain and prairie species found at the Site. The xeric tallgrass prairie was once a more common grassland along the Front Range, extending in a narrow band along the mountain front from Colorado Springs to the Wyoming border. The Colorado Natural Heritage Program (CNHP) lists the xeric tallgrass prairie at the Site as the largest known remnant in Colorado and possibly North America.

The Great Plains riparian community, mapped at the Site as riparian (stream channel) woodland and shrubland, is found along streams, and comprises 1 percent of the acreage at the Site. Examples of this community are found in the Rock Creek, Walnut Creek, Woman Creek and Smart Ditch drainages. Cottonwood trees and willows predominate in this community. Another unusual shrub community, dominated by leadplant, is also often found in association with the Great Plains riparian community at the Site. These communities provide important habitat for many of the bird and mammal species found here, including the Preble's Meadow Jumping Mouse.

The tall upland shrubland (seep shrubland) community is found on north-facing slopes primarily in the Rock Creek drainage, and makes up an important, but small, 0.5 percent of the total acreage. This community commonly occurs just above wetlands and seeps. The dominant tall shrubs are hawthorne and choke cherry, which are associated with other shrubs and plants common in the foothills to the west of the Site. It has been identified by the CNHP as a potentially unique shrubland community, possibly not occurring anywhere else. This community is used by many animals throughout the year for cover and is used during the spring by mule deer as fawning areas. Several rare bird

species also inhabit this community during the breeding season.

The wetlands on the Site are most common on north-facing hillsides. The combined acreage of wet meadow, short marsh and tall marsh comprise approximately 6.3 percent of the total Site acreage. One of the largest wetlands on the Site is Antelope Springs, which lies south of the Industrial Area. Another is the long line of seep-fed wetlands along the main branch of Rock Creek. These contain abundant stands of cattails, Baltic rush, sedges and other wetland plants. Particularly uncommon are the abundant watercress communities, growing where springs emerge and flow year round, in this wetland and others across the Site. Although the wetlands at the Site are not unique to the Site, the role they serve in terms of retaining nutrients, sediments, and metals, water purification, and providing forage, cover and nesting habitat for wildlife at the Site is very important.

Other minor vegetation types include annual grass/forb communities, short upland shrubland, minor grassland inclusions, savannah shrubland, ponderosa pine woodland and ornamental plantings. Other groundcover types include ponds, roads, buildings, disturbed areas and parking lots.

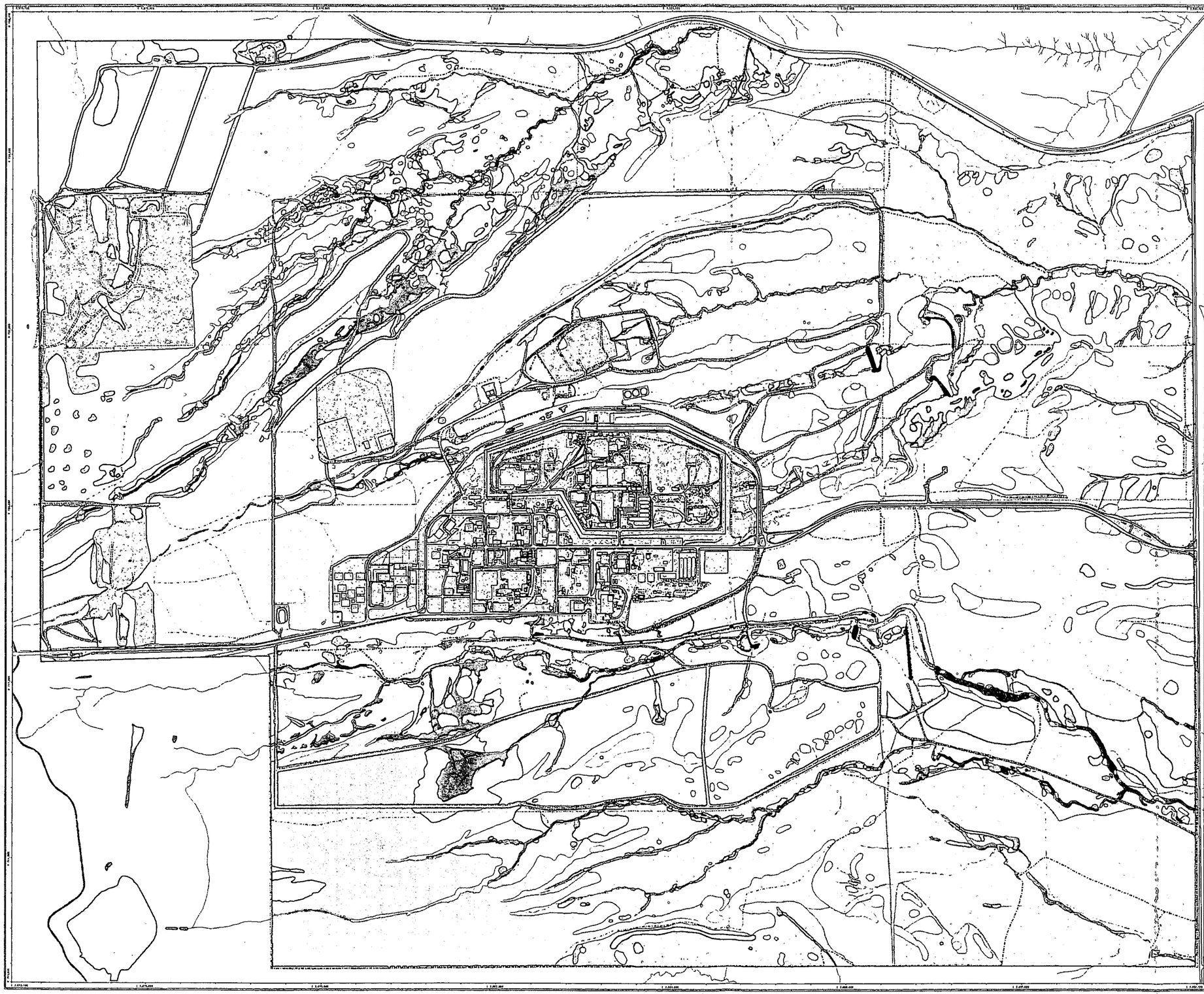

Figure A-1

Site-Wide Water Balance Report

Site Vegetation

LEGEND

- Riparian Woodland
- Leadplant Riparian Shrubland
- Wet Meadow/Marsh Ecotone
- Short Upland Shrubland
- Willow Riparian Shrubland
- Annual Grass/Forb Community
- Xeric Tallgrass Prairie
- Ponderosa Woodland
- Reclaimed Mixed Grassland
- Mesic Mixed Grassland
- Savannah Shrubland
- Tall Upland Shrubland
- Short Marsh
- Xeric Needle and Thread Grass Prairie
- Short Grassland
- Disturbed and Developed Areas
- Open Water
- Riprap, Rock, and Gravel Piles
- Mudflats
- Tree Plantings
- Tall Marsh

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Paved roads
- Dirt roads

DATA SOURCE BASE FEATURES:

Vegetation map data provided by PTI Environmental Services Ecology Group.
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas.
Digitized from the orthophotographs. 1/95

NOTES:

This map does not show all Federally designated wetlands. See the 1995 Site wetlands map prepared by the U.S. Army Corps of Engineers for delineated wetland features.

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

U.S. Department of Energy
Rocky Flats Environmental Technology Site

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Prepared by: DynCorp — THE ART OF TECHNOLOGY

Prepared for: KAISER-HILL COMPANY

May 29, 2002

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Site-Wide Water Balance Model Report

Appendix B

Conceptual Model

May 2002

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B APPENDIX: CONCEPTUAL MODEL

B.1 HYDROLOGIC STRESSES

The Site surface and subsurface hydrologic systems are continuously affected by external influences or stresses. These stresses include both natural and anthropogenic influences, including precipitation and other meteorological effects, import of water from off-Site for domestic use, natural inflows of water from outside the study area boundary and pond operations.

Text supporting the Main Report discussion of hydrologic stresses to the RFETS flow system is presented below. Precipitation is described in Section B.1.1, evapotranspiration (ET) and supporting meteorological data in B.1.1.1, imported Denver Water Board (DWB) Water in Section B.1.2 and surface and subsurface inflows in Section B.1.3.

B.1.1 Precipitation

Precipitation data are available at 15-minute intervals for 10 stations within the RFETS model boundary as shown on Figure B-1. Precipitation is complex, occurs as either snow or rain, and it varies spatially and temporally over the modeled area. As the principal hydrologic stress that drives most of the system response, the spatial and temporal distribution of precipitation was carefully specified in the MIKE SHE code to adequately reproduce system response.

Unlike other Site investigations and hydrologic modeling performed at RFETS (Kaiser-Hill 2000d, 2002a, 2002b), precipitation data from the meteorological stations located on-Site were used as the basis for the SWWB modeling. This gage is referred to as the RFETS Meteorological Monitoring Station (MERCO, Inc., 2000), but in this report it is simply termed the "met-station". It is located on the west side of the Industrial Area, approximately one-mile east-northeast of the west gate. This station should not be confused with gage PG51, located within meters (see Figure B-1).

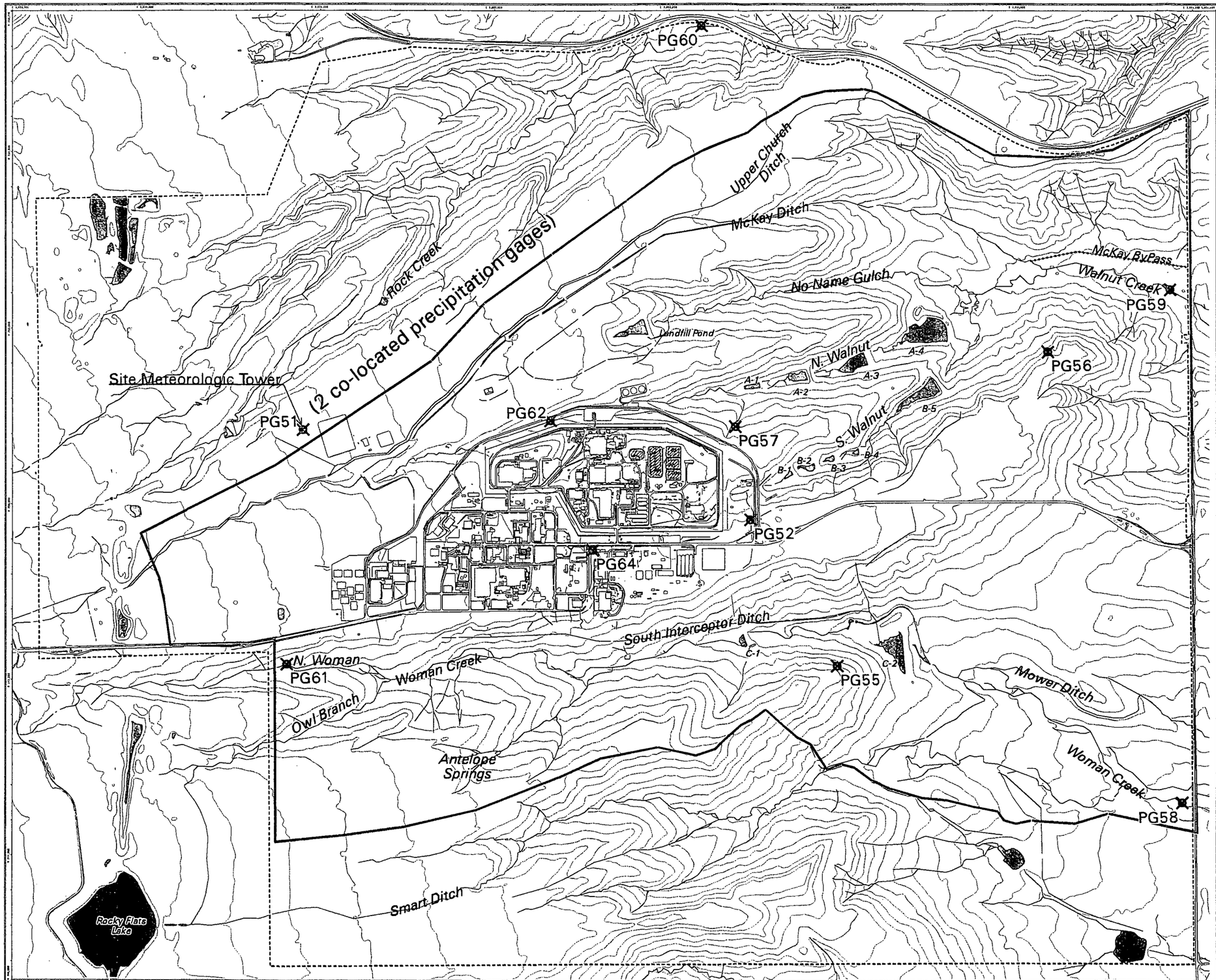


Figure B-1

Site-Wide Water Balance Report

Precipitation Gage Locations

EXPLANATION

- Precipitation Gage
- Site Meteorologic Tower

Standard Map Features

- Buildings and other structures
- Paved roads fill
- Solar Evaporation Ponds (SEPs)
- Lakes and ponds
- Streams, ditches, or other drainage features
- Topographic Contour (20-Foot)
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95
Topographic contours were derived from digital elevation model (DEM) data by Morrison Knudson (MK) using ESRI Arc TIN and LATTICE to process the DEM data to create 5-foot contours. The DEM data was captured by the Remote Sensing Lab, Las Vegas, NV, 1994 Aerial Flyover at ~ 10 meter resolution. DEM post-processing performed by MK, Winter 1997.

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

U.S. Department of Energy
Rocky Flats Environmental Technology Site

GIS Dept. 303-966-7707

Prepared for: DynCorp THE ART OF TECHNOLOGY

Prepared for: KAISER-HILL COMPANY

May 14, 1998

NT_Svr w:/projects/swwb/fy2002/section_b/preop_gages.aml

Precipitation data is recorded every 15 minutes from the 61-meter tower at a height of 0.7 m (2.3 ft) using a NovaLynx instrument with an accuracy of +/- 10 percent of the 0.01 inch (2.5 mm) per tip measurement. The tower Site is located approximately 6,036 ft (1,840 m) above sea level. When snowfall occurs, the heated gage melts it to accurately record the amount of snow water equivalent (SWE) for the event.

Precipitation data are also available at nine of eleven other precipitation stations (PG51, PG52, PG55, PG56, PG58, PG59, PG60, PG61 and PG62) associated with stream gages located on Figure B-1. Data were unavailable for PG57 or PG64. These additional gages are not heated. Gages PG52, PG58, PG59, PG60, PG61 and PG62 are associated with stream gage locations and collect 5-minute precipitation record. The remaining gages, PG51, PG55 and PG56, collect 15-minute record as does the met station. Precipitation data from the stream gages were aggregated over 15-minute intervals for analysis and conversion to model input.

General characteristics and precipitation data from the ten (nine stream gages and one met-station) on-Site gages, shown on Figure B-1, were reviewed for data gaps. Only data from the model calibration period October 1, 1999 to October 1, 2000) were reviewed. The review of precipitation data indicated that some modifications to the surface flow gages were required to account for lack of heating during snowfall events. Snowfall events in surface flow gages were replaced with data from the met-station. Temperature data and a 5-day lag (for melting) were used to determine where to replace recorded snowfall data. This adjustment effectively results in the assumption that there is no spatial distribution of snowfall at the Site. This is probably reasonable because winter events are typically large. Snowdrift is not accounted for, as it is not considered critical to the water balance considering the relatively coarse model grid scale (200-ft by 200-ft or 61m x 61m).

Several notable temporal characteristics are evident in the high-resolution precipitation data at RFETS. Table B-1 summarizes these characteristics for the four seasons during October 1, 1999 through October 1, 2000. Summer months (July through September) had the greatest number of events and intensities, but they were the shortest in duration.

Nevertheless, summer events also produced the most precipitation, nearly three times that of fall events. The maximum event duration occurs during the fall months but intensities

Table B-1. Precipitation Event Characteristics (10/1/99 to 10/1/00)

Data	*Fall*	*Spring*	*Summer*	*Winter*
Number of Events	9	16	24	10
Avg. Max Event Intensity (in/hr)	0.08	0.18	0.31	0.08
Max. Event Intensity (in/hr)	0.16	0.32	2.44	0.28
Avg. Event Total (in)	0.21	0.21	0.22	0.16
Seasonal Totals (in)	1.88	3.31	5.20	1.55
Max. Event Total (in)	0.48	0.63	1.78	0.58
Avg Event Duration (hr)	3.61	2.66	1.54	3.23
Max. Event Duration (hr)	10.75	8.25	9.25	11.00

were lowest, and these months also produced the least amount of precipitation. The annual daily precipitation totals are shown in Figure B-2, and the intensities and durations of individual events are shown on Figure B-3.

Estimating the spatial distribution of precipitation at a 15-minute time interval in a semi-arid environment was a challenging task. An interpolation algorithm developed by Thornton et al. (1997) was used as the basis for developing a computer code, PRCPDIST (Prucha, 2002), that estimates the spatial precipitation distributions across the model area every 15-minutes. A similar approach was used to successfully distribute daily precipitation data over decadal time periods for a large arid/semi-arid basin flow system in the Southwestern U.S. (Prucha, 2002). Although the Thornton algorithm considers effects of elevation that have a more pronounced effect on distributions over larger regions, it also accounts for highly heterogeneous spatial precipitation fields.

Figure B-2. Daily Precipitation (10/1/99 to 10/1/00)

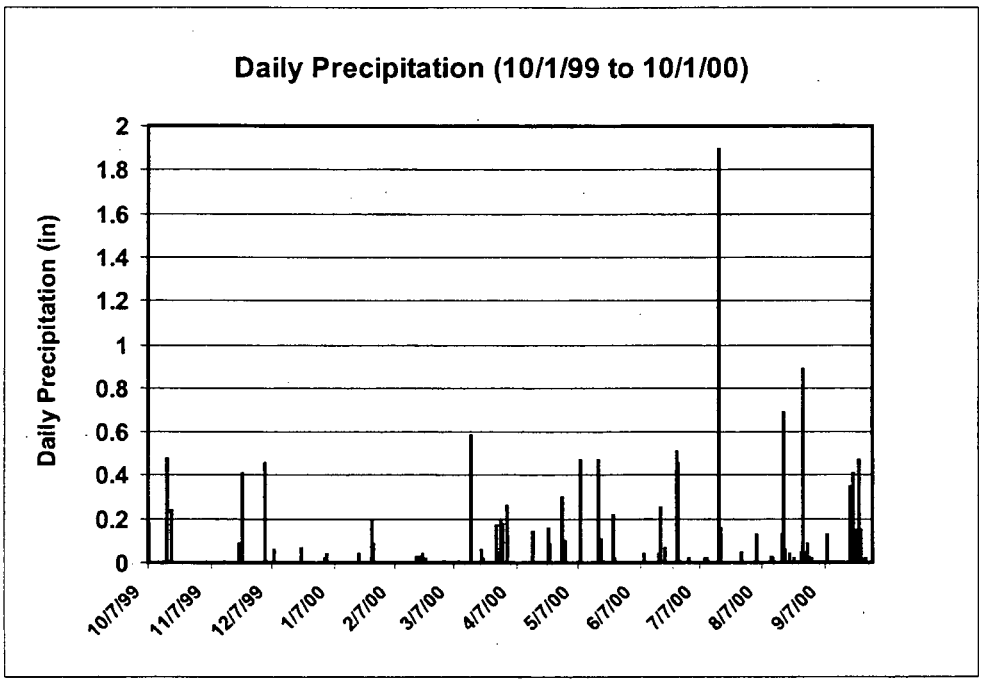
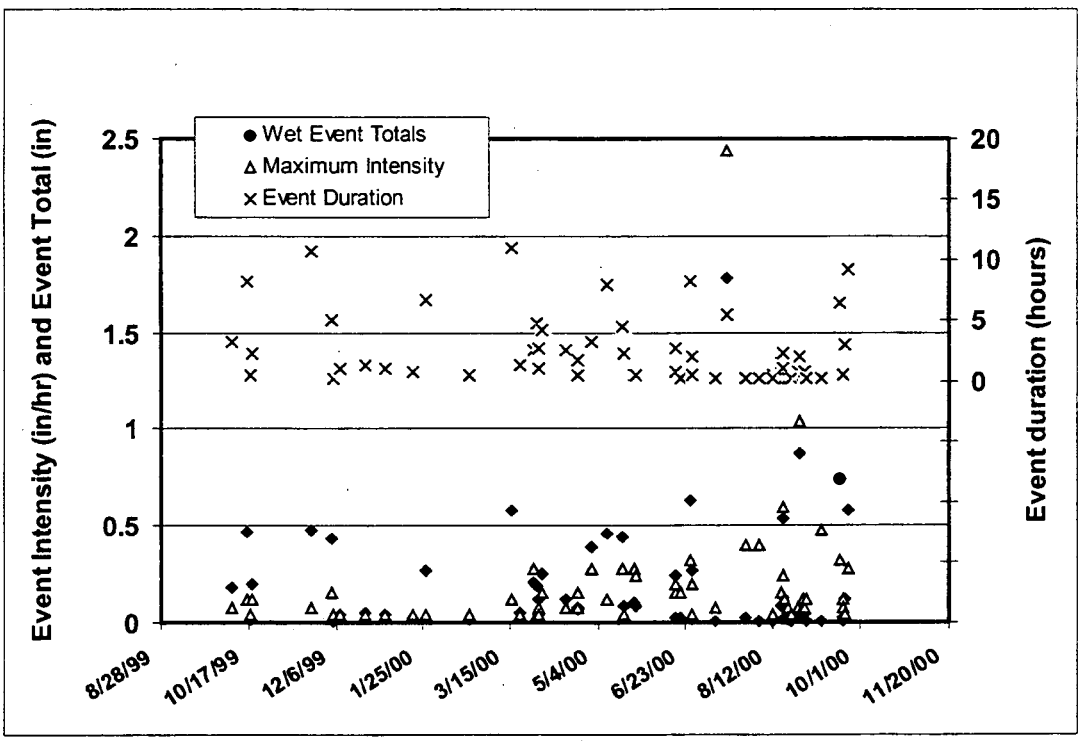


Figure B-3. Precipitation Event Characteristics



For example, if it rains on only one area of the Site and other areas remain dry, the algorithm reproduces this distribution reasonably accurately. The Thornton method utilizes a truncated Gaussian filter weight, with respect to its central point, p, is given by the following equation:

$$W(r) = \left\{ \begin{array}{c} 0; r > R_p \\ \exp\left[-\left(\frac{r}{R_p} \right)^2 \alpha \right] - e^{-\alpha}; r \leq R_p \end{array} \right\},$$

where W(r) is the filter weight associated with a radial distance r from p, Rp is the trunction distance from p and α is a unitless shape parameter. For each interpolation point, a list of filtered weights for each observation point is produced. To prevent data rich regions from dominating the interpolated value at p, the Thornton algorithm reduces the truncation distance, Rp, in data rich regions and increases it in data poor regions. This algorithm requires an average number of precipitation stations, N, for each interpolation point.

At RFETS, elevation differences are small and do not control the spatial distribution of precipitation events (atmospheric controls). As a result, the factor in the algorithm controlling the elevation effect on the spatial precipitation distribution was effectively removed.

A total of 40 precipitation zones were developed using the topography as a guide. Zones were defined within areas of similar morphology and aspects (mesas, hillslopes and stream beds) to account for potentially different precipitation patterns in the lower stream areas compared to the more exposed mesa tops. Maximum precipitation intensities and total annual precipitation (October 1, 1999 to October 10, 2000) are shown on Figure B-4. Results suggested that significant differences in precipitation distribution, nearly 50 percent, occurred over the model. Annual precipitation for the calibration year was highest in the northwest model area and decreased to the southeast. Intensities were distributed in a similar pattern. This suggested that more significant precipitation events result from storms from the northwest.

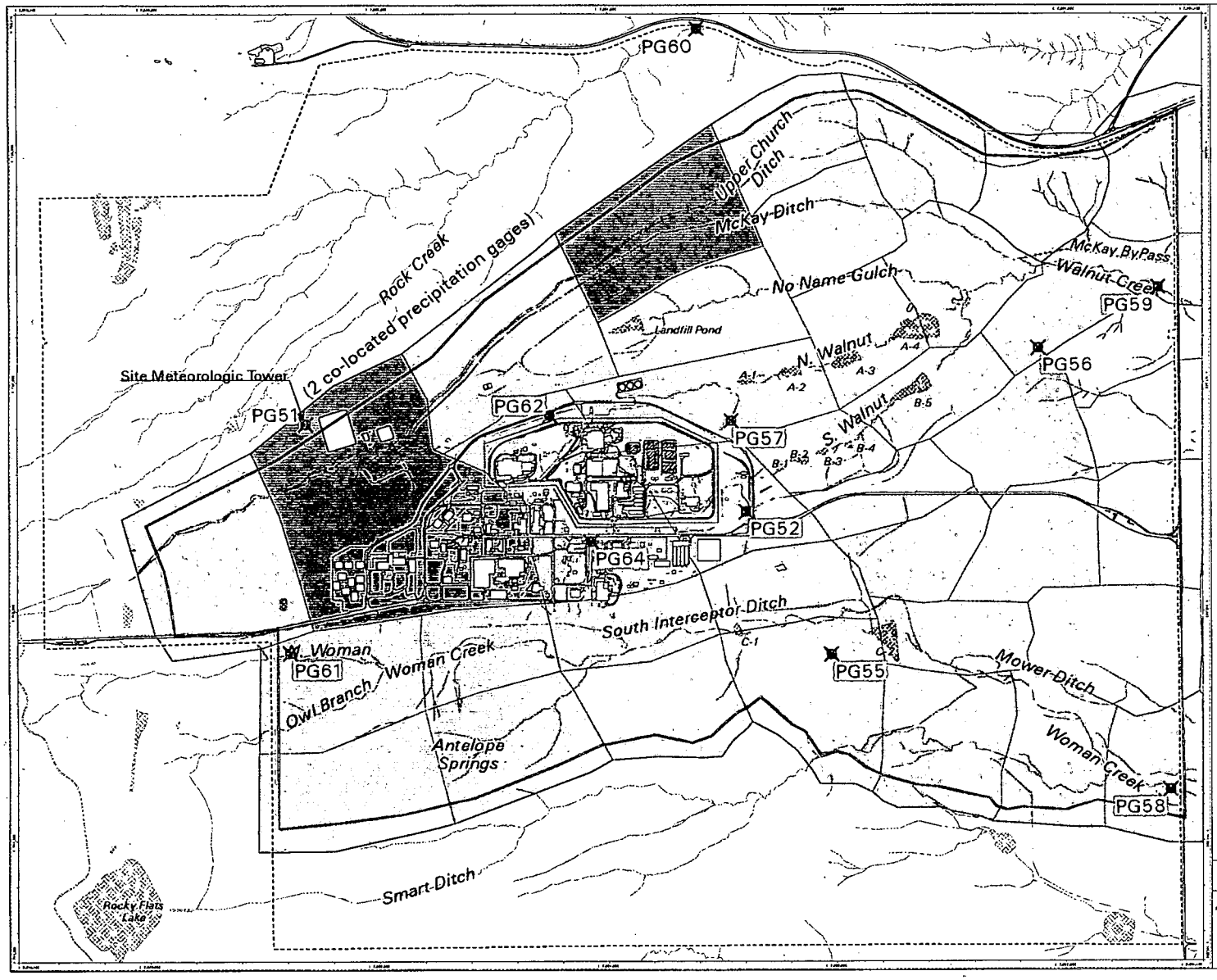


Figure B-4

Site-Wide Water Balance Report

Distribution of Maximum Annual Precipitation Intensity

EXPLANATION

Maximum Precipitation Intensity (in/hr)

- 0.22 - 0.26 (5.6 - 6.6 mm/hr)
- 0.26 - 0.35 (6.6 - 8.9 mm/hr)
- 0.35 - 0.45 (8.9 - 11.4 mm/hr)
- 0.45 - 0.59 (11.4 - 15.0 mm/hr)
- 0.59 - 0.66 (15.0 - 16.8 mm/hr)
- Precipitation Gage
- Site Meteorologic Tower

Standard Map Features

- Buildings and other structures
- Paved roads fill
- Solar Evaporation Ponds (SEPs)
- Lakes and ponds
- Streams, ditches, or other drainage features
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:
Distribution determined by Thornton (1997) method discussed in text.

500 0 500 1000 meters

250 0 250 500 1000 ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

U.S. Department of Energy
Rocky Flats Environmental Technology Site

GIS Dept. 303 966-7707

Prepared by: DynCorp

Prepared for: KAISER-HILL

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B.1.1.1 Evapotranspiration and Meteorological Data

ET is typically the dominant hydrologic process that controls discharge in semi-arid/arid flow systems. It is a complex process representing the combined effect of both plant transpiration and soil evaporation. Its effect on the hydrologic cycle increases as aridity increases. Vegetation has a substantial effect on actual evapotranspiration (AET), though bare soil evaporation also plays a significant role in loss of water to the atmosphere. During non-growth periods (i.e., sowing) and in sparsely-vegetated areas, soil evaporation is more important; otherwise plant transpiration typically dominates the ET. Vegetation, through AET, creates a stress on the hydrologic system and is therefore discussed here. More details on the types and distribution of vegetation are presented in Appendix A.

Potential Evapotranspiration (PET) represents the total possible amount of ET based on Site-specific climate conditions, and topographic, vegetation and soil characteristics. PET was calculated using the available meteorological data described above. It is important to recognize that AET is always less than the PET. Although PET varies both spatially and temporally, temporal variations are more significant. As a result only temporally varied PET was estimated for the SWWB model.

There are many methods to calculate PET, but estimates can vary significantly. Allen et al. (1998) recommends that the Food and Agricultural Organization (FAO56) version of the standard Penman-Monteith equation. This recommendation is based on a detailed analysis of different equations conducted by the American Society of Civil Engineers (ASCE). The REF-ET Program (Version 2.0)(Allen, 2000) was used to calculate hourly PET using Site meteorological data. To fill gaps, data were supplemented by temperature and solar radiation data obtained from DOE's National Renewable Energy Laboratory (NREL) Solar Radiation Research Laboratory (SRRL) located on South Table Mountain (39.74° N, 105.18° W), in Golden, Colorado.

The REF-ET Program (Allen, 2000) was used to calculate the PET for a grass reference crop. Several meteorological data types were used to calculate PET including: (1) solar

radiation; (2) air temperature; (3) humidity; (4) wind speed; (5) soil heat flux; (6) atmospheric pressure; and (7) precipitation. Details of the REF-ET calculation, including a discussion of the input meteorological data used to calculation PET, are discussed below in more detail.

The 61-meter met-station tower also records several other types of meteorological data that are useful for calculating PET required in the SWWB model. Data considered in this study include the following:

- Horizontal wind speed;
- Ambient Air Temperature;
- Barometric Pressure;
- Soil heat flux;
- Relative humidity;
- Incoming/Outgoing Solar Radiation (Black and White);
- Outgoing Infrared Radiation; and
- Dew Point.

Horizontal wind direction and speed, vertical wind speed and ambient air temperature are recorded at 10-m (33 ft), 25-m (82 ft) and 60-m (200 ft) levels, but only the 10-meter wind speed and air temperature data were used in this study. Review of these data showed some gaps in the time record. Additional temperature and global horizontal solar radiation (sum of direct and diffuse) data were obtained from SRRL via their web-Site, (http://midc.nrel.gov/srrl_bms/). These data were obtained at 2-minute intervals and had to be temporally aggregated to match RFETS data every 15 minutes.

All meteorological data were provided at 5-minute or 15-minute intervals. These data were originally input to a Microsoft ACCESS database and summed hourly and then

exported to an Excel file for further filtering/processing. Gaps for all data except temperature and solar radiation were flagged for input to the REF-ET program. Data gaps in temperature and solar radiation are addressed below.

Temperature (10-m height) – Colorado Department of Public Health and Environment (CDPHE) temperature data from five stations surrounding the Site were reviewed, but showed only slight differences in distribution. As a result, only met-station temperature data were used for calculating the PET and for snowmelt input to MIKE SHE. The REF-ET program does not allow gaps in temperature data. The previous day's temperature data were used to fill gaps.

Wind Speed (10-m height) – Data were obtained from the 10-m high met-station instrument instead of 30- and 60-m heights. Wind speed and direction data for five stations for calibration time period were also obtained from CDPHE data, though these were not used because distributed PET estimates were not calculated. REF-ET does not calculated distributed PET. Furthermore, analysis of spatial distributions of wind data did not indicate dramatic differences when averaged over longer time periods (i.e., hourly to daily). The REF-ET program internally uses the 10-m high wind speeds to calculate wind speed at the crop elevation. Data gaps were generally during same time period as solar radiation, but were left blank. REF-ET recognizes these data gaps and estimates wind-speed by other methods suited for semi-arid conditions (Allen, 2000).

Solar Radiation (not net radiation) – The following steps were taken to fill Solar Radiation gaps in the dataset:

- Met-station data were not complete over significant gaps (May 11, 2000 to May 27, 2000);
- Some values were negative, but are very small and probably reflect effects of instrument calibration;
- Upward and downward facing B&W (black and white) and IR (infra-red) Solar Radiation data (pyranometer) data were available but only up-facing B&W (short-

wave) were most complete. Therefore these data were supplied to REF-ET program. NREL data were used to fill gaps in for up-facing solar radiation;

- The solar radiation value was supplied to program REF-ET program (not net radiation); and
- REF-ET uses various assumptions to calculate net radiation based on solar radiation and other supplied variables.

Atmospheric Pressure (mb) was used and gaps were accounted for in REF-ET. Saturated Vapor Pressure (kilopascals) was not used in REF-ET calculations because it produced unrealistic PET values. Dew Point Temperature (^{o}C) were not used because REF-ET produced unrealistic PET estimates. Relative Humidity (as percent) was used directly from met-station data. Gaps were accounted for in REF-ET.

Soil Heat Flux (W/m^2) data were used by REF-ET and gaps were accounted for in REF-ET. Precipitation (in) data exist at 10 gage locations across RFETS, but only the met-station data were used, primarily because this gage is heated and others are not. Latitude and longitude are provided for the met-station (39.89 and -105.21 degrees, respectively)

Figure B-5 shows the variation in calculated PET for 1999-2000, along with other meteorologic data used to calculate the PET. Air temperature and solar radiation followed the same annual PET trend, indicating their relative importance in estimating PET. PET and precipitation data correlated strongly during precipitation events, as shown on Figure B-6. For example, with cloud cover or during a rainfall event, the PET actually drops substantially. When it snows, the PET drop is even more pronounced and can last for as long as the snow cover is present (i.e., high albedo or reflected solar radiation). Estimated winter and summer PET time series, including precipitation events are shown on Figure B-6. It is clear that winter snowfall events, strongly influenced the PET (i.e., days to recover), while summer time storms were short in duration, and typically occurred in later afternoon, well after the peak daily PET. Nevertheless, these summer events still significantly affected the hourly PET signal.

Figure B-5. RFETS Meteorological Data

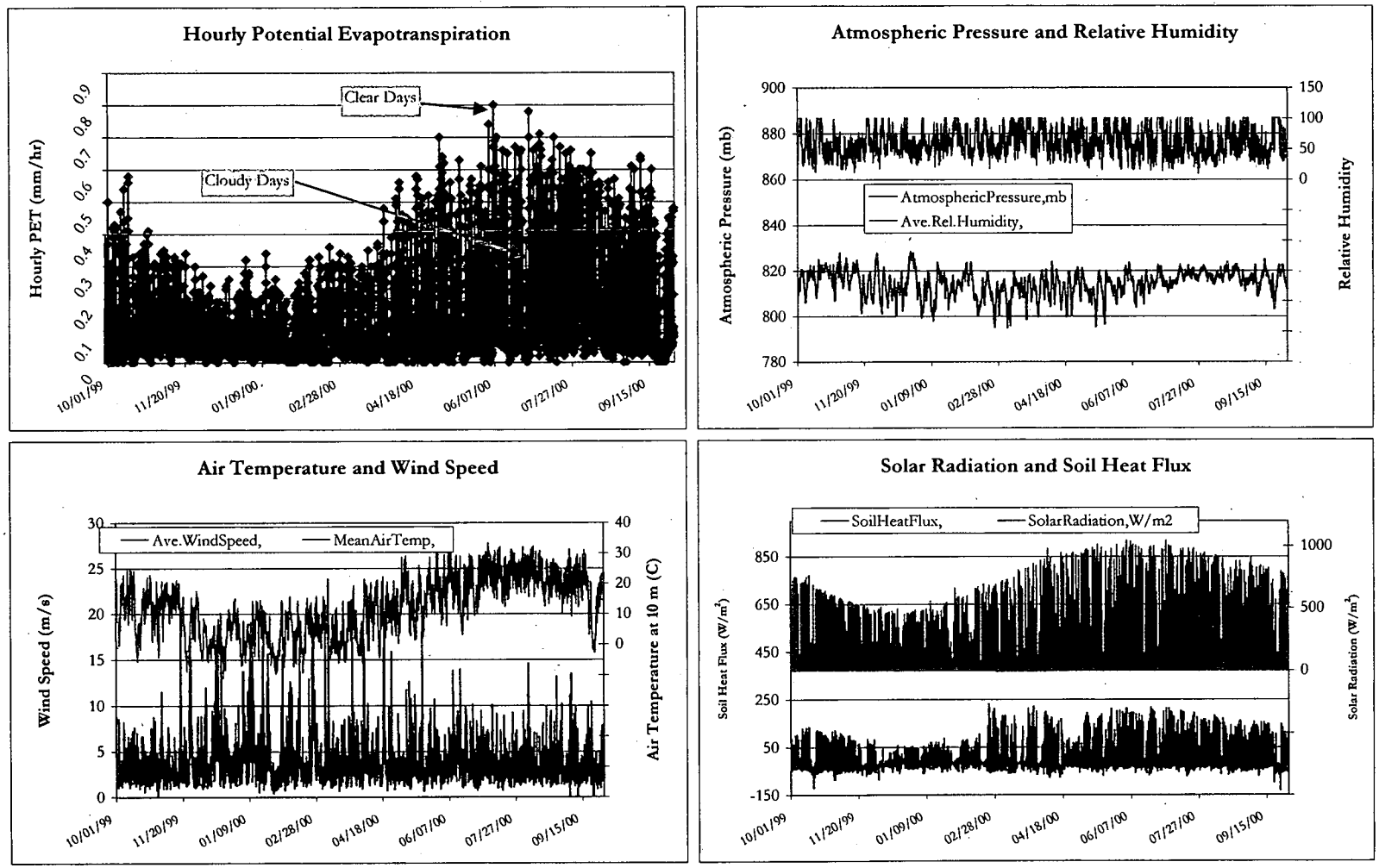
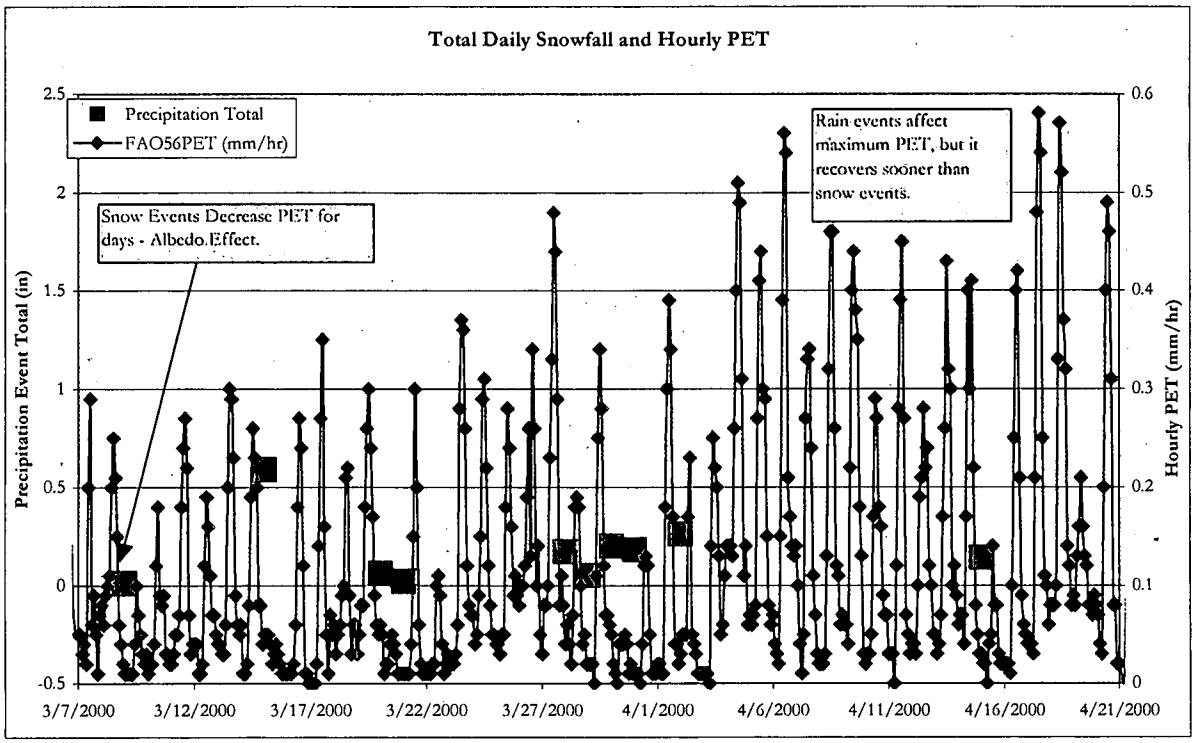
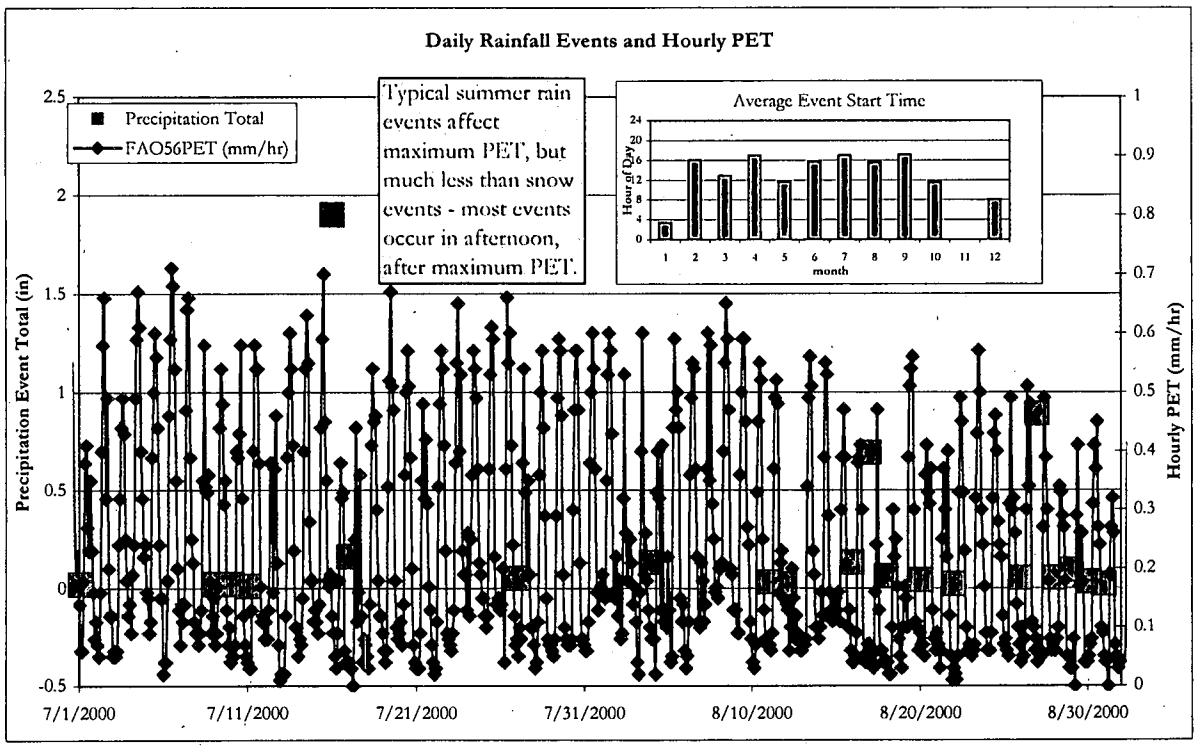


Figure B-6. Daily Precipitation and Hourly PET (Winter and Summer Periods)





The amount of PET (based on hourly estimates using the REF-ET program and Site data) was approximately 51 in (1.3 m). This rate is similar in magnitude to that estimated by Koffer (1989) who calculated annual PET rate for 1989 using the Penman method to be 55 in/yr (1.4 m/yr). Koffer also indicated that a 24-year average produced much lower rates of 39 in/yr (1m/yr). Daniels (1996) estimated AET rates from detailed lysimetric data to be about 22 in/yr (0.6 m/yr) during the unusually wet 1995 year, though he also indicated that annual pan evaporation rates were about 55 in/yr (1.4 m/yr).

B.1.1.2 Vegetation

As noted above, vegetation has a substantial effect on AET and creates a significant stress on the hydrologic system. A review of the scientific literature was conducted to learn about the physical characteristics of vegetation communities found at RFETS. Research focused on quantifying the following specific vegetation parameters:

- Leaf Area Index (LAI) – LAI is the ratio between the amount of leaf area and the amount of ground surface area. Large leafy plants have more surface area, and therefore evapotranspire more moisture to the atmosphere than grasses. The LAI varies over the course of the year in cycle with the growing season. Ranges of LAI values were determined for several of the plant types commonly found at the Site. Mesic grasses common in the Buffer Zone at RFETS, such as *Bouteloua gracilis*, have LAI values ranging from 0.02 in early April to 0.55 in mid-June (Knight, 1973; Hazlett, 1991). In contrast, riparian or wetlands vegetation along the channel bottoms or at seeps have more leaf surface area than grasses and consequently have higher LAI values. The LAI for different *Carex* species, found in wetlands, ranges from 2 to 6 (Aerts and Caluwe, 1994);

- Root Depth – The depth to which roots grow varies widely from one plant species to another. Weaver (1919 and 1920) found the deepest roots of the mesic grassland *Bouteloua gracilis* species at depths of approximately 0.7 to 1 meter (2.4 to 3.3 ft) (0.7 to 1 m). Xeric grassland species root depths ranged from the *Andropogon scoparius*, with a depth of 0.08 meter (0.25 ft) to the *Muhlenbergia*

gracimilla, with a depth of 1.2 m (4 ft) (Weaver, 1919 and 1920). For wetlands, the *Carex acuta* provides a general root depth reference, though it is not specifically found at RFETS. This species has a root depth of 0.35 m (1.1 ft) (Dumortier, 1991); and

- Interception – Interception is a measure of the precipitation depth that is captured and stored on the surface of a plant before the precipitation reaches the ground. Precipitation that is intercepted is available for ET but is not available for infiltration into the ground. A typical value for interception is 0.05 mm (0.002 in).

A discussion of the interpretation of the vegetation parameter values and distribution in the numerical model is presented in Section 5 of the main report. A more extensive discussion of Site vegetation and a vegetation map are presented in Appendix A.

B.1.2 Imported Denver Water Board Water

Another important hydrologic stress on system is imported water. Throughout the year, the Site purchases water from the DWB for on-Site use. The average annual purchase volume (for records from 1996 through 2000) was 420,000 m^3/yr (110 million gallons/ yr). When this value is compared to the average (for the same period of record) annual off-Site discharge of surface water, 970,000 m^3/yr (255 million gallons/ yr).

The water purchased from the DWB is piped onto the Site and stored in the Site Raw Water Pond (see Figure B-7). Water from the Raw Water Pond is pumped to the Site Water Treatment Facility (Building 124), where it is either distributed as raw water to cooling towers or treated and distributed for domestic use. Following use, domestic water is routed to the Site Wastewater Treatment Plant (WWTP) in Building 995. Once treated by the WWTP, water is discharged to Pond B-3. Pond B-3 is transferred daily, during daylight hours, to Pond B-4 which flows directly to Pond B-5. In accordance with pond operation protocols, water in Pond B-5 is released in batches to South Walnut Creek to flow off-Site.

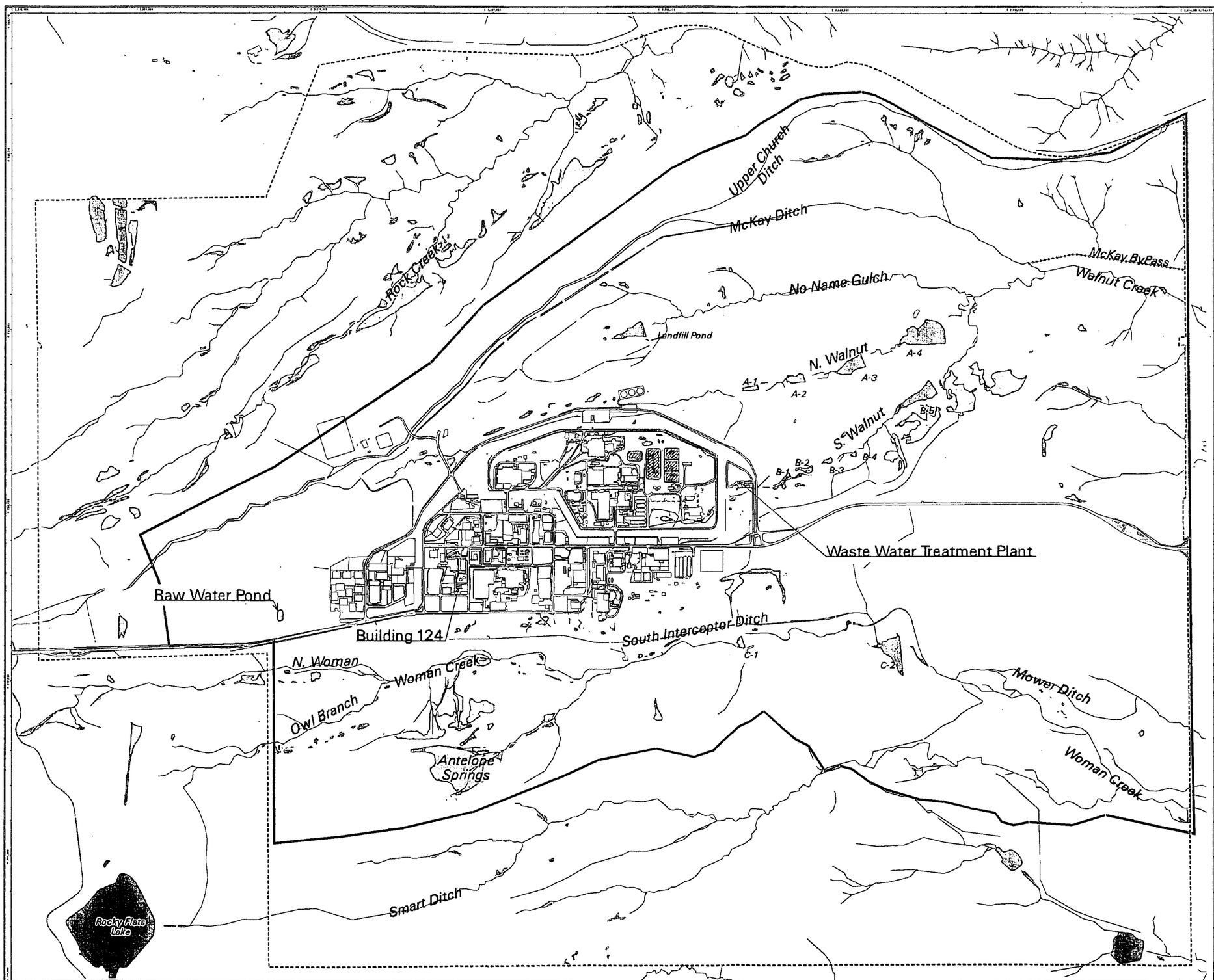


Figure B-7

Site-Wide Water Balance Report

Imported Water Routing through Site

EXPLANATION

- Potential Groundwater Seeps

Standard Map Features

- Buildings and other structures
- Paved roads fill
- Solar Evaporation Ponds (SEPs)
- Lakes and ponds
- Streams, ditches, or other drainage features
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

U.S. Department of Energy
Rocky Flats Environmental Technology Site

GIS Dept. 303-966-7707

Prepared by: DynCorp — THE ART OF TECHNOLOGY

Prepared for: KAISER-HILL COMPANY

May 14, 2003

NT_Svr w:/projects/swwb/fy2002/section_b/surface_water_system.aml

Based on this routing of the DWB water, several Site areas are stressed by the import of water. The Industrial Area subsurface receives water leaking from distribution pipes; Ponds B-3 through B-5 manage the additional flow volume from the WWTP discharge; and South Walnut Creek and Walnut Creek to the Eastern Boundary carry additional discharge volumes. The system response will be discussed in greater detail in Section B.3.1.

B.1.3 Surface Inflow from Western Boundary

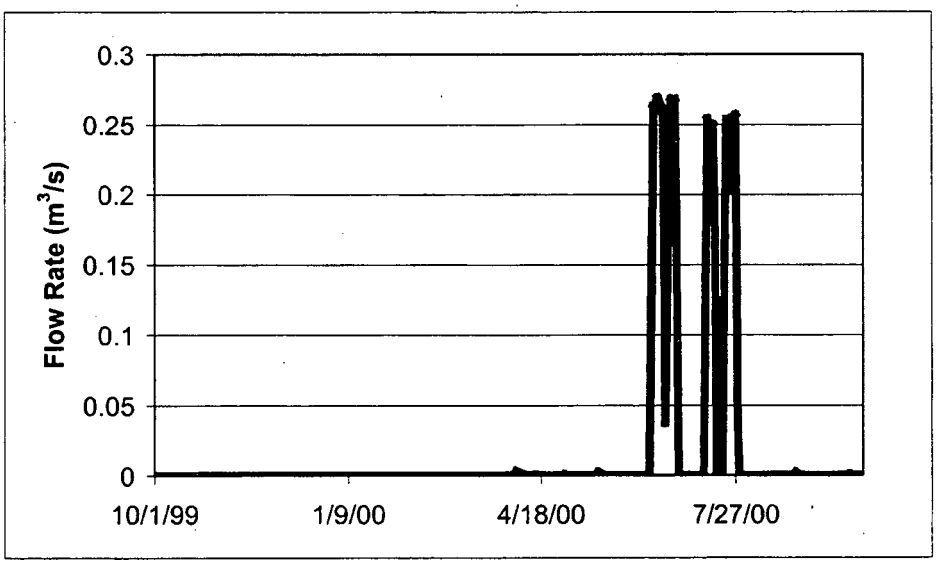
Because the western boundary of the study area divides the larger drainage area, surface inflow to the study area must be considered as a hydrologic stress to the system to define the boundary condition (see Section 5 in the main report). Though surface flow may cross the boundary as both overland and channelized flow, the overland flow contribution was assumed to be negligible compared to the channelized contribution. Discussion of overland flow is provided in Sections B.2.1.1 and B.2.2.1.

From north to south, the channelized inflow points along the western study area boundary are Upper Church Ditch, McKay Ditch, Woman Creek and Owl Branch. These channels are gaged at the study boundary at gaging stations GS45, GS46, GS05 and GS06, respectively (see Figure B-7). Along the southern study area boundary, there is also an surface water channel crossing the boundary (Smart Ditch). Although there is a diversion structure (makeshift quality) in place to direct water away from the study area, the structure is known to leak. Because of the small amount of water involved and the lack of gaged record, this inflow boundary was assumed to contribute no channelized flow.

The catchment for Upper Church Ditch and McKay Ditch (GS45 and GS46) extends roughly 4 km (2.5 miles) west of the study area boundary to Coal Creek. Flow gaged at GS45 and GS46 occasionally includes water pumped from the Boulder Diversion Canal by the City of Broomfield (under junior water rights). Pumping occurred in June and July for WY2000. Flow at these boundary gages is marked by occasional runoff response, but was dominated by intermittent pumping by Broomfield. This can be seen

in the WY2000 annual hydrograph for gages GS45 and GS46 shown below in Figure B-8.

Figure B-8. WY2000 Combined Flow Rate Record for Gages GS45 and GS46

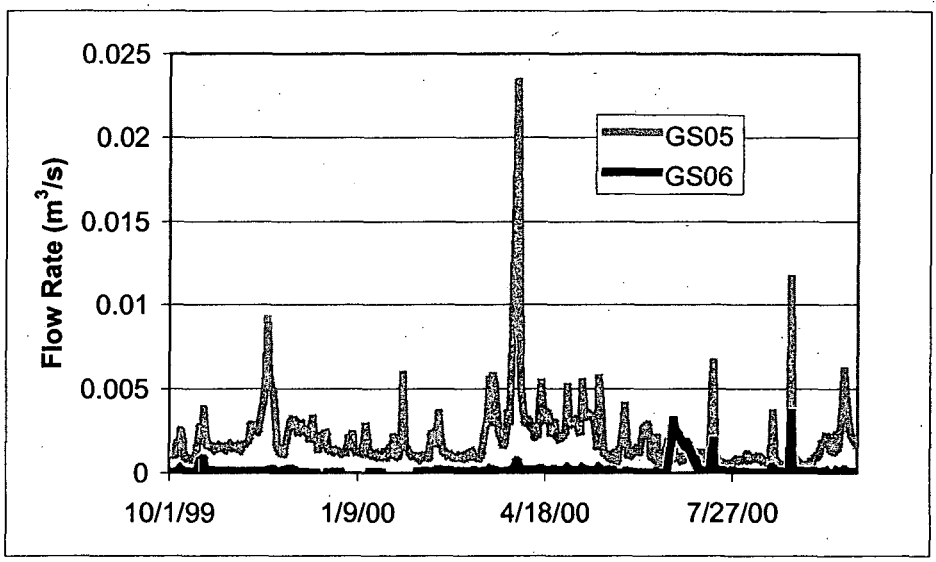


The catchment leading to GS05 extends west roughly 4 km (2.5 miles) to Coal Creek. The GS06 drainage extends west only to the South Boulder Diversion Canal and includes Rocky Flats Lake. Rocky Flats Lake is privately owned and operated and has historically contributed flow to GS06 when discharges were misconfigured. The WY2000 annual hydrograph for gages GS05 and GS06 is presented below in Figure B-9. For more information on these drainages, refer to the Site Master Drainage Plan (EG&G, 1992a).

B.1.4 Pond Management

Management of the Site ponds also constitutes a hydrologic stress on the system. As discussed in the main report, 12 ponds are operated within the SWWB project area. These ponds are operated specifically to minimize contaminant migration and maintain dam safety while managing stormwater runoff.

Figure B-9. WY2000 Flowrate Record for Gages GS05 and GS06



The most significant effect on the system downstream from the ponds can be related to operation of the terminal ponds (Ponds A-4, B-5 and C-2). These ponds are located at the downstream ends of the A-series ponds, the B-series ponds and the SID, respectively. Off-Site discharge of water from the terminal ponds is currently accomplished in batch and release operational modes. The basic procedure for batch release of water is to isolate a terminal pond from inflows[1], monitor to assure compliance with applicable water quality standards and discharge to a tributary exiting the Site. Non-terminal ponds are operated as isolated ponds, as flow-through ponds or batch ponds. Basic operations for each pond are summarized below in Table B-2. This information, as well as historical routing, is presented graphically in Figure B-10.

[1] Note: Only Pond A-4 can be completely isolated from inflows.

*Table B-2. Description of Basic Pond Operational Modes**

Pond Name	Basic Operational Mode	Primary Transfer/ Discharge Destination	WY2000 Transfer/ Discharge Count
Pond A-1	Isolated**	Pond A-2	0
Pond A-2	Isolated**	Pond A-3	0
Pond A-3	Batch and Release	Pond A-4	9
Pond A-4	Batch and Release	North Walnut Creek to off-Site	2
Pond B-1	Isolated**	Pond B-2	0
Pond B-2	Isolated**	Pond A-2	0
Pond B-3	Batch and Release	Pond B-4	366
Pond B-4	Flow Through	Pond B-5	N/A
Pond B-5	Batch and Release	North Walnut Creek to off-Site	8
Pond C-1	Flow Through	Woman Creek to Off-Site	N/A
Pond C-2	Batch and Release	Woman Creek to Off-Site	0
Landfill Pond	Batch and Release	Pond A-3	0

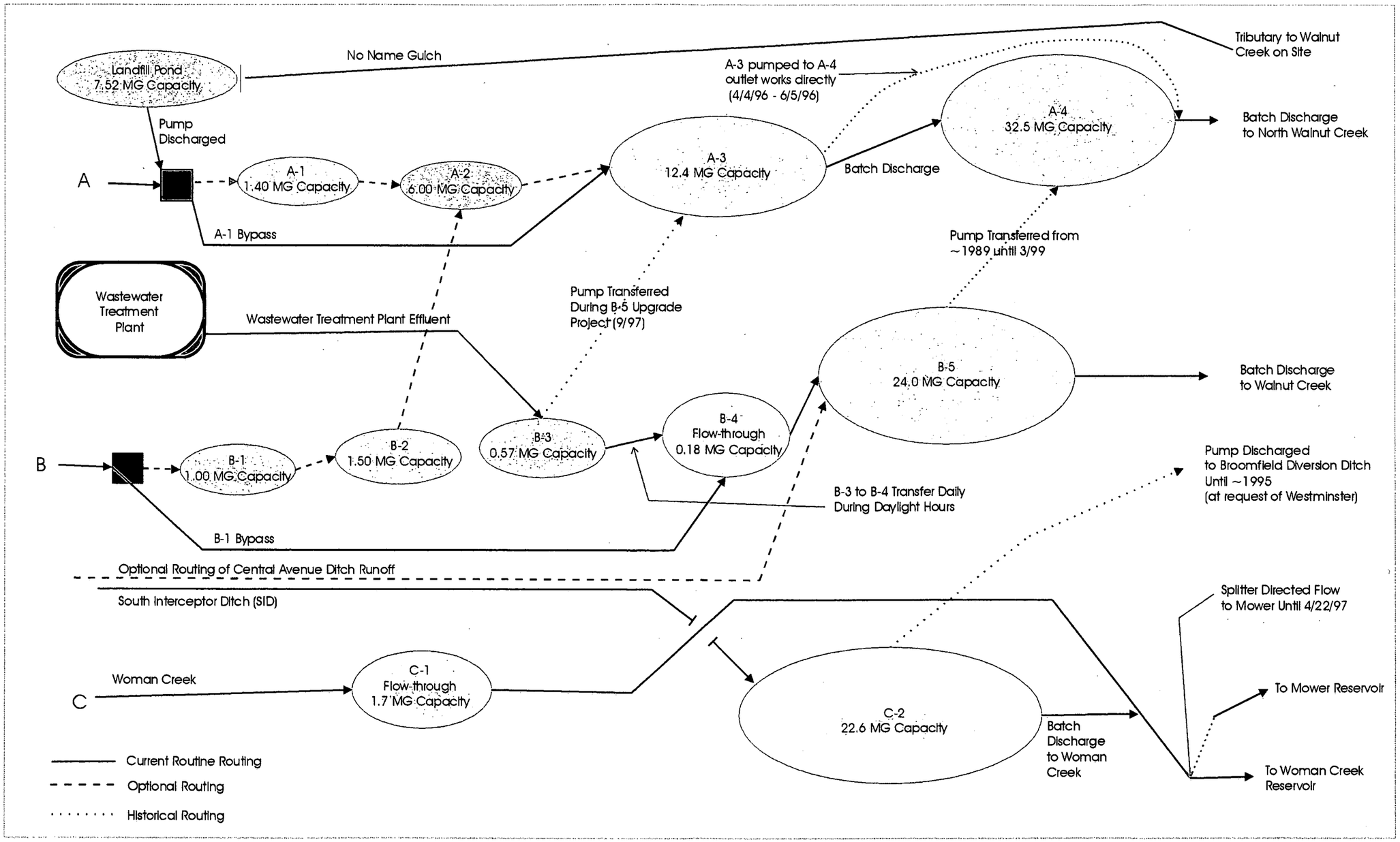
*The drivers for these procedures are the Site *Pond Operations Plan* (POP), the Clean Water Act (CWA), the *Rocky Flats Cleanup Agreement* (RFCA), *State Dam Safety and Dam Construction Regulations* (2 CCR 402-1) and DOE Order 5480.4 *Environmental Protection Safety and Health Standards.*

**Isolated from channelized inflow for normal climate conditions.

For a more detailed description of pond operations and contingencies, refer to the Site *Pond Operations Plan* (POP)(RMRS, 1995).

Local and downstream hydrologic conditions are affected by these operational protocols. For example, detention of water creates local wetland areas, while creating artificial, intermittent channel flow in downstream channels. The hydrologic response of the system to pond management is discussed in detail in B.3.1.3.

Site-Wide Water Balance Report
Figure B-10
Pond Routing Schematic



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B.2 CONCEPTUAL MODEL STRUCTURE

This section describes the structure and hydraulic properties associated with different integrated conceptual model components.

B.2.1 Surface Flow System

B.2.1.1 Overland Flow

Overland flow refers to flow of water over the surface, not including water in channels and ponds. The routing and dynamics of overland flow are determined by the nature of the Site surfaces. Surface feature such as vegetation, buildings, pavement, local depressions and micro-topography all influence overland flow in the model. The structure and hydraulic parameters of the Site surfaces are discussed in the following sections. Factors leading to the generation of overland flow, including soil and vegetation properties, are discussed in detail in section B.2.2.1.

B.2.1.1.1 Surface Structure

B.2.1.1.1.1 Topography

The Site topography determines how overland flow will be routed by gravity to the channel and pond systems. A digital, ground-surface elevation data-set was used to generate the interpolated topographic surface scaled for the model grid. This topographic surface scaled for the model grid resolution, is used directly in the MIKE SHE model. Generally, in the Buffer Zone, the ground surface slopes from the mesa tops to direct overland flow to channels. Routing within the Industrial Area is more complex due to berms roof drains and storm drains.

B.2.1.1.1.2 Impervious Areas

Impervious area refers to surface materials, such as pavement, that allow for a rapid overland runoff response to precipitation and no or little infiltration. Currently, a significant portion of the Site is covered by impervious surfaces. These surfaces include:

(1) asphalt and concrete roads; (2) sidewalks; (3) parking lots; and (4) building rooftops. For the purposed of this project, impervious surfaces were mapped in Arcview from aerial photographs then meticulously ground-truthed.

Most of the impervious surface area is concentrated within the Industrial Area (see Figure 2-1). Within the study area boundary, roughly 6 percent is impervious, while roughly 50 percent is impervious within the Industrial Area. Additionally, though not completely impervious, the New and Present Landfill surface soils are largely impermeable.

B.2.1.1.1.3 Micro-Topography and Local Depressions

Micro-topography and local depressions refer to low-lying areas on a very small scale and on a larger scale, respectively. These areas can trap overland runoff for eventual evaporation or infiltration. In the model, these are combined as depression storage, which is defined, uniformly across a model grid cell, as the depth at which overland flow will occur. Based on general topographic and land surface characteristics within the model area, depression storage characteristics were assessed for two main areas, the Buffer Zone and the Industrial Area.

In the Buffer Zone, Site ponds constitute the main local depressions. In the model, the ponds are defined within the channel network and are not described as part of the overland flow system (see Section B.2.1.3 for more information). Other local depressions, small areas on the east side of the Site where gradients are low, are defined by the topography. The micro-topography was set through calibration efforts to account for small-scale depression storage.

In the Industrial Area, the Solar Ponds (see Figure D-2 in Appendix D) represent the major local depression. This area was set in the model as one meter of depression storage to allow for capture of rainfall. Micro-topography in the Industrial Area was set to zero based on calibration findings. Though there is micro-topography in the Industrial Area, the effect is much less pronounced compared to the Buffer Zone.

B.2.1.1.1.4 Roughness

Surface roughness is a representation of the hindrance to overland flow. Roughness can be a function of vegetation and surface material. In the model, based on calibration simulations, overland roughness was specified for three surface conditions: impervious surface (>45 percent imperious coverage), partially-impervious surface (0 – 45 percent impervious) and vegetated surface. In general, the vegetated surface had a higher roughness, with the lowest roughness assigned to the impervious surface. The resulting hydraulic properties are discussed further in the next section.

B.2.1.1.1.5 Routing

Delineation of the major surface water drainage areas is presented in the main report (Figure 2-1). As discussed previously, overland runoff routing is defined by gravity flow. On the scale of the model grid, this is defined by topography. Other factors that define overland routing include: (1) roof drain orientation; (2) berms; (3) local topography not captured within the model grid scale; and (4) directional channels too small to include in the channel network. To capture the effects of these factors on routing, overland flow areas are defined within the model. These areas subdivide the overland flow regime with no-flow boundaries. These areas were specified based on digital subdrainage delineation of topography and extensive field-truthing by Site hydrologists. These areas are discussed further in Numerical Model Development (Section 5 of the Main Report and Appendix D).

B.2.1.2 Hydraulic Properties

Surface roughness and detention storage depths define the hydraulic properties for overland flow. With no measured values available, these settings were developed during calibration based on a refinement of published values (Chow et. al., 1988).

The overland roughness is defined as a surface Manning M-value (with roughness increasing as the M-value decreases). M-values were differentiated generally based on general surface types for the Buffer Zone and Industrial Area.

Buffer Zone areas can be described as pasture to light brush with weeds to dense brush. Paved areas of the Industrial Area are interspersed with non-paved, grass-covered, gravel covered and packed-dirt areas. Based on these descriptions and calibration efforts with 15-minute flow record, an M-value range of 3 to 20 was established for the overland roughness across the Site. The input for the numerical model is described in Section 5 of the main report.

B.2.1.3 Channel and Pond Flow

In the conceptual model, all channelized flow occurs within the network of Site channels and ponds. Channels and ponds can receive water from overland flow, drain systems, pond discharges, upstream inflows or groundwater infiltration. The significant pathway for loss of water from the channels is to groundwater; whereas, ponds can lose significant water to groundwater, evaporation or manual pond discharges.

The routing and dynamics of channel and pond flow are determined by the structure of the system and Site operations. The structure and hydraulic parameters that make up the channel and pond network are discussed in the following sections. Manual operation of pond discharges and transfers is discussed in Section B.1.4.

B.2.1.3.1 Structure

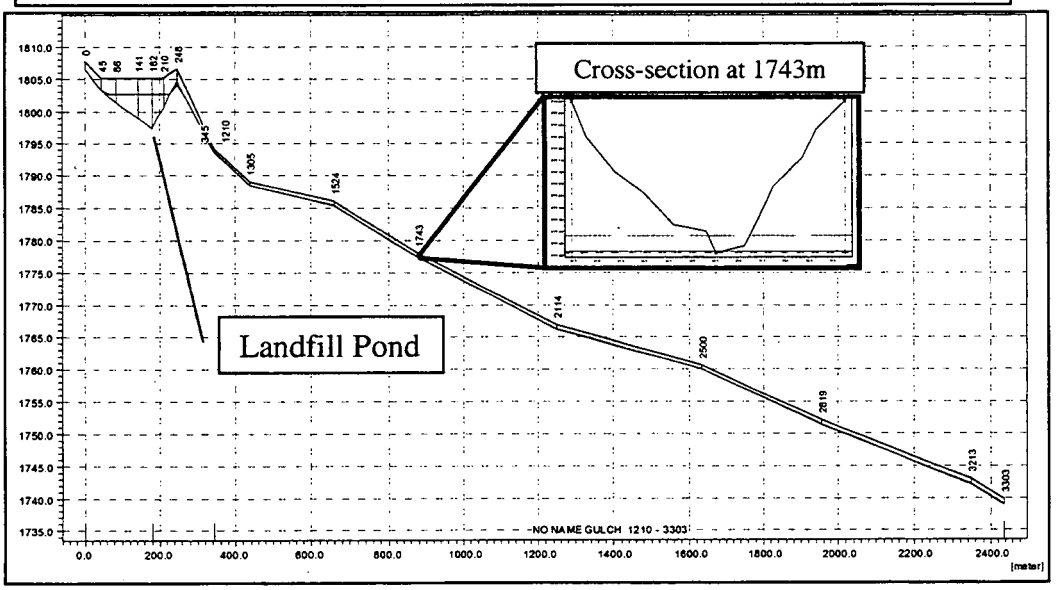
B.2.1.3.1.1 Channel Cross-Sections

The structure of the channels and ponds defines their physical makeup, and how they connect (in three dimensions) to route water and interact with other model components. The structure of both the channels and ponds were defined using available surveyed cross-section data (Kaiser-Hill, 2000d; Merrick, 1992). Where data were unavailable in the Buffer Zone, cross-sections were defined based on the 2-foot contour information and refined based on field observations. In the Industrial Area, channel geometry was assumed to be triangular to allow for stable solutions for fast-moving water on steep slopes. Pond cross-sections, including spillway inverts, were developed from detailed survey information (Woods, 2001).

Channel and pond cross-sections were combined to produce profiles of the surface water flow system. These profiles represent the essential structure of the channelized surface system. An example profile and cross-section are presented in Figure B-11.

Figure B-11. Example Channel Profile and Cross-Section: Landfill Pond and No Name Gulch

Note: X-Axis corresponds to distance (in meters) downstream from inlet to Pond C-2.



Network Complexity

As part of conceptual model development, the appropriate level of channel network complexity was determined. The appropriate level of complexity was defined as the detail needed to capture the required integrated model response (see Section 6 of the main report for more discussion of calibration targets).

The appropriate level of complexity is the most suitable compromise between an overly complex solution and a simple efficient solution. Including every mapped channel and tributary within the model boundary area would have created an over-complicated system with a greater chance for instabilities, undetected error and long run times. Including too

few channels could underestimate channelization (forcing overland flow), resulting in a poor estimates of flow volume and dynamics at measurement points.

The final appropriate complexity was determined using a combination of professional judgement, Site knowledge, field walk-downs and refinement in the calibration process. The result is a network that is highly complex and inclusive of all major drainages and subdrainages. Most simplifications were made to small, poorly-defined tributaries. The final conceptual network is shown overlaying the full channel network in Figure D-4 (Appendix D).

B.2.1.3.2 Hydraulic Properties

Channel roughness is the resistance to flow within the channel, and can be a function of channel bottom and bank materials as well as other material within the channel, such as vegetation, debris or riprap. Channel roughness was researched and tested to complete the hydraulic picture of slope and area created by the structure.

Natural channels on-Site vary greatly in roughness. There are concrete-lined, dirt-lined, and to grass-lined channels within the Industrial Area. Similar conditions exist in the Buffer Zone with areas of riprap drop structures, gravel-bottom channels and cattail-choked channel. Figure B-12 through Figure B-14 are Site photos demonstrating this variability.

A distribution of channel resistance values (defined as Manning M-values) were developed using survey information gathered as part of the Site Actinide Migration Evaluation Project (Kaiser-Hill, 2000d), Site knowledge, field notes and the calibration process. Applied M-values range from 10 to 33.3. This range is reasonable compared to published values in Chow et al. (1988), and the maximum recommended range of 10 to 100 in the *MIKE 11 User Guide* (DHI - Water and Environment, 2000b).

Figure B-12. View of Central Avenue Ditch in the Site Industrial Area

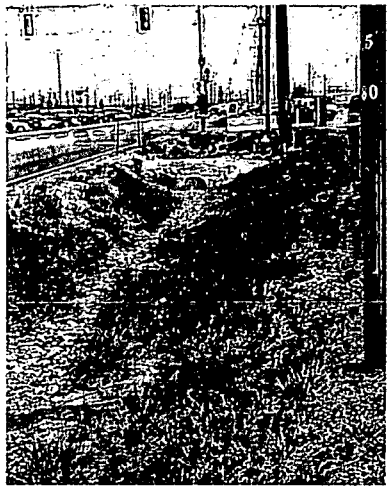
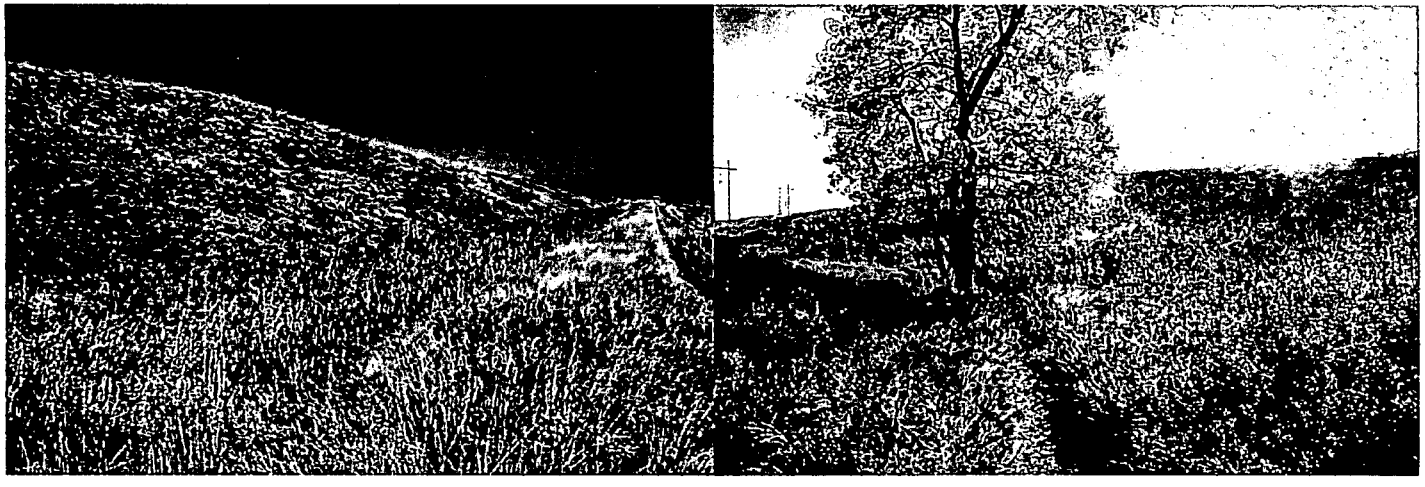


Figure B-13 & 14. Views of South Interceptor Ditch and Lower Walnut Creek (right) in the Buffer Zone



B.2.2 Subsurface Flow System

The subsurface flow system consists of the unsaturated and saturated zones. The unsaturated zone is defined from ground surface to the groundwater table, which varies in time. The saturated zone is defined from the groundwater table to the bottom of the weathered zone. The description of these zones focuses only on relevant aspects to developing the MIKE SHE model. The structure and hydraulic properties of the unsaturated zone are described in Section 3.3.2.1 and saturated zone of the in Section 3.2.2.2.

B.2.2.1 Unsaturated Zone

B.2.2.1.1 Structure

The U.S. Geologic Survey (USGS) surficial deposits (shown on Figure B-15) were used to define the spatial distribution of unconsolidated material that comprise the unsaturated zone in the model area. A full description of the unconsolidated material is described in detail in the Hydrogeologic and Geologic Characterization Reports (EG&G 1995a and 1995b). The United States Department of Agriculture (USDA) Soil Conservation Service (SCS) developed map units based on aerial photographs to reasonably predict the soil types that have formed near the surface on the geologic units in the area. Although, this information is useful in erosion modeling (Kaiser-Hill, 2000d), it was not used for the SWWB model to define the unsaturated zone because hydraulic properties were only for the near-surface soils and were less consistent with on-Site unsaturated and saturated zone distributions.

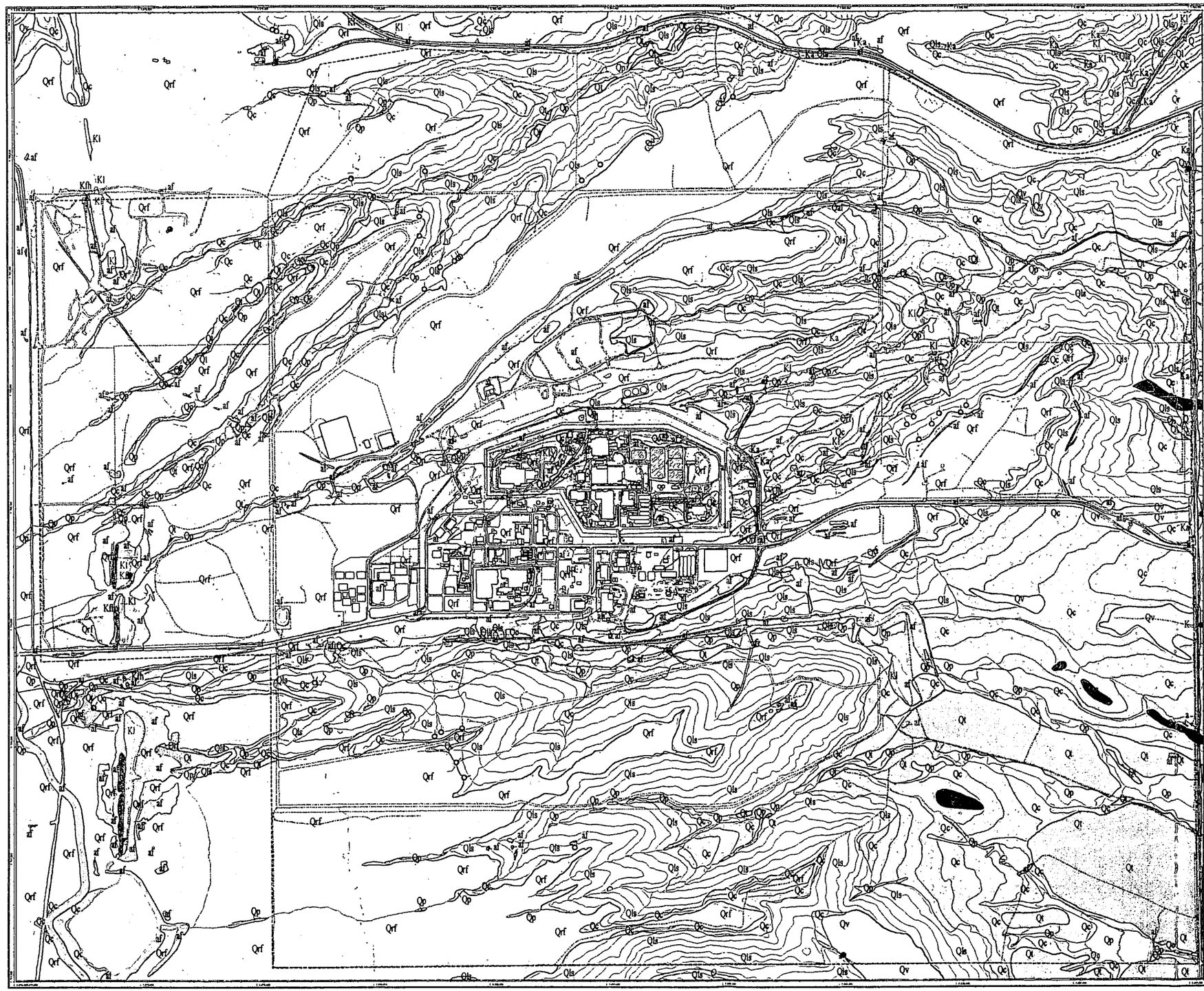


Figure B-15

Site-Wide Water Balance Report

Surficial Geologic Map

Produced in cooperation with the U.S. Geological Survey

Geologic Map Units

af - Artificial fill
Qp - Post-Piney Creek and Piney Creek Alluvium
Qt - Terrace Alluvium
Qc - Colluvium
Qls - Landslide deposits
Qs - Slocum Alluvium
Qv - Verdos Alluvium
Qrf - Rocky Flats Alluvium
Ka - Arapahoe Formation
Kl - Laramie Formation
Kfh - Fox Hills Sandstone

Symbols

- Shallow closed depression
- Scarp of young landslide
- Areas of vegetation at and near springs
- Boundary of gravel and clay pit
- Spring
- Strike and dip of beds
- Clast identification site
- Capitol Mine (abandoned)
- Geologic Units boundaries

Standard Map Features

- Buildings and other structures
- Solar Evaporation Ponds (SEPs)
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Topographic Contour (20-Foot)
- Rocky Flats boundary
- Paved roads
- Dirt roads

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

Topographic contours were derived from digital elevation model (DEM) data by Morrison Knudson (MK) using ESRI Arc TIN and LATTICE to process the DEM data to create 5-foot contours. The DEM data was captured by the Remote Sensing Lab, Las Vegas, NV, 1994 Aerial Flyover at ~ 10 meter resolution. DEM post-processing performed by MK, Winter 1997.

Location of buildings, roads, and fences by Facilities Engr., EG&G Rocky Flats, Inc. - 1991.
Hydrology by Water Resources Division USGS - (date and author unknown)
Geologic Mapping : Shroba, R.R., and Carrara, P.E. Preliminary Surficial Geologic Map of the Rocky Flats Plant and Vicinity, Jefferson and Boulder Counties, Colorado: U.S. Geological Survey Open-File Report 94-162, Scale 1:6000
Site source of topo base; see OFR 94-162 (on map).

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Phone: (303) 966-3387
Pager: (303) 212-6255

N

4.5 0 9.0 18.0 Miles

2.50 0 5.00 10.00 K

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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Different studies have described possible hydrologic effects of features like macropores, caliche layers and interflow. However effects of these on the system hydrology were considered secondary to average unsaturated zone hydraulic properties. At the regional SWWB model scale, the USGS surficial deposits are assumed to represent average unsaturated zone conditions. (A low permeability caliche layer, occurring mostly in the unsaturated zone, exists over part of the model area (Smith, 2001); however, Koffer (1989) found that this layer is fractured due to the frost action and does not prevent groundwater recharge).

Typical thickness of the unsaturated zone varies from 0 ft, usually at or near streams, to about 100 ft (30.5 m) near the western model boundary. Its structure is assumed to be regionally homogenous within each surficial geology type as defined by the USGS surficial deposit areas. The exception is that in some limited areas, like the Industrial Area, groundwater levels are below the bottom of the unconsolidated materials (i.e., in the bedrock). Under these conditions, the unsaturated zone is defined by two distinct layers, the higher permeability unconsolidated material and underlying bedrock layer. As groundwater levels change throughout the year, the extent of these areas also changes. Over the scale of the model, these areas are limited in extent; the important processes, like infiltration and groundwater recharge, will be dominated by the structure of overlying unconsolidated materials.

B.2.2.1.2 Hydraulic Properties

For the model area, data on unsaturated zone hydraulic properties are limited in horizontal and vertical extent. Important hydraulic properties controlling the unsaturated zone flow included: (1) the saturated hydraulic conductivity; (2) moisture retention characteristics; and (3) pressure-variant unsaturated hydraulic conductivity variation. The saturated hydraulic conductivity data was probably the most important property because it controlled surface ponding and recharge rates. The only study that provided regional scale data is by Fedors and Warner (1993). They used tensiometers to obtain unsaturated zone properties for the top 15 cm of surface soil at RFETS. Figure B-15

shows USGS surficial deposits used to define regional scale unsaturated zone hydraulic properties.

Three primary soil types were defined based on the USGS surficial deposits and Fedors and Warner (1993) study. They consist of Rocky Flats Alluvium (Qrf), Colluvium (Qc) and Valley-Fill Alluvium (Qvf). From this study, Table B-3 summarizes key hydraulic data derived from this study for these three surficial deposits. The Colluvium includes all soil types except Qrf and Qvf. The distribution of these soil types is shown on Figure B-15. Artificial fill (af) areas are assumed to take on similar soil properties as the native material they replaced (i.e., adjacent soils give good indication).

Retention characteristics for the three primary surficial deposits are nearly indistinguishable. Residual and saturated moisture contents for each of the soil types are similar (i.e., ranging from about 0.18 to 0.44). The number of tensiometer tests performed for Qrf, Qc and Qvf soils are 24, 13 and 11, respectively. Geometric means of the saturated hydraulic conductivity values based on tensiometer results indicate relatively high values for all three soils, with the Qrf (24 samples) being highest (0.0002 m/s) in Table B-3. Apparently, these *in-situ* tests are two to three times higher than estimates derived in the laboratory, or by grain-size distribution methods. Fedors and Warner attributed this notable difference to the ability of the tensiometers to measure the *in-situ* effect of structure like macropores. The tensiometer-derived saturated hydraulic conductivity values were also about two orders magnitude higher than estimates obtained through well data. Based on the limited occurrence of overland flow and relatively high recharge rates previously reported (Kaiser-Hill, 2000d), it was reasonable to assume that saturated hydraulic conductivity values in the unsaturated zone are higher at the surface and probably decrease to the groundwater table.

Table B-3. Unsaturated Zone Hydraulic Properties

			Unsaturated Hydraulic Properties (Fedors and Warner, 1993)				
	Thetasat	Thetar	Lab Ksat m/sec	Rawls et al Method m/sec	Kozeny-Carman McWhorter 1977 m/sec	Fair-Hatch formula Fair & Hatch, 1933 m/sec	Ksat - Tensiometer. (geomean) m/sec
Qal	0.42	0.18	6.78E-08	7.78E-07	2.16E-05	1.35E-07	6.3E-05
Qc	0.44	0.23	8.20E-07	5.70E-07	1.40E-04	1.00E-05	4.3E-05
Qrf	0.43	0.18	7.16E-07				2.4E-04

Note: Geometric mean of Qrf is high compared to Ksaturated from well data.

B.2.2.2 Saturated Zone

B.2.2.2.1 Hydrogeologic Structure

Details of the Site geologic data are summarized in the Geologic Characterization Report (EG&G, 1995b). The structure of the saturated flow zone is defined by the Upper Hydrostratigraphic Surface (UHSU) presented in the Hydrogeologic Characterization report (EG&G, 1995a). The two key hydrogeologic units within the UHSU are the weathered bedrock and overlying unconsolidated material. Descriptions of the lithology in both of these units are presented in Appendix A. Additional borehole data from geotechnical investigations prior to Site construction and from post-1995 environmental wells, were used to modify the top surface of the weathered bedrock, unweathered bedrock and the Arapahoe Sandstone units all of which were defined in the EG&G report (1995a). General characteristics of these modified geologic units are described below. The approach and data used to develop these structures are presented in Section B.2.2.2.1.1.

The most important hydrogeologic structure in the model area is the surface between the unconsolidated materials and the weathered bedrock zone (Arapahoe and Upper Laramie Formations). The top of the weathered bedrock is shown on Figure B-16.

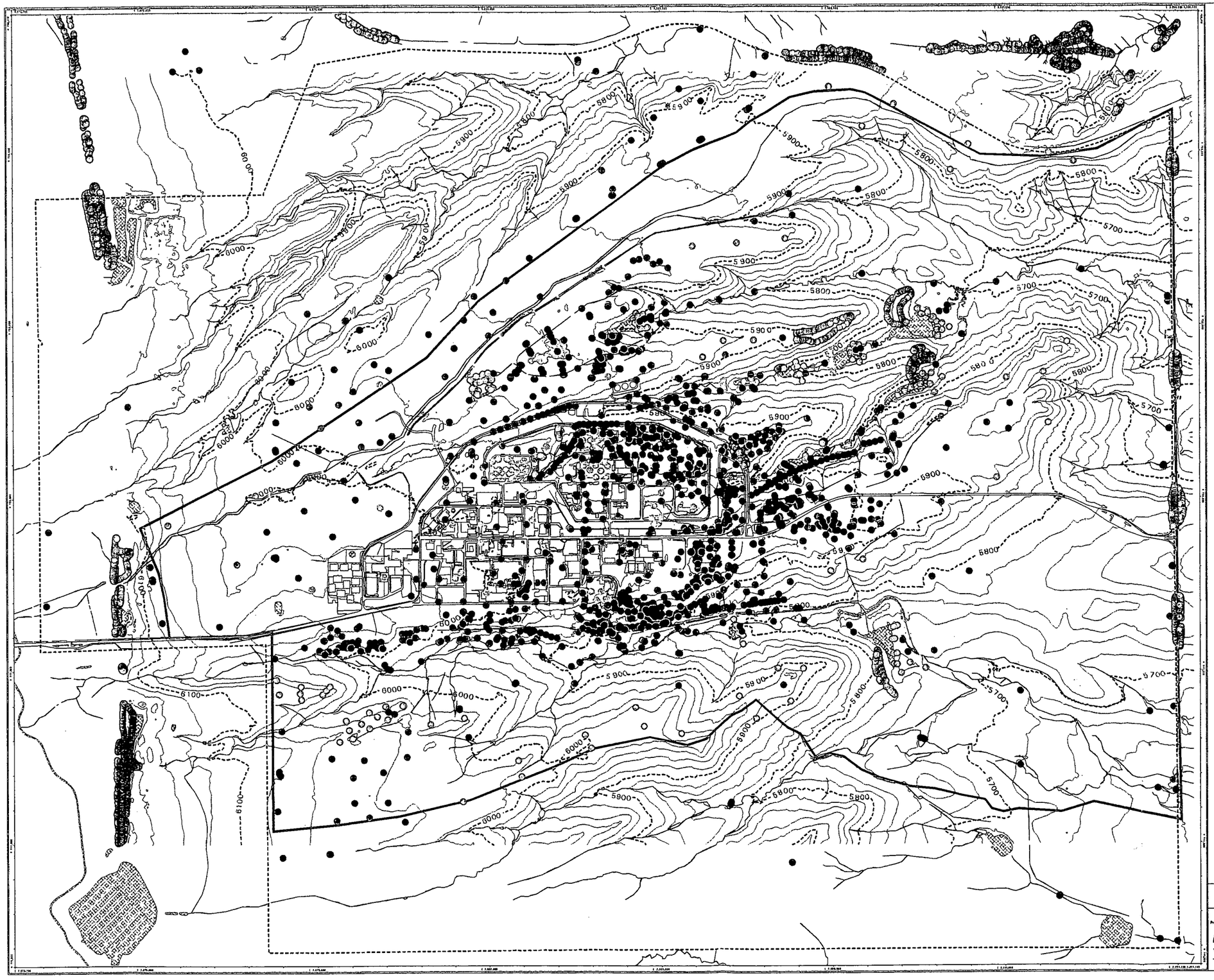

Figure B-16

Site-Wide Water Balance Report

Weathered Bedrock Surface

EXPLANATION

- Top of Weathered Bedrock (100 foot interval)
- Top of Weathered Bedrock (20 foot interval)
- Site Master 14 Well Database
- Environmental Borings
- Engineering Borings
- Interpolation Control Points

Standard Map Features

- Lakes and ponds
- Streams, ditches, or other drainage features
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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May 13, 2002

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This contact surface extends over the entire model area, except where it outcrops in small isolated areas. The weathered bedrock layer exhibits higher permeabilities than the underlying unweathered bedrock and therefore, a second surface is defined by this contact. Over the scale of the model, the top of the weathered bedrock surface follows the surface topography. It is deeper to the west (40 to 100 ft thick) (12.1 to 30.5 m) and thins to the east (5 to 30 ft) (1.5 to 9.1 m).

The bottom of the UHSU is also defined by this contact surface. This contact is less well defined than the top of the weathered bedrock, because it is based more on observable weathering features (i.e., fractures, friability iron-oxide stains) than on lithology. The top of the unweathered bedrock (Figure B-17) closely mimics the top of the weathered bedrock surface. Locally, the weathered bedrock thickness ranges from 10 to 60 ft (3 to 18.3 m) thins to the east.

The last important geologic structure is the Arapahoe Formation Sandstone, a permeable bedrock unit embedded within the claystone/siltstone matrix of the Arapahoe and Laramie Formations (its thickness and lateral extent is shown on Figure B-18). The Arapahoe Formation Sandstone distribution is not well characterized by borehole data outside of the Industrial Area (i.e., higher density of wells). They are stratigraphically located in the upper parts of the weathered bedrock where they subcrop the unconsolidated material. The sandstones important hydraulically because they route water preferentially through the weathered bedrock and can control discharge through some seeps.

B.2.2.2.1.1 Development of Subsurface Geologic Structures

For the purposes of the SWWB modeling project, geologic surfaces were refined from the EG&G 1995 reports using additional data. The approach used to modify the following geologic structures included:

- Top of weathered bedrock surface;
- Top of the unweathered bedrock; and

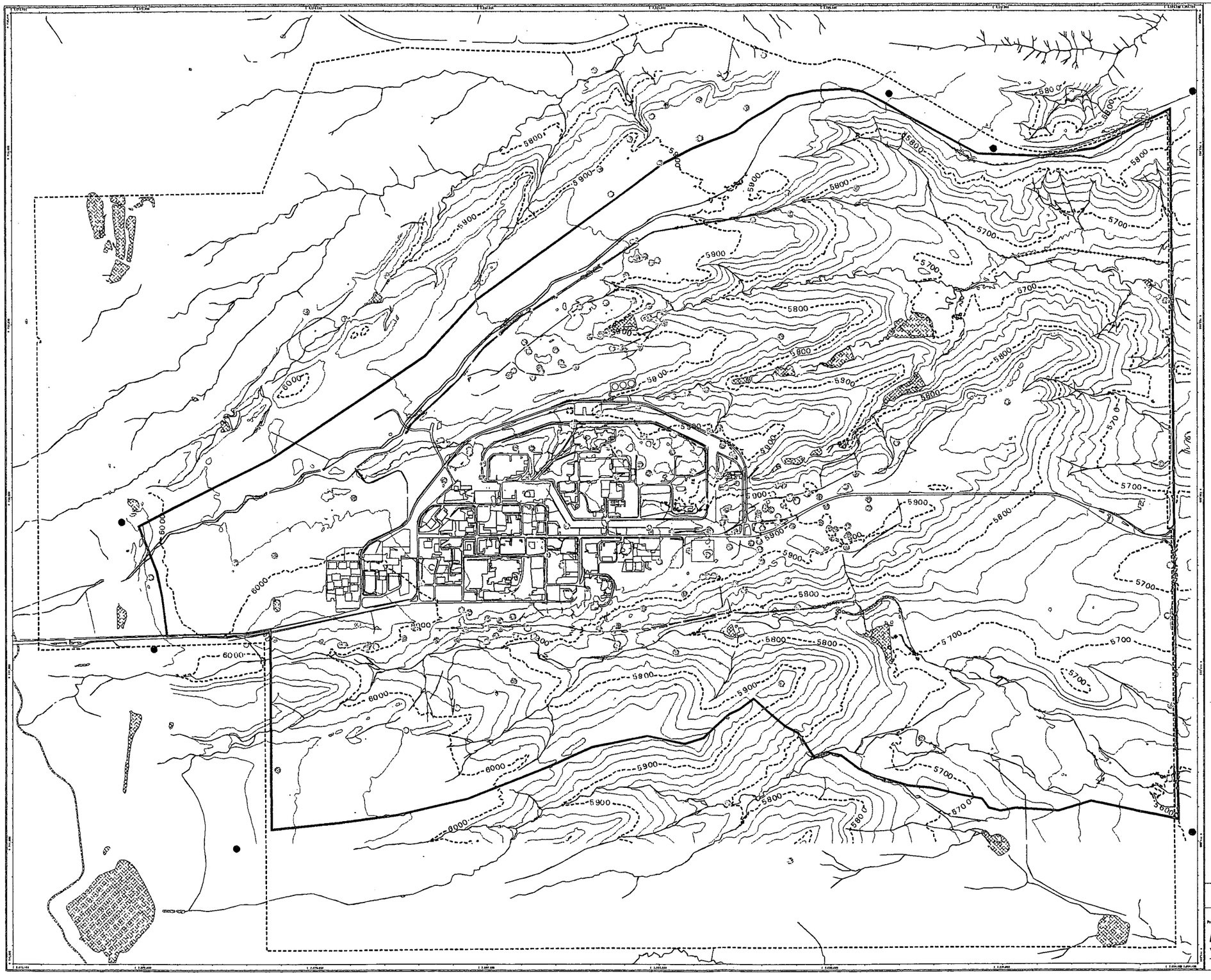

Figure B-17

Site-Wide Water Balance Report

Unweathered Bedrock Surface

EXPLANATION

- Top of Unweathered Bedrock (100 foot interval)
- Top of Unweathered Bedrock (20 foot interval)
- Boring Control Points
- Interpolation Control Points

Standard Map Features

- Lakes and ponds
- Streams, ditches, or other drainage features
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:
Boring control points are from the Site Master 14 well database and environmental borings.

50 0 100 200m
250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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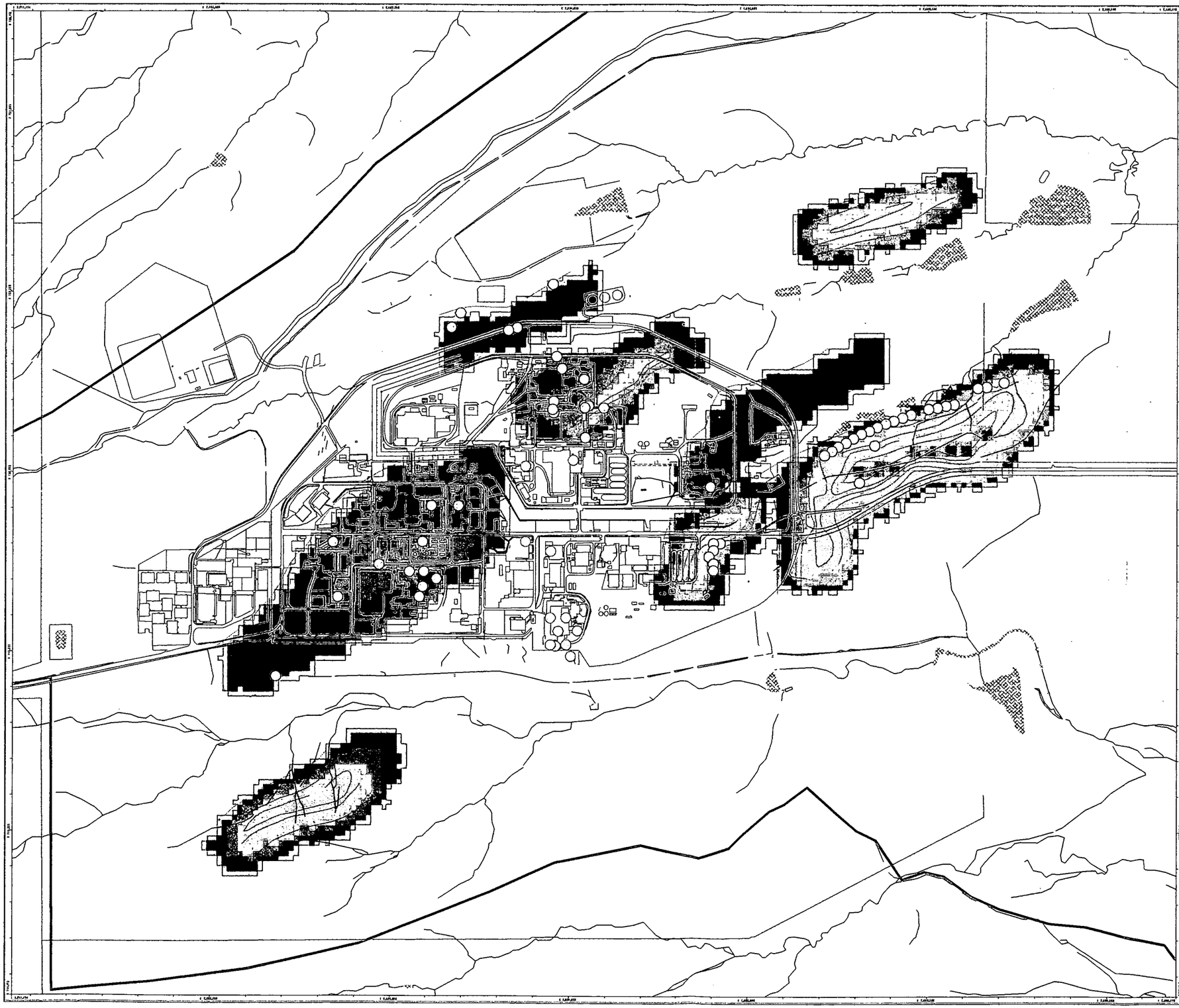

Figure B-18

Site-Wide Water Balance Report

Interpreted Lateral Extent and Thickness of Arapahoe Sandstone

EXPLANATION

- Additional Sandstone Borehole Data Point (not from EG&G 1995b report)
- Arapahoe Isoliths

Thickness (ft)

- 1 - 2 (0.3 - 0.6 m)
- 2 - 4 (0.6 - 1.2 m)
- 4 - 6 (1.2 - 1.8 m)
- 6 - 8 (1.8 - 2.4 m)
- 8 - 26 (2.4 - 7.9 m)
- 26 - 30 (7.9 - 9.1 m)
- 30 - 34 (9.1 - 10.4 m)
- 34 - 40 (10.4 - 12.2 m)

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Paved roads
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:
Base contours taken from EG&G (1995b), modified with additional points from geotechnical borehole data.

45 0 90 180m
250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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- Occurrence and thickness of the Arapahoe Sandstone.

The basic approach used to develop each geologic surface involved the following steps:

- Depths below ground surface at each control point were used to create interpolated surfaces of depths (this approach prevents typical overshoot and undershoot problems when interpolating elevation data);
- Next, interpolated surfaces were reviewed for obvious outlier points (these were removed and the surface re-interpolated);
- This surface was then interpolated onto a regularly spaced, 10-ft (3 m) grid over the entire model area (a depth value was obtained for each 10-ft grid point);
- The interpolated grid points were then imported to a database where they were subtracted from ground surface elevations also interpolated onto the same 10-ft regularly-spaced grid to produce geologic surface elevations for the units indicated above; and
- The interpolated geologic surfaces in the database at 10-ft grid spacings were averaged using GIS techniques to estimate appropriate average elevations for each MIKE SHE grid cell.

Data used to create the geologic surfaces was provided by the Site Geologist (Smith, 2001). Available data were obtained from a master well list originally developed by EG&G (1995b) and from supplemental environmental and engineering borehole databases (Smith, 2001).

B.2.2.2.1.1.1 Top of Weathered Bedrock

The master well list was reviewed and only wells with bedrock contact information were used. All wells without coordinates were also removed, leaving 905 control points. The environmental and geotechnical engineering borehole datasets were processed in the same manner. After purging, these provided 633 and 157 additional points, respectively.

The 1695 data points were then used to interpolate an initial surface using a Natural Neighbor algorithm in the Surfer Program, by Golden Software. Approximately 2.5 million grid points were used to define the interpolated surface to capture details of the surface. Interpreted surfaces were reviewed by a Site Geologist (Smith, 2001). His suggestions were incorporated prior to using the surface in the model. Additional control points were added for in bedrock outcrop areas. Data from engineering boreholes A-7, A-32 to A-35 and B-10 to B-18 were removed as outliers. Additional control points were added iteratively to reproduce Site features like dams and the shooting range. Control points were also added in areas of sparse borehole data. This includes plateau ridges and areas external to the model boundary.

Figure B-16 shows the final interpolated top of weathered bedrock surface, including surface control points and additional controls to aid interpolation. General observations are presented in Section 3.3.2.2.1.1.

B.2.2.2.1.1.2 Top of Unweathered Bedrock

An identical procedure was used to create the top of unweathered bedrock surface. Because this contact is more difficult to identify and is deeper, much fewer control points were available. As such, it was less constrained. The master well list provided 121 control points, and 95 control points were added from the environmental dataset. Figure B-17 shows the contoured top of unweathered bedrock surface, including control points. General observations are presented in Section 3.3.2.2.1.1.

B.2.2.2.1.1.3 Definition of Arapahoe Sandstone

The distribution of Arapahoe formation sandstones were digitized from the Geological Characterization Report (EG&G, 1995). A total of 71 additional borings with Arapahoe Sandstone contacts were used improve the EG&G surfaces. The reported sandstone depths and cross-sections were examined to determine which sandstone lenses were interbedded.

In the MIKE SHE model, where Arapahoe Sandstone lenses subcrop unconsolidated material, Model Layer 3 was assigned to the entire unit. Otherwise, Arapahoe Sandstone lenses (embedded in the siltstone/claystone matrix of the Arapahoe or Laramie Formations) were assumed to be part of Model Layer 4. In these cases, Model Layer 3 was assumed to be a minimum thickness of 0.5 m of claystone/siltstone material, while the thickness of Model Layer 4 was defined by the Arapahoe Sandstone thickness determined through analysis of the new geologic data, and a claystone/siltstone matrix to the bottom of the weathered bedrock zone. A composite horizontal hydraulic conductivity for Model Layer 4 was determined based on the relative thickness of the Arapahoe Sandstone and claystone/siltstone matrix. Figure B-18 shows the lateral extent and thickness of the Arapahoe Sandstone included in the SWWB model.

B.2.2.2.2 Subsurface Utilities and Remediation Systems

The structure associated with the subsurface utilities is described here, while the flow responses are described in B.3.2.4. The subsurface utilities description provided here also includes groundwater remediation systems.

In general, there are two ways that the subsurface utilities affect groundwater flow; one is through pipeflow interactions with groundwater and the other is the effect of higher permeability trench backfill material. Pipes that route fluids likely influence groundwater flows more than trenches, but trenches for all utilities are more extensive. Although, subsurface utility locations are known reasonably well, flow conceptualization was difficult because specific as-built details such as depth, width, backfill material or effective leakance values were generally unavailable. As a result, the flow conceptualizations were based on the best information available.

Four primary types of subsurface pipelines are considered hydraulically important to flow within the Industrial Area. These include the following:

- Footing Drains;
- Storm Drains;

- Sanitary Sewers; and
- Water Supply Lines.

In addition to these pipelines, trench effects on groundwater are considered for the following utilities:

- Alarms;
- Communications;
- Natural Gas;
- Process Waste Lines; and
- Electric.

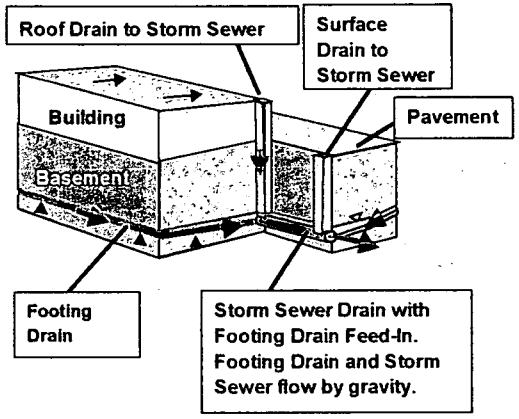
The following groundwater remediation systems are also considered in the conceptual flow model for the RFETS:

- Solar Pond Treatment System;
- Present Landfill:
  - Groundwater Interception Trench, and
  - Slurry Wall;
- East Trench System;
- Mound Plume System; and
- 881-Hillside French Drain System.

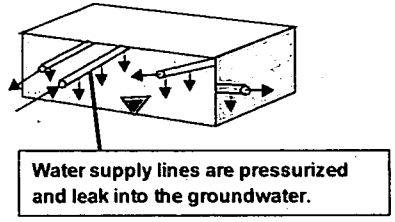
Figure B-19 illustrates the structure and flow for each of the four primary pipe utilities. Building footing drains discharge groundwater into nearby streams, the ground surface or adjacent subsurface storm drain system. These drains are efficient at maintaining constant water levels in the vicinity of buildings to prevent inflows to basements. Storm drains behave similarly, but are not associated with buildings and direct flows to the main Industrial Area drainage channels (i.e. SW093, GS10 and SW027) via gravity flow. Although flow can leak from storm drains into groundwater (during events), net flow estimates (ASI, 1991c) suggest these act more as groundwater drains.

Figure B-19. Structure and Flow for Each of the Four Primary Pipe Utilities

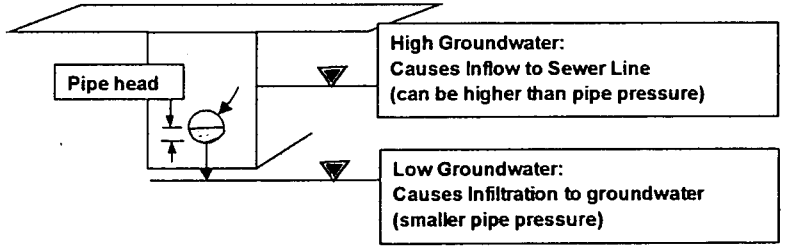
Storm Drains and Building Footing Drains



Water Supply Lines



Sanitary Sewer Lines



Sanitary sewers act as groundwater drains where groundwater levels are higher than the internal pipe flow levels, and as a source of groundwater recharge where groundwater levels are below internal levels. Based on net flow estimates (ASI, 1991a), these pipelines are thought to be more effective groundwater drains. Water supply lines are pressurized, but typically leak in urban settings. Therefore, these lines were assumed to only provide recharge to the groundwater.

Backfill trench effects on groundwater flow are shown on Figure B-19. Groundwater can be preferentially routed along trenches if levels rise up above the trench invert elevations. This is because the trench backfill material around the utility lines is typically a higher permeability material (like sand) than the upper backfill material (native soils).

B.2.2.2.2.1 Utility trench dimensions and backfill material

Underground utilities are usually located in backfilled trenches or in concrete ducts within such trenches. The process of excavating a trench, laying bedding material, laying the utility (or duct) and backfilling the trench usually disturbs the native soil and changes its engineering and hydraulic properties. The extent to which these properties are affected depends on the following: (1) the trench length; (2) width and depth; (3) whether bedding material is laid at the base of the trench; and (4) how the remainder of the trench is backfilled and compacted.

No as-built drawings of trench construction were available from a search of Site Engineering Records. However, a few drawings showed planned trench construction techniques. Table B-4 summarizes information on utility trench dimensions and backfill material.

Table B-5 summarizes information on subsurface utility trench depths and lengths based on analysis of available data. Two sources of information were used to determine the utility depths, the Site Utility Plan (DOE, 1999a) and Site engineering drawings. Depths specified in the MIKE SHE model considered information from both sources. Depths for footing, storm and sanitary drains are variable throughout the model area and were based on information available in Site engineering drawings.

Table B-4. Subsurface Utility Trench Details – Engineering Drawings

Utility	Depth	Width	Backfill
Raw water	Average 6'	Pipe OD +12"	Sand and/or soil
Firewater	Average 6'	Pipe OD +12"	Sand and/or soil
Potable water	Average 6'	Pipe OD +12"	Sand and/or soil
Process line	Varies	Pipe OD +12"	Sand and/or soil
Steam[2]	Average 7'	Pipe OD +12"	Sand and/or soil
Condensate[2]	Average 7'	Pipe OD +12"	Sand and/or soil
Footing drains[3]	Varies	Pipe OD +12"	Sand and/or soil
Storm drain/culvert[3]	Varies	2'-7-½"	Sand below or around; compacted soil or concrete above
Sanitary sewer	Varies, ≥3'	Pipe OD + 16"	Strip of sand below pipe, 0.5OD x ≥6"; compacted soil around & above pipe; manholes may leak
Nitrogen[2]	Average 7.5'	Pipe OD +12"	Sand and/or soil
Electric power	≥3'	Pipe OD +12"	} May be in
Telephone	Average 4.5'	Pipe OD +12"	} combined trench
Alarm	Average 4.5'	Pipe OD +12"	} or duct
Data	Average 7'	Pipe OD +12"	Sand and/or soil

Table B-5. Sub-Surface Utility Summary

Utility	[1]Utility Depth (ft, bgs)	Reference	Utility Depth (Engineering Drawing Review) (ft, bgs)	[2]Trench Depth below pipe invert (ft, bgs)	Assumed Utility Depths (feet, bgs)	[2]Trench Widths (feet)	Total Utility Length (miles)
1 Footing Drains		Site Engineering Drawings	Varies	0.5	Eng. Drawing	2	5.0
2 Storm Drains	4' - 8'	From Diana Woods[3](DRIP)	Varies	0.5	Eng. Drawing or 6'	2	9.6
3 Sanitary Sewer	4' - 8'	From Diana Woods (manhole inverts)	Average 3'	0.5	10' - [3]DRIP study	2	10.2/12.5
4 Water Supply Lines	5' - 8'	[4]Master Utility	Average 6'	0.5	6	2	28.6
5 Alarm Lines	2'-6" - 3'	Master Utility	Average 4.5'	0.5	3	2	18.1
6 Communications	1' - 8'	Master Utility	Average 4.5'	0.5	4.5	2	39.0
7 Natural Gas	4'	Master Utility	Average 7.5'	0.5	4	2	10.2
8 Electric	1'-6" - 3'	Master Utility	>3'	0.5	3	2	69.2
9 Process Waste	4' - 8'	Master Utility	Varies	0.5	8	2	8.9
							211.0

Notes:
1 Utility depth ranges obtained from Master Utility Plan (DOE. 1999a).
2 Utility trench depth below pipe invert and trench width are both assumed values based on engineering drawing reviews.
3 Hayes, W.L., Woods, D.K., and Yashan, D., 1994. Drainage Repairs and Improvements Plan for the RFETS.
4 Master Utility (DOE. 1999a)
5 Discussion with site excavators indicated that trench widths were typically 2 feet wide, though if pipes were buried below 5 feet, at the groundsurface the trench width could be as much as 5 feet wide. For the purposes of modeling, trench widths were assumed to be 2 feet wide.
6 Based on review of existing site engineering drawings indicate backfill material is more typically sand.
7 Trench backfill material overlying the sand placed beneath and around utility pipes is assumed to be adjacent native material.

B.2.2.2.2.2 Sanitary Lines

The best available data on sanitary sewers were obtained from the Site Engineering Records and are shown on Figure B-20. Two types of lines are present, active and inactive lines. The total combined length of utility lines is 12.5 miles, while active lines are only 10.2 miles in length. Active lines affect groundwater in two ways, through flow interactions with pipeflow and by trench backfill material. Trenches of inactive lines are assumed left in place. Therefore, groundwater flow will be affected by only the permeable trench backfill material. Pipe invert elevations were determined only for active lines from manhole inlet/outlet inverts (Woods, 2001).

B.2.2.2.2.3 Storm Sewers

Storm sewer lines shown on Figure B-21 were obtained from the Site GIS group, with edits from the Site Subject Matter Expert (Squibb, 2001). These lines connect to the main Industrial Area surface drainages (i.e., SW093, GS10 and SW027) from parking lots or buildings. The original coverage included surface culverts and drain segments too short (i.e., less than 50 ft) (15.2 m) to consider in the modeling report. These features were removed from the coverage, resulting in a total length of approximately 9.6 miles (15.4 km). Assumptions were made in defining the connectivity of the some storm drains to larger Industrial Area streams, because the original coverage was unclear. Invert elevations were obtained mainly from engineering drawings for the main surface drainages included in the Drain Repairs and Improvement Plan (DRIP), (Hayes et. al., 94). Other invert elevations were obtained through detailed review of individual building plans, mainly in the SW027 catchment.

B.2.2.2.2.4 Building Footing Drain Lines

Figure B-22 shows the outline of building footing drain lines. The Site does not have a monitoring program in place to monitor flow at all footing drain outfall locations. For the purposes of the SWWB project, a Site-wide assessment of footing drain outfall locations was conducted. Existing published information (EG&G, 1992a; EG&G, 1993a; RMRS, 1996a) and notes from field walk-downs were considered and applied to the model.

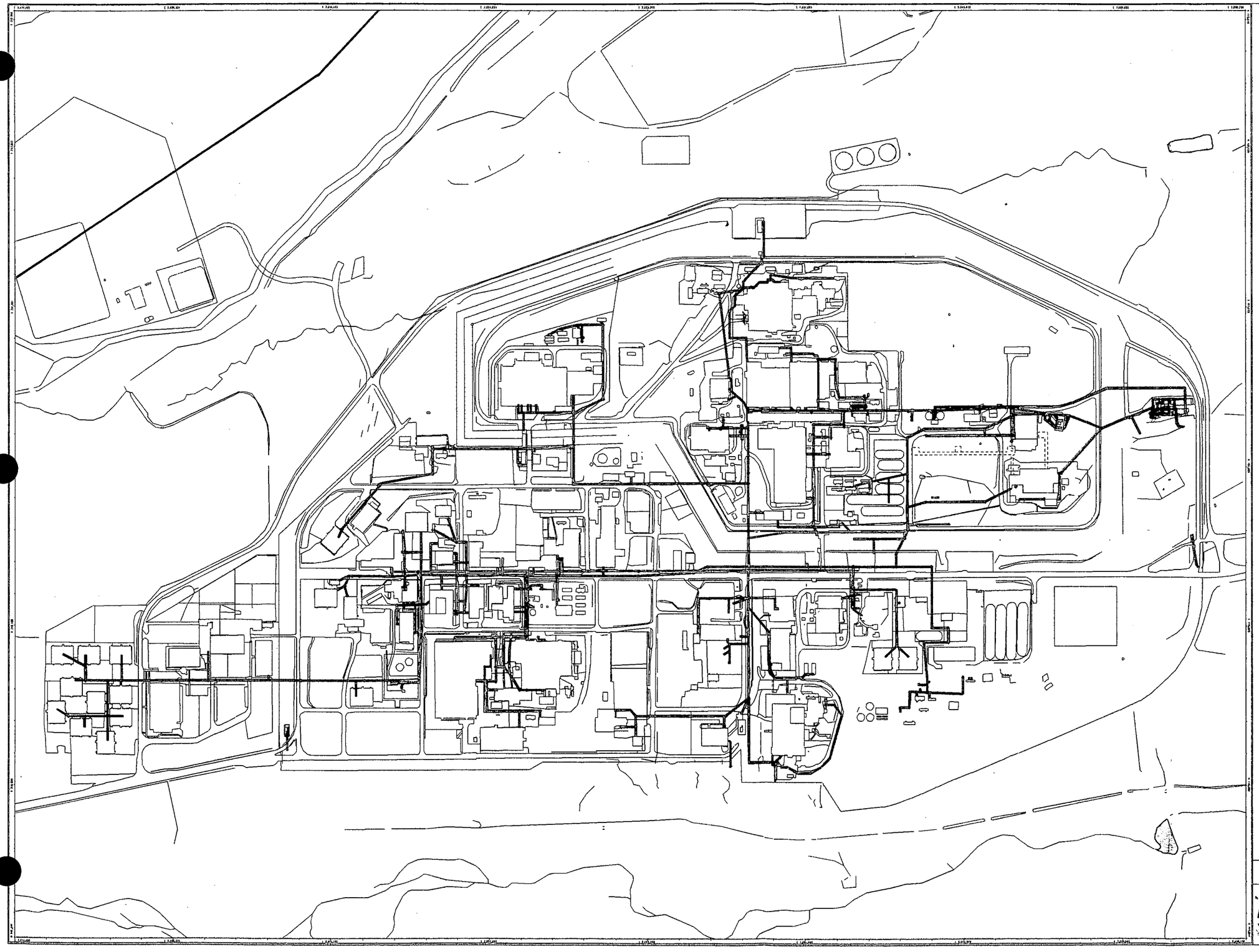


Figure B-20

Site-Wide Water Balance Report

Sanitary Sewer Lines Active and Inactive

EXPLANATION

- Active Sanitary Lines
- Inactive Sanitary Lines

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. I/Ob

30 0 40 80m

100 0 200 400ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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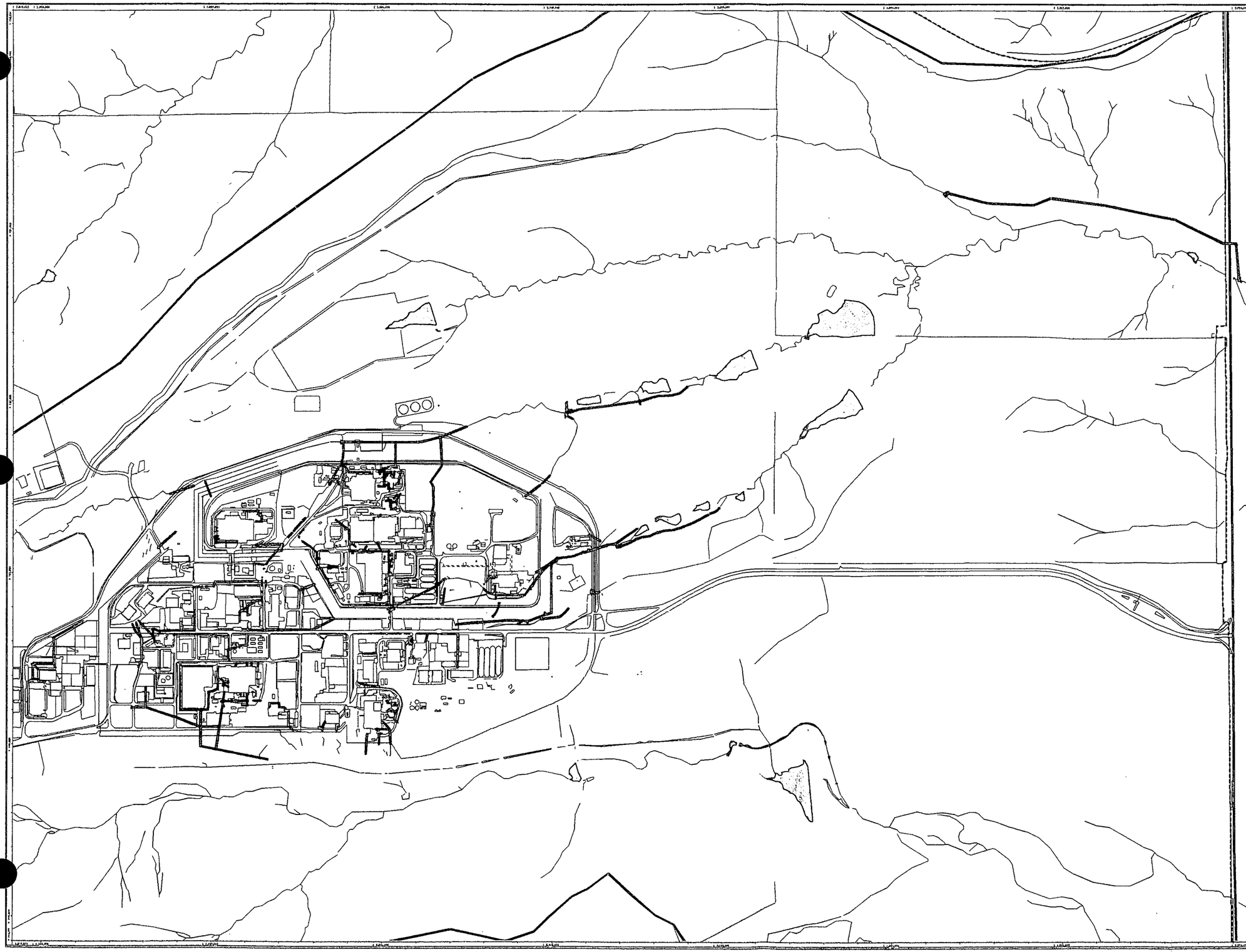

Figure B-21

Site-Wide Water Balance Report

Storm Sewer Lines

EXPLANATION

Storm Sewer Lines

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas.
Digitized from the orthophotographs. 1/95

45 0 90 180m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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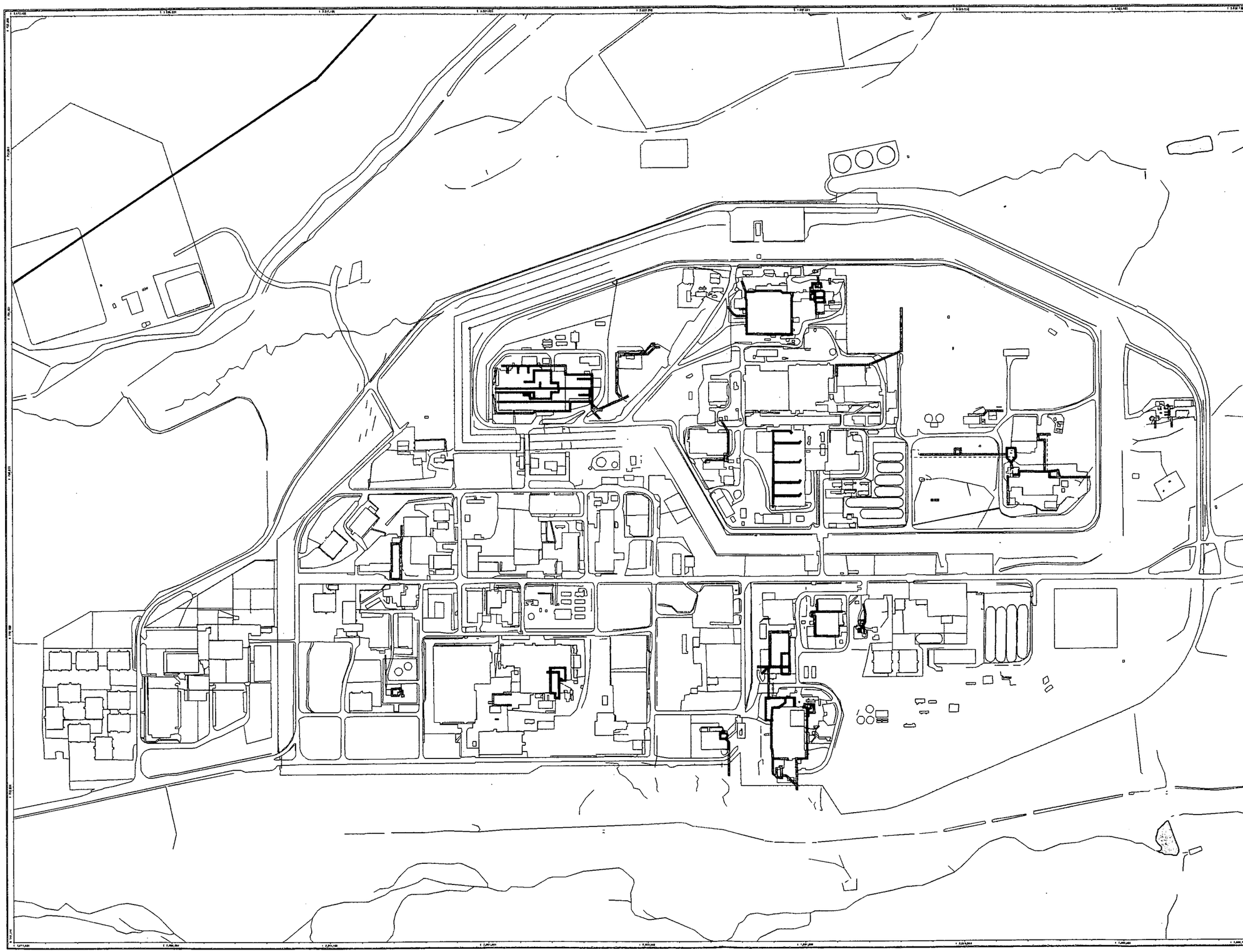

Figure B-22

Site-Wide Water Balance Report

Footing Drain Locations

EXPLANATION

Footing Drains

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by H-G&G RSI, Las Vegas. Digitized from the orthophotographs. 1/95

20 0 40 80m

100 0 200 400ft

State Plane Coordinate Projection
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B.2.2.2.2.5 Process Waste Lines

Site process waste lines are shown on Figure B-23. They are for the most part deactivated, with the exception of flow around the western end of Building 771 and at the southern end of Building 881. AutoCAD drawings were obtained from the Site Engineer, for the process waste lines and were largely consistent with the Site Utility Plan (Woods, 2001; DOE, 1999a). A more recent report, the Industrial Area Sampling and Analysis Plan (Kaiser Hill, 2001), shows more accurate details about the process waste lines. Approximate depths to process lines are also provided in this report (Table B-5). Original process waste lines were consistent with those in the Site Utility Plan (DOE, 1999a). Other new process waste lines are also included, but were not presented in the coverage (Woods, 2001). The AutoCAD drawings were imported into ArcView and new process lines were added. Minor modifications to the AutoCAD drawings were made to eliminate most text lines so that these would not be included in estimates of process line lengths.

B.2.2.2.2.6 Other Subsurface Utilities

Water supply lines considered in the model are shown on Figure B-24, and electric, communication, natural gas and alarm utility lines are shown on Figure B-25.

B.2.2.2.2.7 Remediation Systems

The location of groundwater remediation systems is shown in plan view on Figure B-26. Conceptually, each remediation system intercepts groundwater via a permeable subsurface trench as shown on Figure B-27. Intercepted flows are first treated at the Solar Ponds Plume Remediation System, the East Trenches Plume Remediation System and the Mound Plume Remediation System. Flow from these systems is then routed to downstream surface flows. Flows from the Present Landfill Interception trench and 881-Hillside French Drain are simply routed to downstream surface flows. Slurry walls cause groundwater to flow around them as shown on Figure B-27. Slurry walls and interception trenches in each system were assumed keyed into the bedrock. Details of each system are discussed briefly in the following sections.

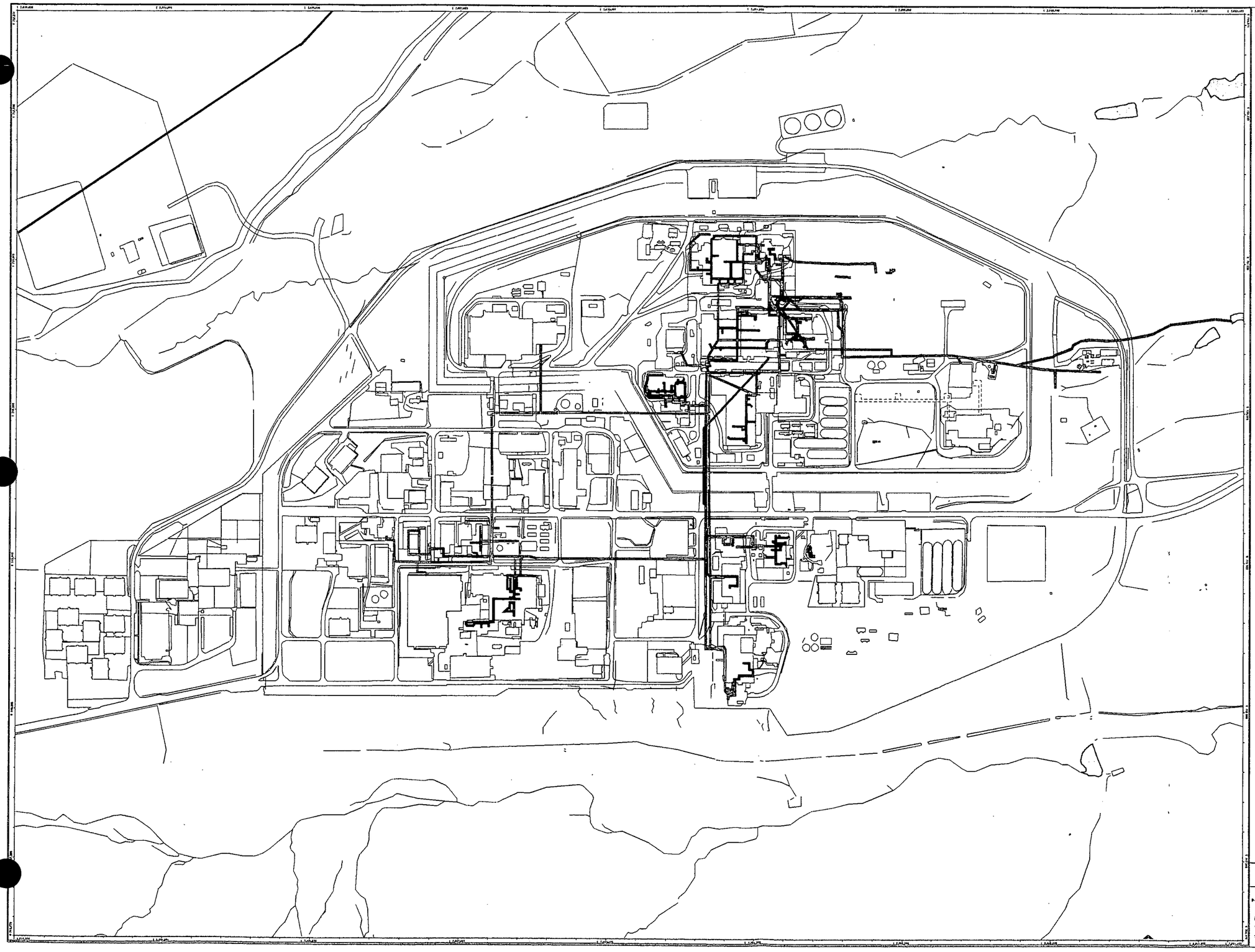

Figure B-23

Site-Wide Water Balance Report

Process Waste Lines

EXPLANATION

- Original Process Waste Lines
- New Process Waste Lines

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Paved roads
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by H&S RSI, Las Vegas. Digitized from the orthophotographs. 1/95

20 0 40 80m

100 0 200 400ft

State Plane Coordinate Projection
Colorado Central Zone
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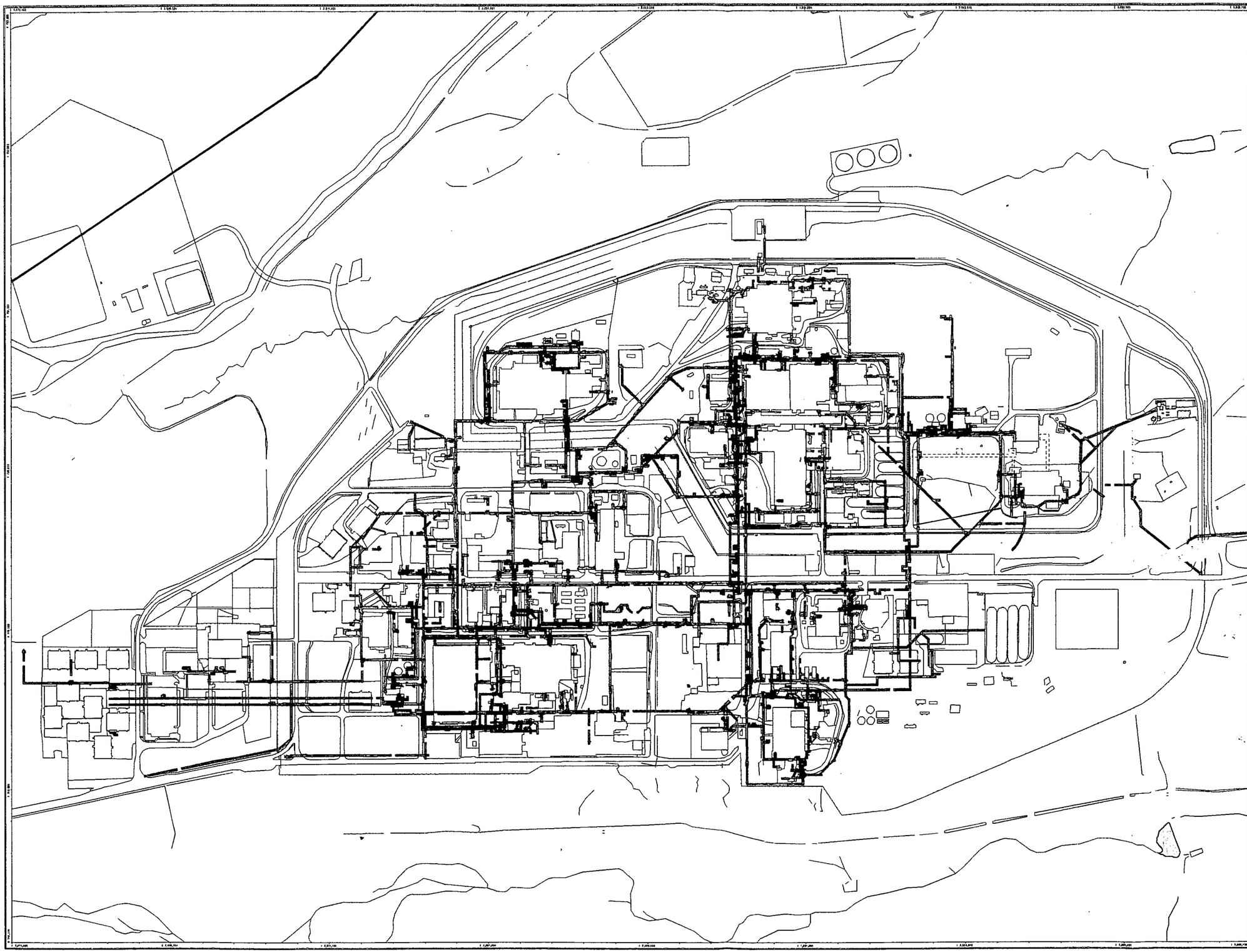

Figure B-24

Site-Wide Water Balance Report

Water Supply Lines

EXPLANATION

Water Supply Lines

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

30 0 40 80m

100 0 200 400ft

State Plane Coordinate Projection
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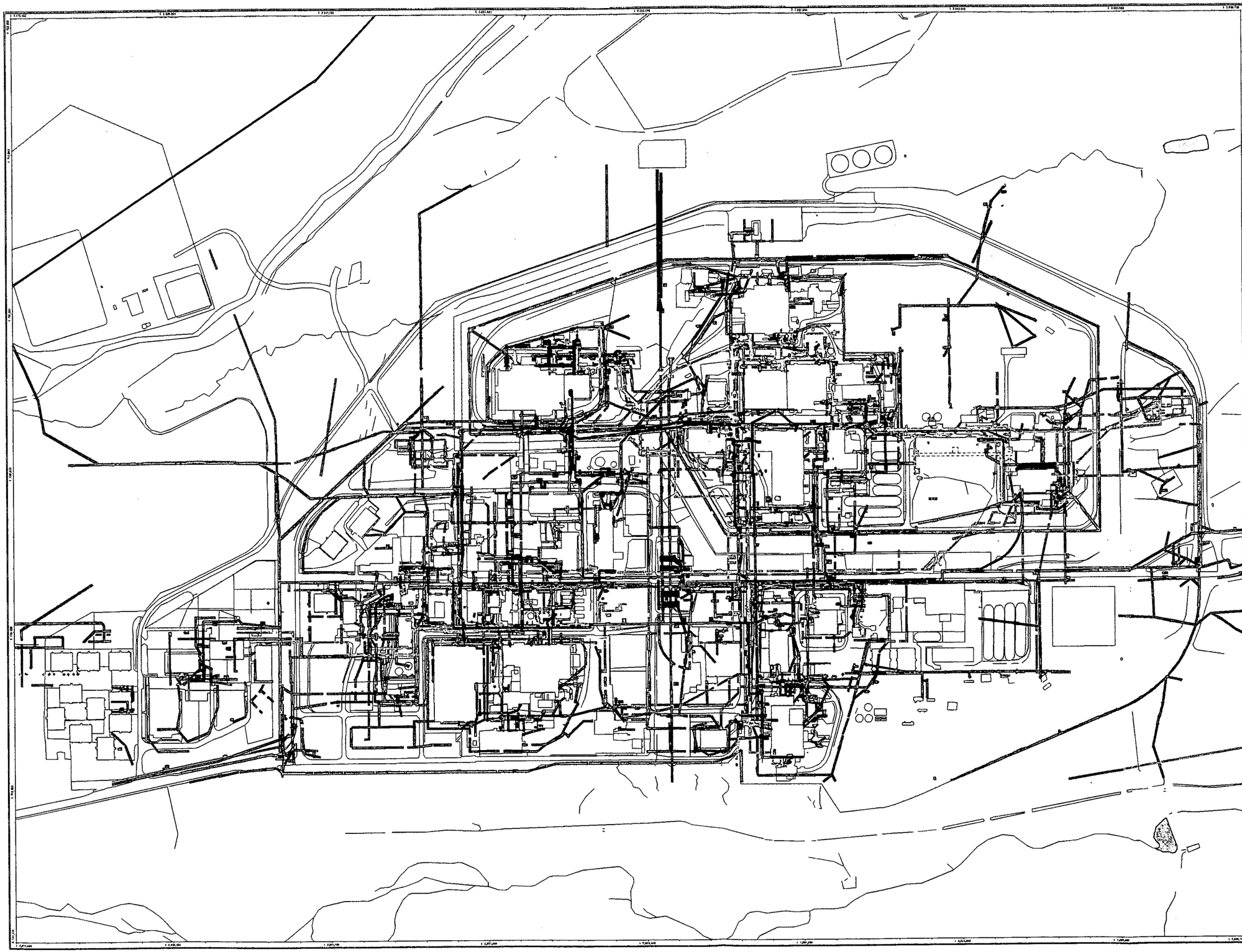

Figure B-25

Site-Wide Water Balance Report

Electric, Communication, Natural Gas and Alarm Lines

EXPLANATION

- Electric
- Communication
- Natural Gas
- Alarm

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/9h

20 0 40 80m

100 0 200 400ft

State Plane Coordinate Projection
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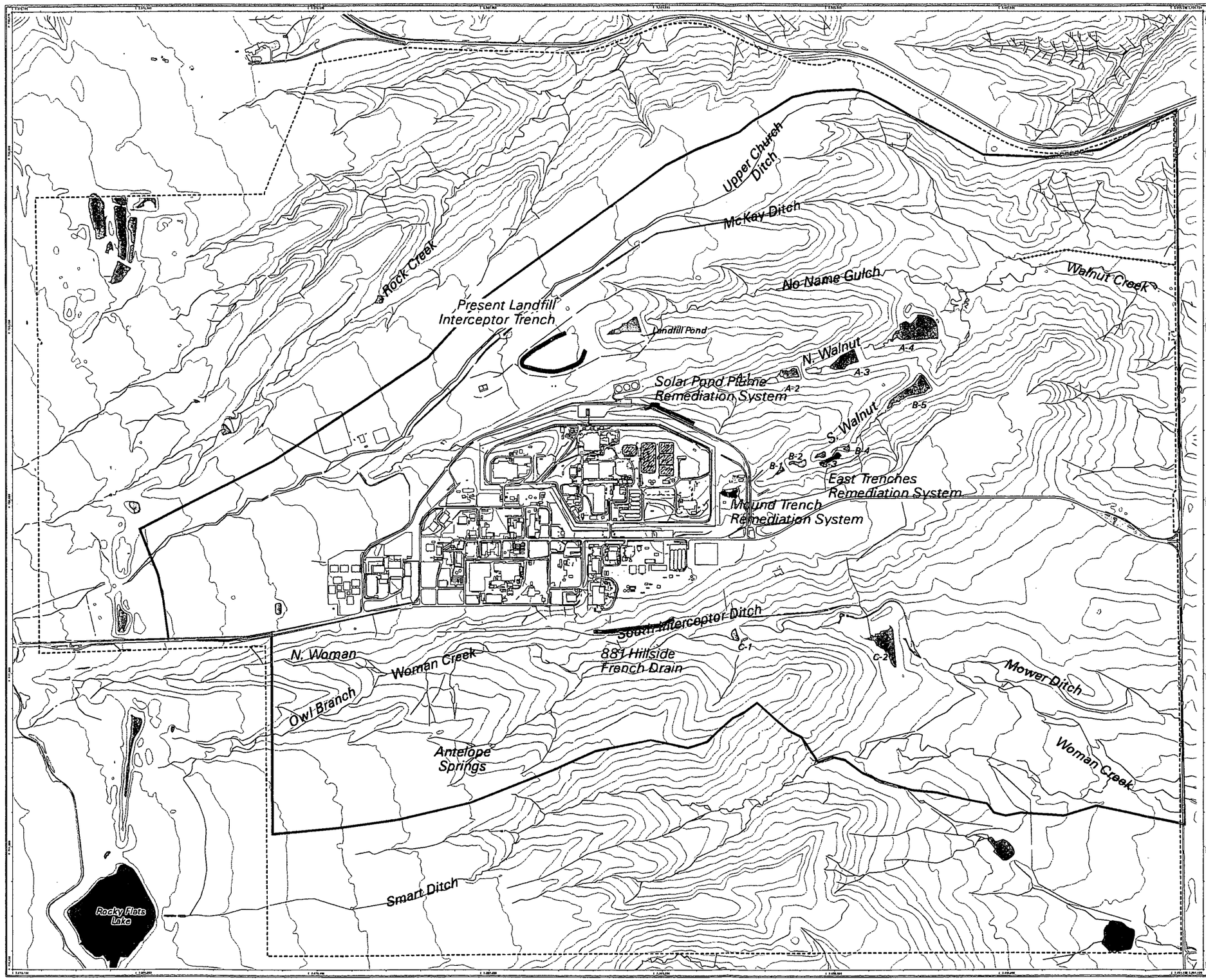

Figure B-26

Site-Wide Water Balance Report

Remediation Systems

EXPLANATION

- Remediation System

Standard Map Features

- Buildings and other structures
- Paved roads fill
- Solar Evaporation Ponds (SEPs)
- Lakes and ponds
- Streams, ditches, or other drainage features
- Topographic Contour (20-Foot)
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95 Topographic contours were derived from digital elevation model (DEM) data by Morrison Knudson (MK) using ESRI Arc TIN and LATTICE to process the DEM data to create 5-foot contours. The DEM data was captured by the Remote Sensing Lab, Las Vegas, NV, 1994 Aerial Flyover at ~ 10 meter resolution. DEM post-processing performed by MK, Winter 1997.

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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GIS Dept. 303-966-7707

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Prepared for: KAISER-HILL

May 13, 2002

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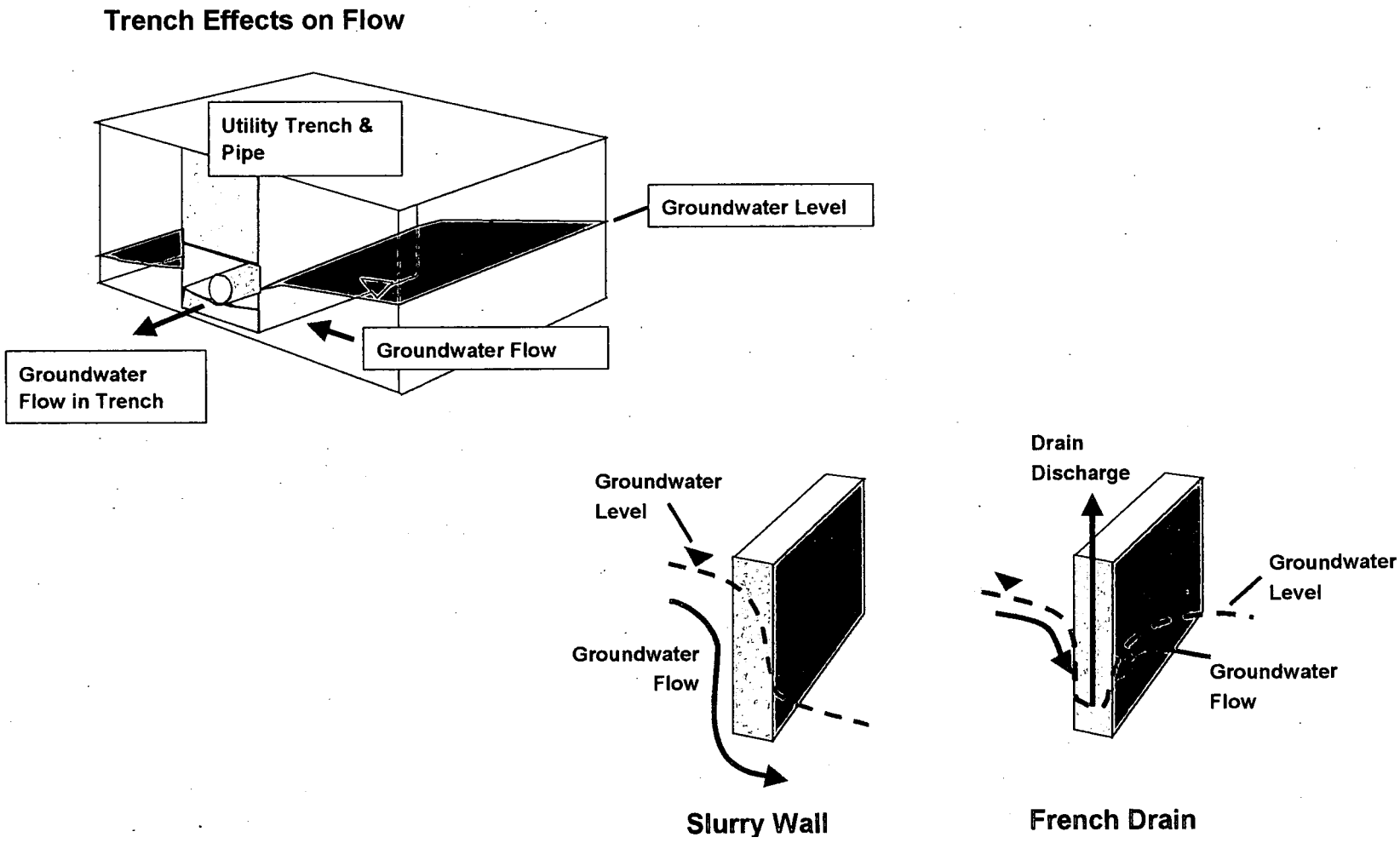
Figure B-27. Conceptual Interception Trenches and Slurry Walls



Solar Pond Plume Remediation System

The Solar Pond Plume Remediation System was simulated in MIKE SHE using the drain boundary condition. This required specification of trench invert elevations, leakance and location of drain cells and discharge points (streams, local internal cells or boundary cells).

Present Landfill

The Present Landfill consists of four hydrologic structures namely, the Groundwater Interception Trench(s), Surface Runoff Interception Trench, Slurry Wall and the Landfill Pond. These were modeled in the SWWB model.

Groundwater Interception Trench

As-built design drawings for the Groundwater Interception Trench on the western perimeter of the Present Landfill provided profiles with invert elevations. The perforated pipes within the permeable trench are 6-to 8-in (15 to 20 cm) diameter and are generally about 20 ft (6.1 m) below grade. The interception trench extends approximately 2,600 ft (793 m). Groundwater extracted from this drain system is routed through closed joint pipe that drains to the head of No Name Gulch. This pipe was not simulated in MIKE SHE because it did not provide a substantial amount of flow.

The Groundwater Interception Trench was simulated in MIKE SHE as a drain in Layer 1. The bottom of the interception trench defines the bottom of Model Layer 1, and it also defines the invert elevation of the drain boundary condition. The interception trench was relatively small compared to a MIKE SHE grid cell and as such, the leakance value was adjusted so that cumulative simulated outflow from the interception trench roughly matched the trench outflow (estimated at 3 gpm to 11 gpm [$2x10^{-4}$ to $7x10^{-4}$ m^3/s]). Drains were routed to No-Name Gulch downstream.

Adjacent MIKE SHE cells were selected to prevent by-pass groundwater flow into the Present Landfill cells. Some cells did not closely match the location of the interception

trench because the MIKE SHE cell is considerably larger than the trench dimension. As such, an effective leakance and average invert elevation were specified for the cell.

Surface Runoff Interception Trench

The Surface Runoff Interception Trench is defined in the ArcView stream shape file provided by the Surface Water Group. The Interception Trench was not be simulated explicitly in MIKE SHE as streamflow. Instead, it was simulated as overland flow for two reasons. First, the source area for this trench is limited in size and was not expected to produce substantial flows. Secondly, immediately upstream of Surface Water Interception Trench is an "access road". Further, flow in the trench was not gaged. Surface topography and the 200-ft (61 m) grid routed runoff reasonably well to the appropriate down-slope stream location.

Slurry Wall

Two slurry walls exist on the north and south sides of the Present Landfill just east of the Groundwater Interception Trench and were modeled in the SWWB model. As-built plans (1982) included plan-views and profiles for each wall. The total length of both slurry walls is about 700 ft (213 m), and is divided roughly equally on the north and south sides of the Present Landfill. The slurry walls appear to be keyed into the bedrock, though, it was uncertain whether this extends into unweathered bedrock over the entire length of the slurry walls. Conceptually, the slurry wall was blended to be narrow and represented with a low saturated hydraulic conductivity.

Landfill Pond

The Present Landfill Pond is fed by landfill leachate and surface runoff. It is pumped to the A-3 Pond at certain times, but no transfers were performed during the calibration year. The limited surface runoff (i.e., limited source area), and leachate inflow to the pond are generally small enough to allow water levels to evaporate off, keeping the pond level relatively uniform.

The Landfill Pond was simulated using MIKE 11. A simple branch defined the pond extent, with a specified boundary condition of zero flow at upstream end. For more dicussion of Pond structure, transfers and evaporation, see Appendix D.

East Trench System

The East Trenches Remediation System is about 1200 ft long (366 m). It extends 20 ft (6.1 m) below ground surface (bgs). It drains to Pond B-4. As-built drawings were used to determine invert elevations and discharge location.

Mound Plume Remediation System

The Mound Plume system is about 200 ft (61 m) long. Groundwater is discharged to south Walnut Creek above GS10. As-built drawings were used to determine invert elevations and discharge location.

881 Hillside French Drain System

The 881-hillside French Drain is about 1000 ft (305 m) long and extends parallel to the hillslope below Building 881. It was deactivated during the model calibration year and discharges to the South Interceptor Ditch (Kaiser-Hill, 2000e). Trench invert elevations were obtained from as-built drawings.

Solar Pond Plume Remediation System

The Interceptor Trench at the base of the Solar Pond Treatment system was considered in the model. Groundwater is first treated and then routed downstream into North Walnut Creek. Invert elevations were obtained from as-built drawings.

B.2.2.2.2.8 Building Basements

The location and outlines of building basements were investigated because these affect saturated zone flows. Basement locations are consistent with footing drain locations (Figure B-22). Conceptually, the basement walls and slabs act as semi-impermeable flow boundaries in the saturated zone and impede inflows. Because all basements that

intercept groundwater have associated footing drains and in some instances, sumps, the footing drains were hydraulically important. Because the footing drains intercept possible groundwater inflows to building basements, the basements under current conditions did not impact system flows.

In the Land Configuration Scenario, where basement slabs and walls were left in place and associated footing drains and sumps were deactivated, their impact on saturated zone flows was more pronounced. As a result, the effects of building basement walls and slabs were modeled in the Land Configuration Scenario using slurry walls.

B.2.2.2.2.9 Seeps

Shallow groundwater discharges to ground surface at seep locations. Seeps form in areas where less permeable bedrock outcrops at ground surface, forcing overlying groundwater flowing in the more permeable unconsolidated material to discharge. Seep areas, like Antelope Springs, are important hydrologically because they provide fast runoff during rainfall events due to saturated conditions at the ground surface in addition to a relatively constant groundwater discharge.

Graphics are presented in Section 3 of the main report, showing conceptually how seeps operate. Locations where active and formerly active seeps are located are shown on Figure B-9. Most of the seep areas are inactive except in much wetter years, like WY1995.

B.2.2.2.3 Hydraulic Properties

Hydraulic data for the saturated zone are defined by surficial geologic units and bedrock lithofacies described in the Hydrogeologic Characterization Report (EG&G, 1995a) and supplemented with additional data since 1995. Important hydraulic properties for the saturated zone include: (1) hydraulic conductivities; (2) storage coefficients; and (3) leakance values associated with subsurface utilities or streams. Leakance values represented the effective resistance to flow associated with utilities or streams. No on-Site data existed for these values, and thus they must be determined through modeling.

Saturated hydraulic conductivity values are available are described in a report by EG&G (1995a). These data were obtained mainly through well testing. Average geometric means of conductivity values for the three primary units of the UHSU are reported. They are 2.06×10^{-4}, 1.15×10^{-4} and 2.16×10^{-3} cm/s for Rocky Flats Alluvium, Colluvium (landslide material and colluvium) and Valley-Fill Alluvium, respectively (EG&G, 1995a) (shown on Figure B-15). The Rocky Flats Alluvium exhibits the highest degree of heterogeneity with conductivities ranging from 7.18×10^{-8} to 5×10^{-2} cm/s. Geometric means of weathered bedrock units including claystones, siltstones, Arapahoe Formation sandstone and other sandstones were estimated as 8.82×10^{-7}, 2.88×10^{-5}, 7.88×10^{-4} and 3.89×10^{-5} cm/s, respectively. Vertical conductivity values for the surficial and weathered bedrock units were unavailable, and it was assumed to be within a ratio of one tenth of the horizontal conductivities.

Published information on storage coefficients, or specific yield, at RFETS was limited. These data were typically determined through pumping tests, but these data were unreliable (Smith, 2001) due to the low well yields. Typical values reported in the literature (Freeze and Cherry, 1978) indicate that specific yields range from 0.01 to 0.3 for unconfined aquifers and from 0.005 to 0.00005 in confined aquifers.

B.3 OBSERVED HYDROLOGIC RESPONSE

Characterizing the observed hydrologic system response well was important in developing a successful integrated model. The MIKE SHE model parameters were adjusted to reproduce this behavior. Emphasis was placed on describing the system response in terms of directly-quantifiable data, termed "calibration" data. Other system qualitative data, like seep areas or gaining/losing reaches along streams that support the response are also described here.

B.3.1 Surface Water Response

This section describes the observed surface water response to the system hydrologic stresses described in Section B.1. The response is discussed in terms of overland flow and

surface water flow for the Industrial Area and Buffer Zone. In addition, discussion is provided to present the observations for pond water balances and snowmelt.

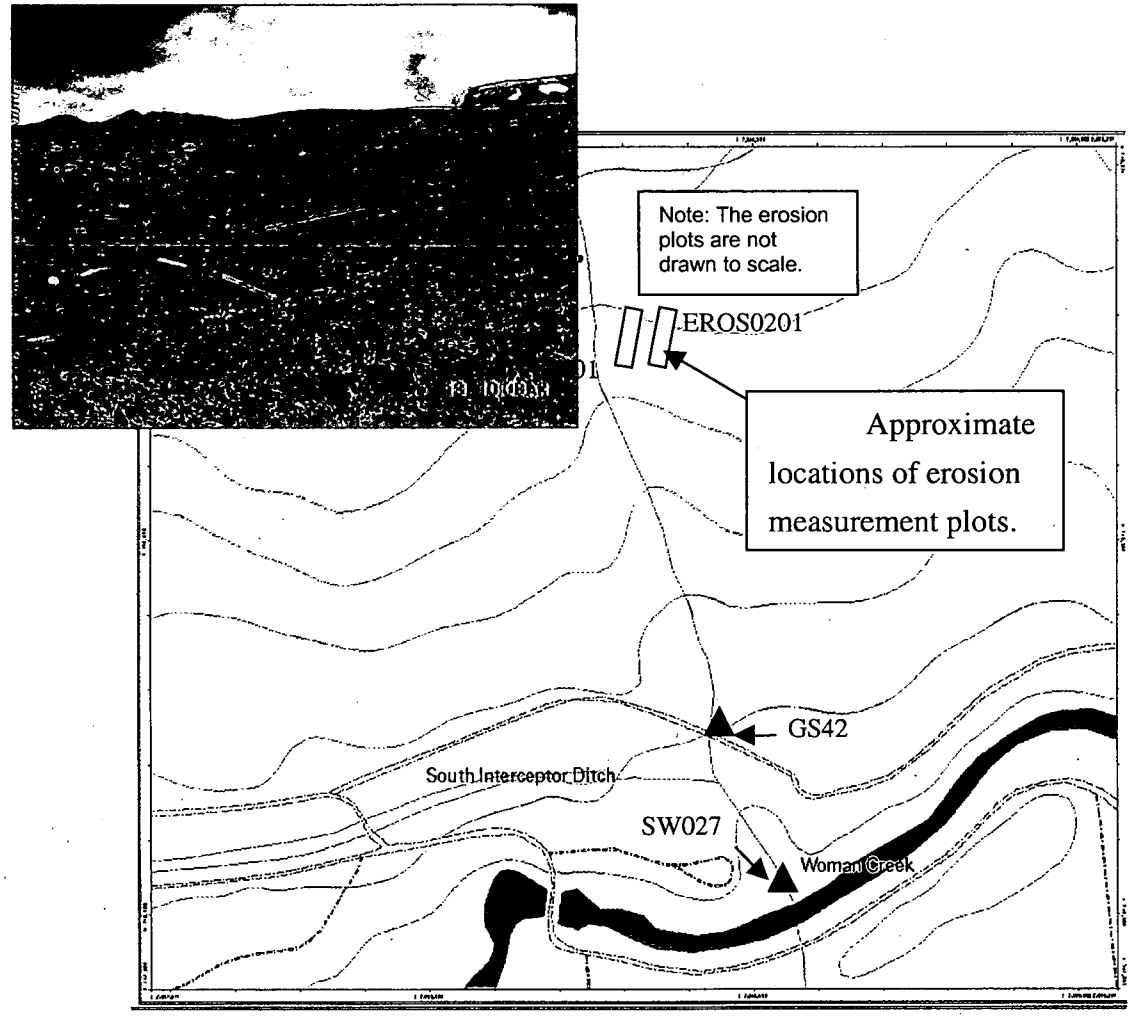
B.3.1.1 Overland Flow

Routine overland flow measurement is not performed at the Site. The limited data set included simulated rainfall experiments (performed off-Site) and erosion plots (installed on-Site). Both data collection exercises were performed as part of the Site Actinide Migration Evaluation (AME) Project (Kaiser-Hill, 2000d). The purpose of the rainfall experiment was to compare erosion from burned natural plots, as opposed to developing runoff coefficients. The rainfall simulation experiment applied extremely high precipitation intensities to generate runoff (~2.5 in/ hr or 64 mm/ hr). In contrast, the erosion measurement plots located on-Site, south and east of the Industrial Area, were operated under natural rainfall conditions. These generated runoff samples on four occasions during WY2001 and are presented in Figure B-28.

In FY01, the AME installed two erosion plots on a hillslope in the GS42 to collect eroded material for determination of particle size enrichment and actinide enrichment. Runoff and erosion rates were also measured. Each of the two plots have dimensions of 3 m (10 ft) wide by 10 m (33 ft) long on an approximate 9 percent slope. Run on (surface flow onto the Site not entering in channels) by overland flow outside the plot area was prevented by 5-inch metal strips creating vertical barriers around the plots. There were no barriers to groundwater seep flow, though vegetation suggested no active seeps in the area. The runoff was collected in a gutter that drains to a plastic container.

The following conceptual picture of overland response was developed from information from the erosion plots, observations by Site surface water monitoring and calibration efforts to define soil infiltration parameters (see Section B.2.2.1.1).

Figure B-28. Location and Description of AME Erosion Plots



B.3.1.1.1 Industrial Area

Overland runoff was observed in response to precipitation on impervious surfaces in the Industrial Area. Due to the presence of the impervious surface, overland runoff was observed in response to both large and small precipitation events. The photos in Figure B-29 were taken in the Industrial Area during a moderately-intense event on August 9, 2001. During this storm, roughly 0.9 in (23mm) of rain fell over 2 hours.

B.3.1.1.2 Buffer Zone

Observed overland runoff in the Buffer Zone has not been well documented. The high infiltration and vegetation interception (see Sections B.2.2.1 and B.1.1.2) prevent even relatively high precipitation events from producing ponding that could lead to runoff. For the model calibration year (October 1, 1999 to October 1, 2000), the highest intensity precipitation event produced 0.61 in (15 mm) in a 15-minute time period. Even with this intensity, Horton-type overland flow (Dunne, 1978) probably did not occur over most of the Buffer Zone because the saturated hydraulic conductivities of the surface soils area are relatively high. Ponding will only occur if the precipitation intensity is greater than the saturated hydraulic conductivity, assuming a unit pressure gradient develops in the unsaturated zone. Figure B-30 shows images of the Buffer Zone during the same August 9, 2001 precipitation event pictured in Figure B-29.

Observed data alone do not present a clear picture of overland flow in the Buffer Zone. Relevant observed data included erosion plot observations from WY2001 and Site personnel observations from the largest recorded precipitation event in recent history at the Site, the May 1995 event. Both sources of data asserted that water was observed to flow over the ground surface; however, the mechanism for this response to precipitation is unclear.

Figure B-29. Observed Overland Runoff in the Industrial Area for 8/9/01 Precipitation Event

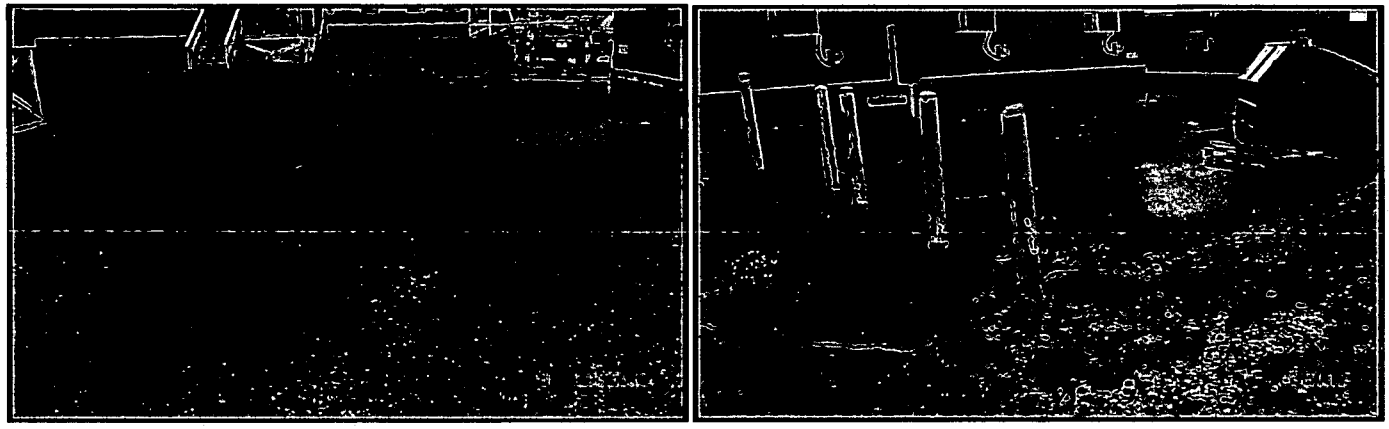
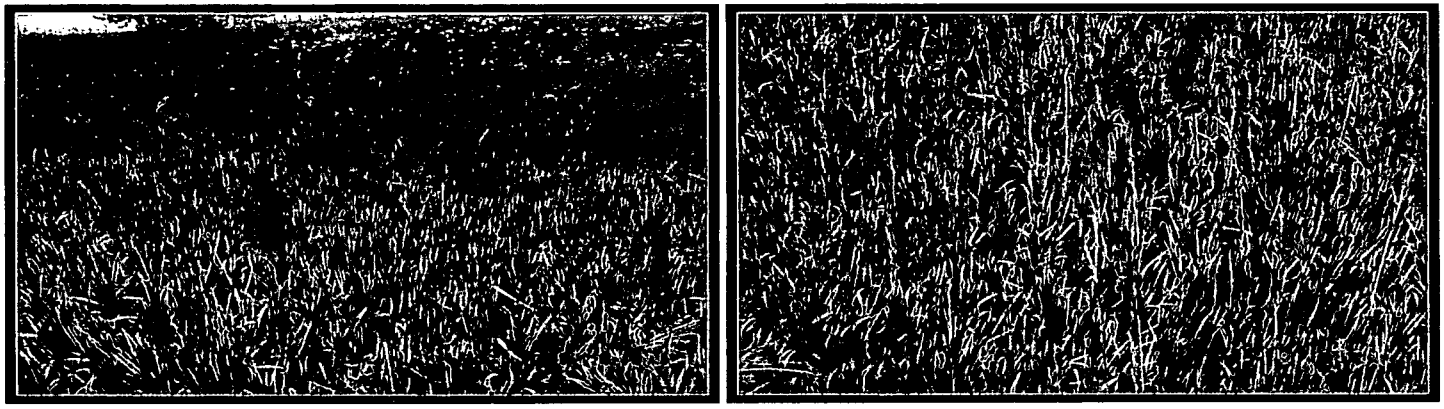


Figure B-30. Buffer Zone Images for August 9, 2001 Precipitation Event



As described briefly in Section B.3.1.1, erosion plots were installed to measure sediment erosion produced runoff samples on the hillside south and east of the 903 Pad in WY2001. Four events produced measurable runoff; three in May and one in July. The May events were low intensity, longer-duration events (all 15-minute readings were less than 0.09 in/hr [2 mm/hr]). The July event was an extremely high intensity event (0.64 in (16 mm) recorded in one 15-minute reading). The May, 1995 event was a long-duration, low-intensity event that covered more than a week.

Because of the response to low-intensity events, it is unclear whether the observed overland flow is attributed to the classic mechanism of precipitation intensity exceeding infiltration rates or to saturation excess due to antecedent conditions. For WY2000, the model calibration demonstrated that overland runoff was a small to negligible contribution to total channel flow in the Buffer Zone.

B.3.1.2 Channel Flow

Since October, 1996, channel flow across the Site has been extensively monitored, with 15-minute data for all gages. Prior to 1996, records vary in quality and frequency, but in some cases, provide additional data back to 1992. These data sets were evaluated in detail to develop the conceptual model for channel flow response to hydrologic stresses. The conceptual model is described below for the Industrial Area and Buffer Zone, focusing on the five major drainages identified on Figure 2-1 in the main report.

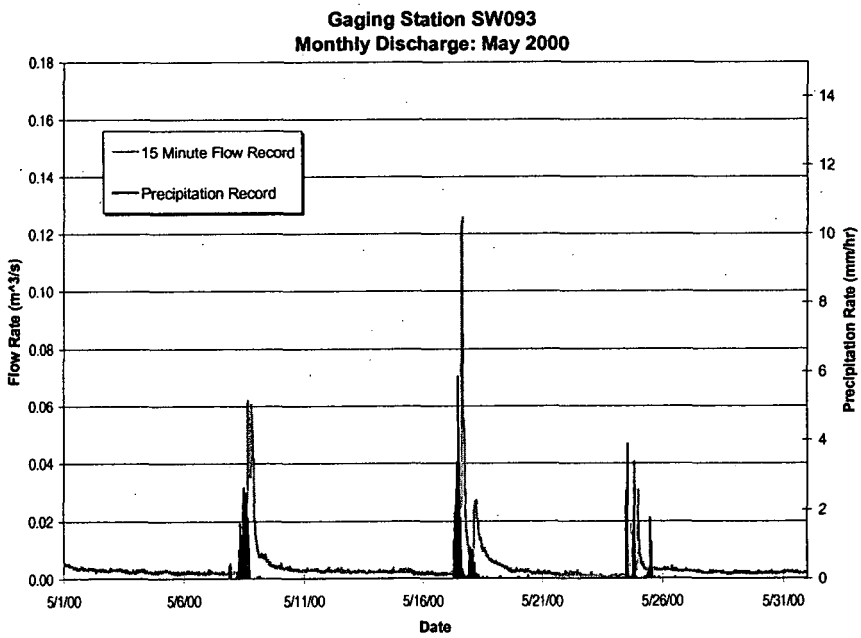
B.3.1.2.1 Industrial Area

In general, hydrographs in the Industrial Area are characterized by rapid, sharp response to large and small precipitation events. This response can be attributed to impervious surfaces as discussed in Section B.2.1.1.1.2. The observed channel flow for each of the three major drainages of the Industrial Area,(SW093, GS10 and SW027) is detailed below.

B.3.1.2.1.1 Station SW093 Drainage Basin

As shown on Figure 2-1, the SW093 drainage extends through most of the northern portion of the Industrial Area and the hillside to the north. This is a complex drainage, including impervious and vegetated surfaces, as well as sanitary, storm and footing drains. Roughly 30 percent of the SW093 drainage is impervious. The impervious surface area is responsible for the rapid and peaky runoff response to precipitation. An example hydrograph of 15-minute flow record is presented in Figure B-31, along with the observed precipitation. As seen in this figure for May, 2000, SW093 channel flow responds rapidly to each precipitation event throughout the year.

Figure B-31. Example Hydrograph – Gaging Station SW093



The SW093 hydrograph also exhibits a constant low flow that will be described as baseflow. The term baseflow is being used generally here to include contributions from drain flow and the more classical definition of baseflow, the contribution from groundwater leaking into the channel. The baseflow at SW093 varies between roughly 0.001 and 0.003 m^3/s (or 0.04 to 0.1 cubic feet per second [cfs]). The higher baseflow rate is typically observed in the spring and fall.

Within the SW093 drainage, several footing drains discharge to the surface. Footing drain flows are monitored at the major outfall locations from Building 371 and Building 771. There are additional outfalls, which are not measured due to problems locating the outfall, or no contamination concern exists to require flow monitoring. The Building 779 and Building 771/774 footing drain outfalls have been observed to flow frequently. Within the SW093 drainage, estimates of measured drain flow amount to roughly $3x10^{-4}$ m^3/s (0.01 cfs) for WY2000. This amounts to roughly 15 percent of the estimated total baseflow. The remaining observed baseflow at SW093 is likely composed of groundwater leaking into the channel or the underground pipes that route portions of the channel (see Figure D-4 in Appendix D). Baseflow is frequently observed in the western portion of Walnut Creek, which flows to SW093. This section of Walnut Creek has also been observed to receive flows leaking out of the man-made structure to the north, McKay Ditch. Additionally, there may be contributions from water leaking from domestic distribution and smaller, unmeasured footing drain discharges.

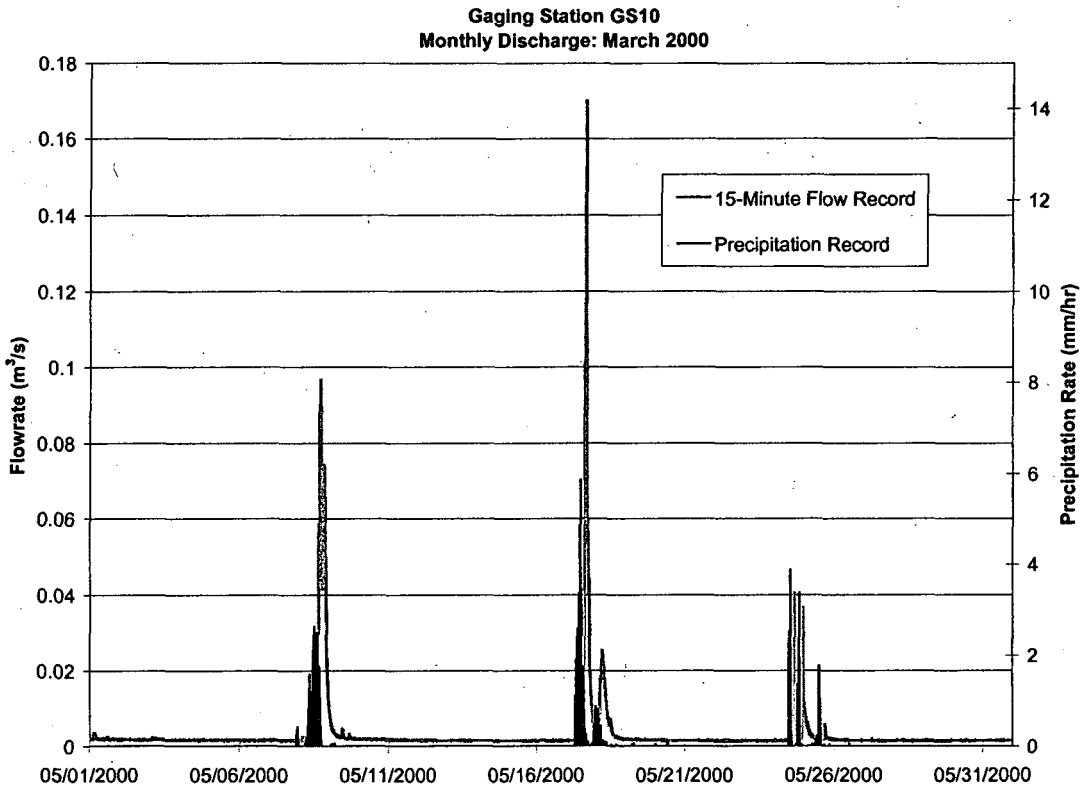
An average of 210,000 m^3 (7.4 million cf) are measured at SW093 annually (determined using 1997 through 2001 data). In WY2000, 160,000 m^3 (5.7 million cf) were measured, which is 25 percent below the 5-year average. Typically (average of 1997 through 2001 data), the volume measured at SW093 is roughly 30 percent of the volume measured at the study area discharge point for Walnut Creek (GS03). In WY2000, SW093 flow volume contributed a greater proportion, comparing at 50 percent.

B.3.1.2.1.2 Station GS10 Drainage Basin

The GS10 drainage extends through the central Industrial Area as shown in Figure 2-1. As for SW093, the GS10 drainage is complex and primarily industrial. The drainage includes: (1) impervious surface; (2) vegetated surface; (3) sanitary drains; (4) storm drains; (5) footing drains; and (6) groundwater treatment systems routing to surface water. Roughly 50 percent of the GS10 drainage is impervious. The impervious surface area is responsible for the rapid and peaky runoff response to precipitation. An example hydrograph of 15-minute flow record is presented in Figure B-32, along with the

observed precipitation. The response is similar to that observed for SW093, with channel flow responding rapidly to each precipitation event.

Figure B-32. Example Hydrograph – Gaging Station GS10



As observed for SW093, GS10 also exhibits a constant low flow that will be described as baseflow. Again, the term baseflow is being used generally here to include contributions from drain flow and the more classical definition of baseflow. The baseflow at GS10 varies between roughly 0.001 and 0.003 m^3/s (or 0.04 to 0.1 cfs). The higher baseflow rate is typically observed in the spring and fall.

Several footing drains discharge to the surface within the GS10 drainage. Footing drain flows are monitored at the major outfall locations from buildings in the 400 Area, Building 886 and Building 707. Also, the Mound Plume Remediation System outfalls to the surface channels within the GS10 drainage. There are additional outfalls which are

not measured due to problems locating the outfall, or a lack of contamination concern to trigger flow monitoring. Within the GS10 drainage, estimates of measured drain flow amount to roughly 1.3×10^{-3} m^3/s (0.05 cfs) for WY2000. This amounts to roughly 85 percent of the estimated total baseflow. The remaining observed baseflow is likely composed of water leaking from domestic distribution and groundwater leaking into the channel or the underground pipes that route portions of the channel (see Figure D-4 in Appendix D).

An average of 140,000 m^3 (5.0 million cf) are measured at GS10 annually (using data from 1997 through 2001). In WY2000, 120,000 m^3 (4.2 million cf) were measured, which is 12 percent below the five-year average. Typically (averaged data from 1997 through 2001), the volume measured at GS10 is roughly 20 percent of the volume measured at the study area discharge point for Walnut Creek (GS03). In WY2000, GS10 flow volume contributed a greater proportion (40 percent).

B.3.1.2.1.3 Station SW027 Drainage Basin

The SID drainage area corresponds to the SW027 drainage area. The drainage extends north from the SID and includes small portions of the south Industrial Area (see Figure 2-1). Roughly 10 percent of the SW027 drainage is impervious. The SID itself is a man-made channel, constructed into the hillside south of the Industrial Area to route potential contamination into Pond C-2 before it reaches Woman Creek. The SID is a fairly steep channel (averaging 3.2 percent across the entire length), with several riprap drop structures and low-lying cattail-filled sections. The SW027 drainage is partially industrial, with paved surfaces, storm drains, footing drains and the 881 Hillside French Drain System (see Section B.3.2.4.2) which routes to surface water.

An inflow tributary near the west end of the SID, GS22 produces an Industrial Area-type surface water response (typical of SW093 and GS10). See Figure 2-1 for the location of GS22. The annual GS22 hydrograph is characterized by sharp runoff peaks and baseflow ranging from 1×10^{-4} to 8.5×10^{-3} m^3/s (0.005 to 0.03 cfs). Throughout the year, most of

the GS22 contribution is dampened or lost across the length of the SID before it reaches SW027.

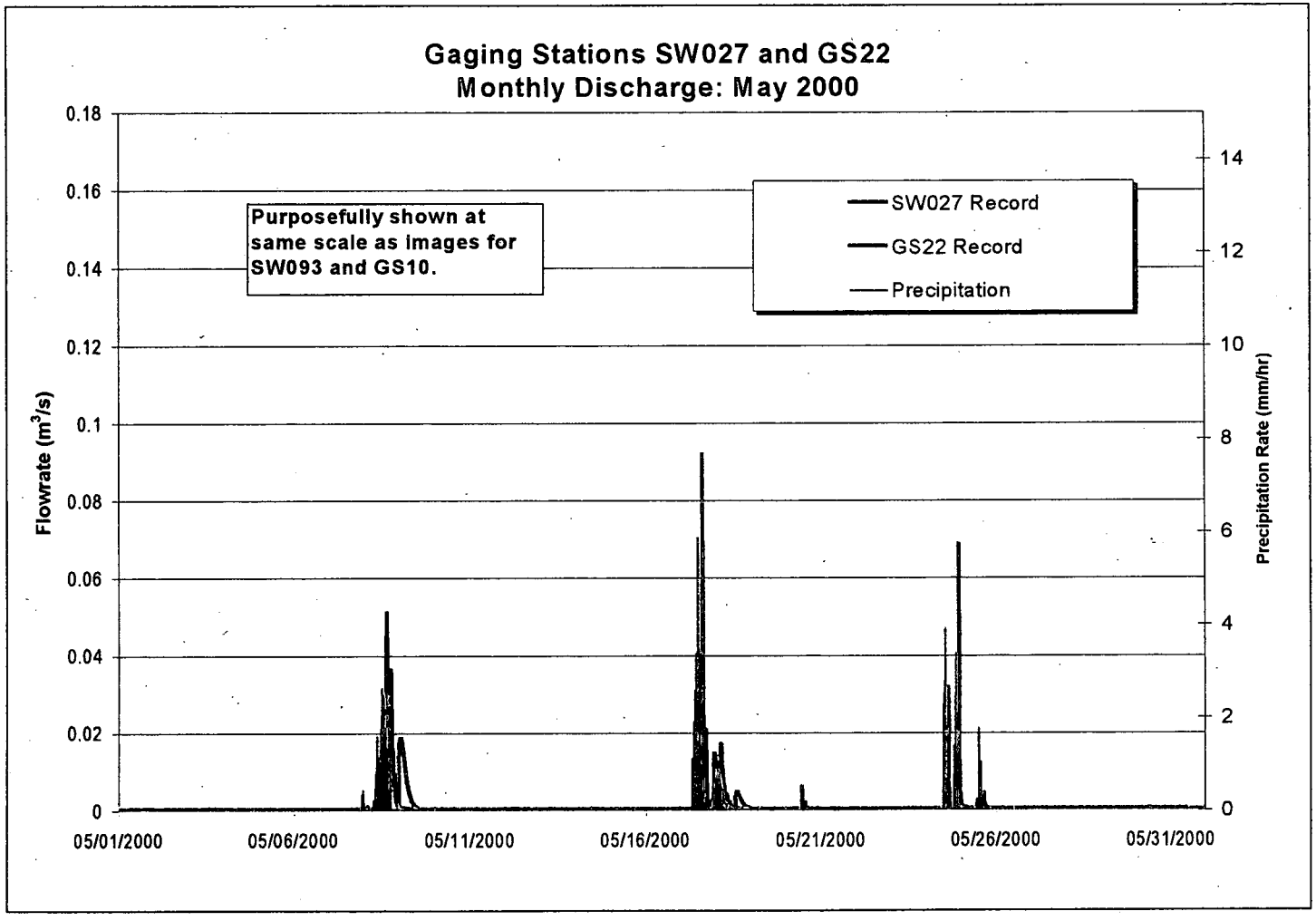
An example hydrograph of 15-minute flow record is presented in Figure B-33, along with the observed precipitation. GS22 flow is also provided to demonstrate loss along the reach. In contrast to SW093 and GS10, the GS22 response to precipitation is much smaller and delayed by up to a full day.

Typically, during the months of November through March, SW027 shows no flow response to precipitation. Most years, SW027 shows some baseflow between April and June, with intermittent periods of baseflow occasionally observed between June and November. Several low-lying sections of the channel support cattails and are saturated throughout the year.

Several footing drains release to the surface within the SW027 drainage. Buildings 444, 447 and 460 footing drain flows are monitored at GS22. Additional outfalls have been observed to flow but are not measured (e.g. from Buildings 881, 883 and 850). Baseflow observed at GS22 is likely composed of a combination of footing drain discharge and groundwater leaking into the underground pipes that route the channel (see Figure D-4 in Appendix D). Baseflow observed in the SID is composed primarily of groundwater leaking into the channel. The 881 Hillside French Drain System also discharges into the SID, but at a very low flow rate (8×10^{-6} m^3/s).

An average of 30,000 m^3 (1.1 million cf) are measured at SW027 annually (1997 through 2001). In WY2000, 14,000 m^3 (0.5 million cf) were measured, which is 55 percent below the 5-year average. Typically (averaged data from 1997 through 2001), the volume measured at SW027 is roughly 10 percent of the volume measured at the study area discharge point for Woman Creek (GS01). This average percentage was matched in WY2000. It should be noted that Pond C-2 was not released during WY2000; the volume comparison is made only for relative comparison.

Figure B-33. Example Hydrograph – Gaging Stations SW027 and GS22



B.3.1.2.2 Buffer Zone

B.3.1.2.2.1 Walnut Creek

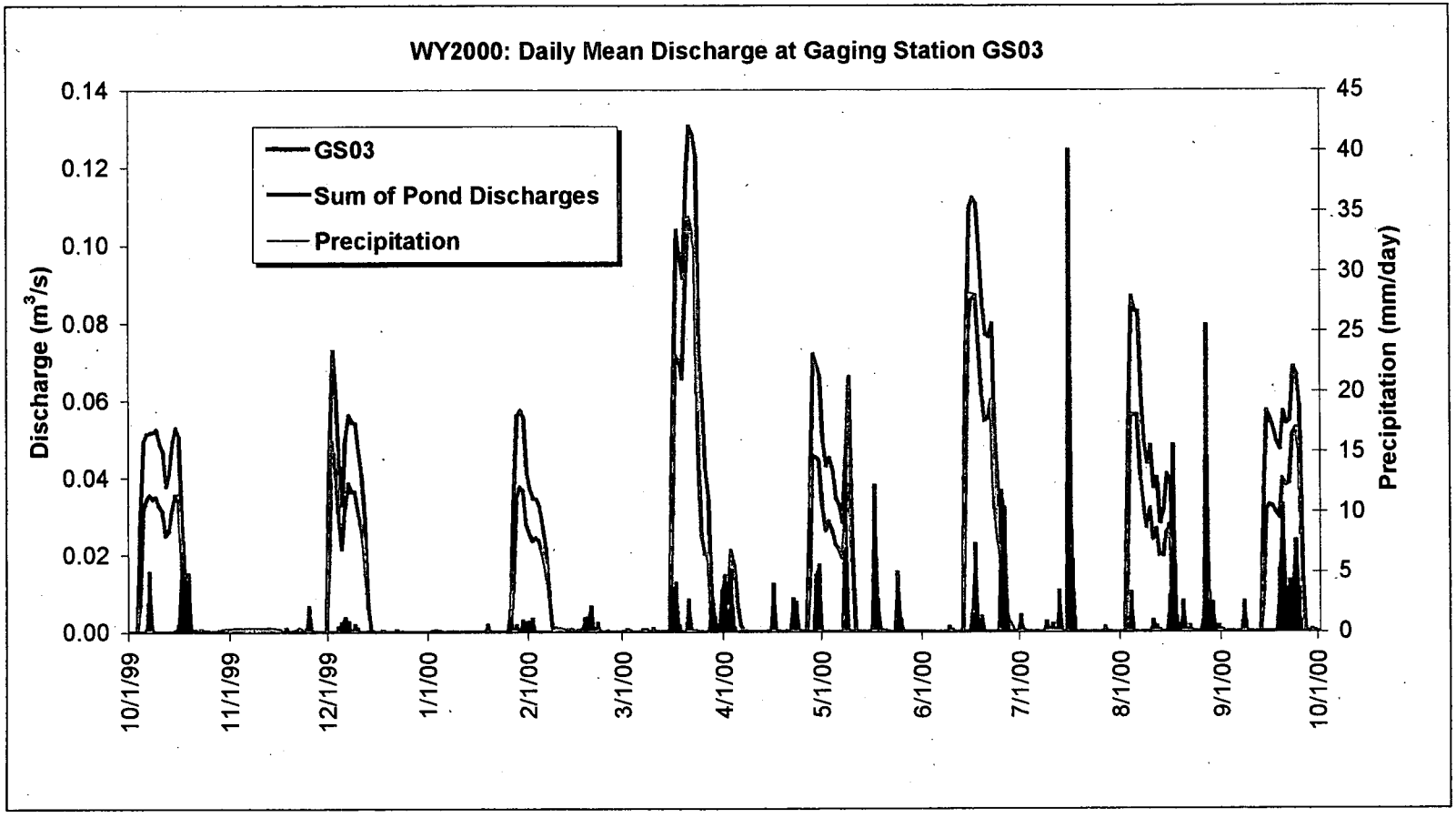
Within the study area, the Walnut Creek drainage extends from gaging station GS03 to the west and north model boundaries. This drainage includes the GS10 and SW093 drainages as well as the Present Landfill, A-series and B-series Ponds. As a result, the drainage is partially industrial, containing subsurface drains, groundwater collections and treatments systems (Solar Ponds Plume, Mound Plume, Present Landfill System and East Trenches System) and impervious surfaces. The entire drainage is roughly 10 percent impervious. This drainage also receives discharge of imported water from the WWTP, as described in Section B.1.2.

The observed GS03 hydrograph for WY2000 is presented below in Figure B-34. The eight dominant features on the hydrograph are all pond discharges. For comparison, both pond discharge volume (measured at the discharge point of the ponds) and volume measured at GS03 (at the end of the channel within the study area) are shown. Daily precipitation totals are also shown.

Figure B-34 clearly shows that pond discharges dominate the annual hydrograph for the GS03 drainage. Another important observation from Figure B-34 is that the reach between the Ponds and the GS03 measurement point is typically a losing reach throughout the year. Each of the pond discharges shows a significant loss of volume from the discharge point to GS03.

Baseflow is occasionally observed at GS03; however, it is difficult to identify seasonal trends. Pond discharges complicate the near-stream groundwater seasonal response, masking any baseflow seasonality.

Figure B-34. Observed WY2000 Hydrograph and Hyetograph at GS03 (with Pond Discharge Volumes)



An average of 630,000 m^3 (22 million cf) are measured at GS03 annually (1997 through 2001). In WY2000, 330,000 m^3 (12 million cf) were measured, which is 48 percent below the 5-year average. Typically (averaged data from 1997 through 2001), the volume measured at the discharge point for the ponds is 90 percent of that observed at GS03. In WY2000 however, the pond discharge volume amounted to 140 percent of the flow observed at GS03. This can be explained by a significant water loss of between the discharge point and GS03 and by lower than average contributions from local tributaries.

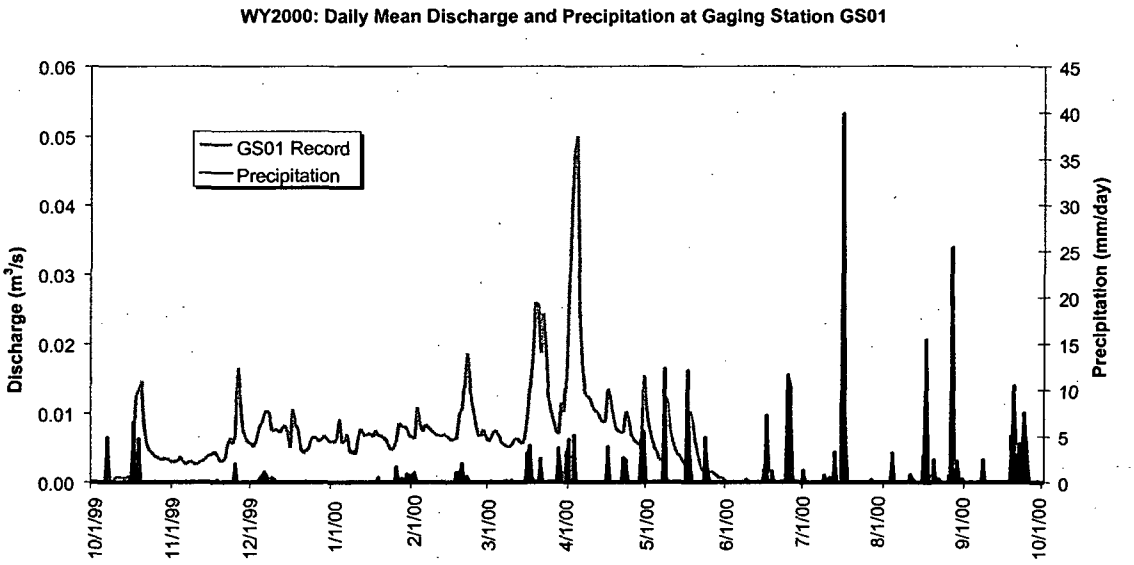
Annual discharge of imported water from the WWTP amounts to 240,000 m^3 (0.8 million cf) typically (averaged data from 1997 through 2001). This volume was comparable in WY2000 at 230,000 m^3. Within the B-series ponds, this accounts for 86 percent of the average discharge volume to Walnut Creek (72 percent in WY2000).

B.3.1.2.2.2 Woman Creek

Within the study area, the Woman Creek drainage extends from gaging station GS01 to the west and south model boundaries. This drainage includes the SW027 drainage because the detention pond at the end of the SW027 drainage (Pond C-2) is periodically released to Woman Creek. (It is important to note that during WY2000, Pond C-2 was not discharged, effectively isolating the SW027 drainage.) The Woman Creek drainage includes a small portion of the Industrial Area (within the SW027 drainage), as well as Ponds C-1 and C-2. Additionally, the largest Site seep, Antelope Springs, contributes water throughout the year to the Woman Creek drainage. Antelope Springs provides constant baseflow and storm hydrographs, due to runoff from areas of saturation. Compared to Walnut Creek, Woman Creek is a more natural system, with less than 3 percent impervious surface area, and no contribution from imported water. As a result, seasonal trends are more apparent in the GS01 record.

The observed GS01 hydrograph and hyetograph for WY2000 are presented below in Figure B-35.

Figure B-35. Observed WY2000 Hydrograph and Hyetograph at GS01



The figure above shows zero flow from June through the end of the water year, despite observed precipitation events during this period. This seasonal trend is repeated in data sets from the previous years. Typically, neither baseflow nor runoff response to precipitation are observed at GS01 between roughly June and October. This suggests a local (near-stream) groundwater table controlled largely by vegetation (ET). The net result is two distinct periods each year, where the GS01 drainage as a whole, either gains or loses flow.

GS01 discharge and all measured inflows to GS01 are presented in Figure B-36. The important seasonal trend of gain/loss is demonstrated clearly in the Figure B-37. In this figure, inflows to the main channel (GS05, GS06, Antelope Springs and Pond C-2 discharge) are subtracted from the observed GS01 discharge for the three years of record. In this figure, the main channel is losing water during periods where the difference is negative and gaining water during periods when the difference is positive. The annual trend clearly repeats itself each year and does not follow precipitation.

Figure B-36. Observed WY2000 Hydrographs for GS01, GS05, GS06, and GS16

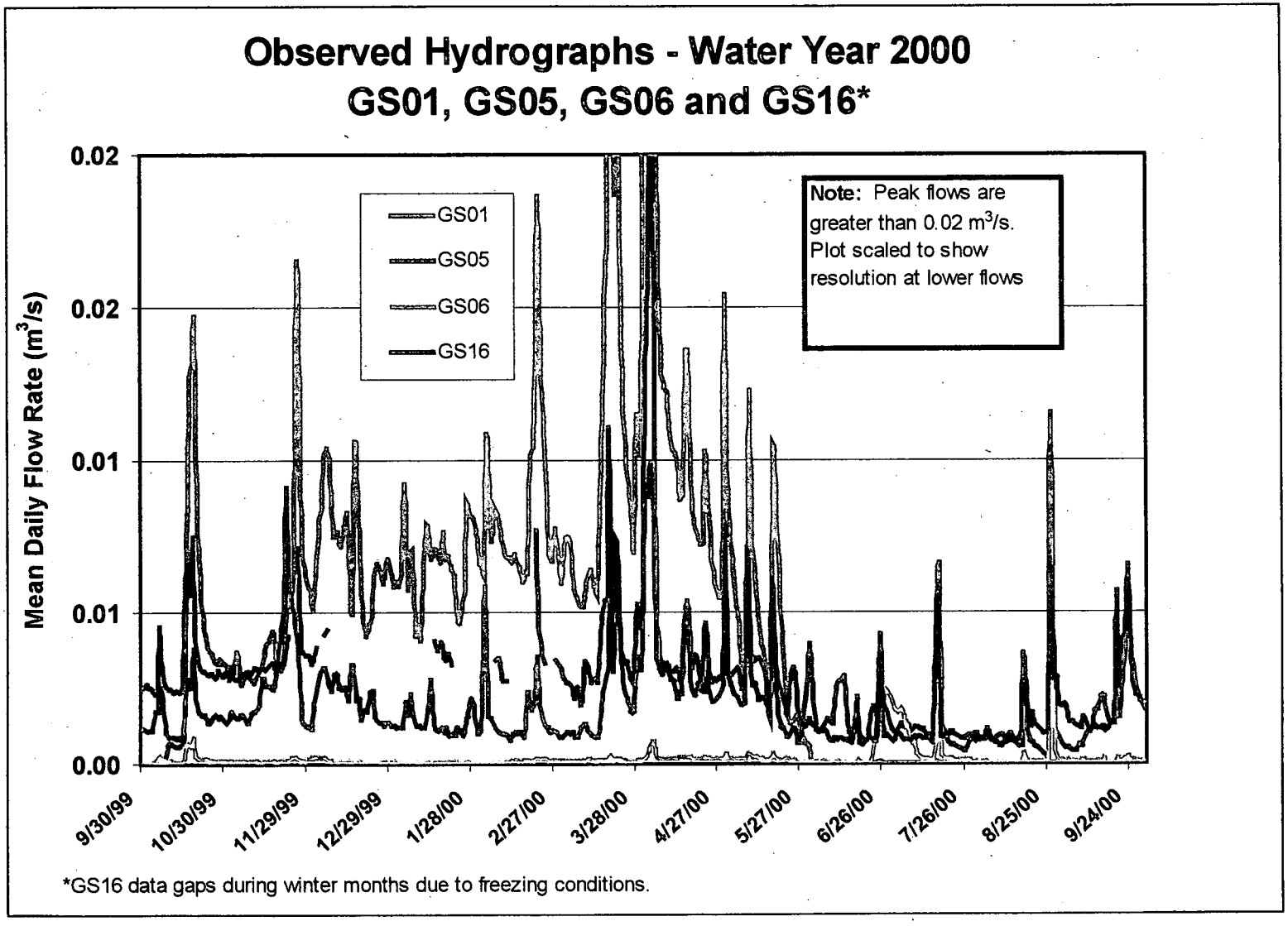
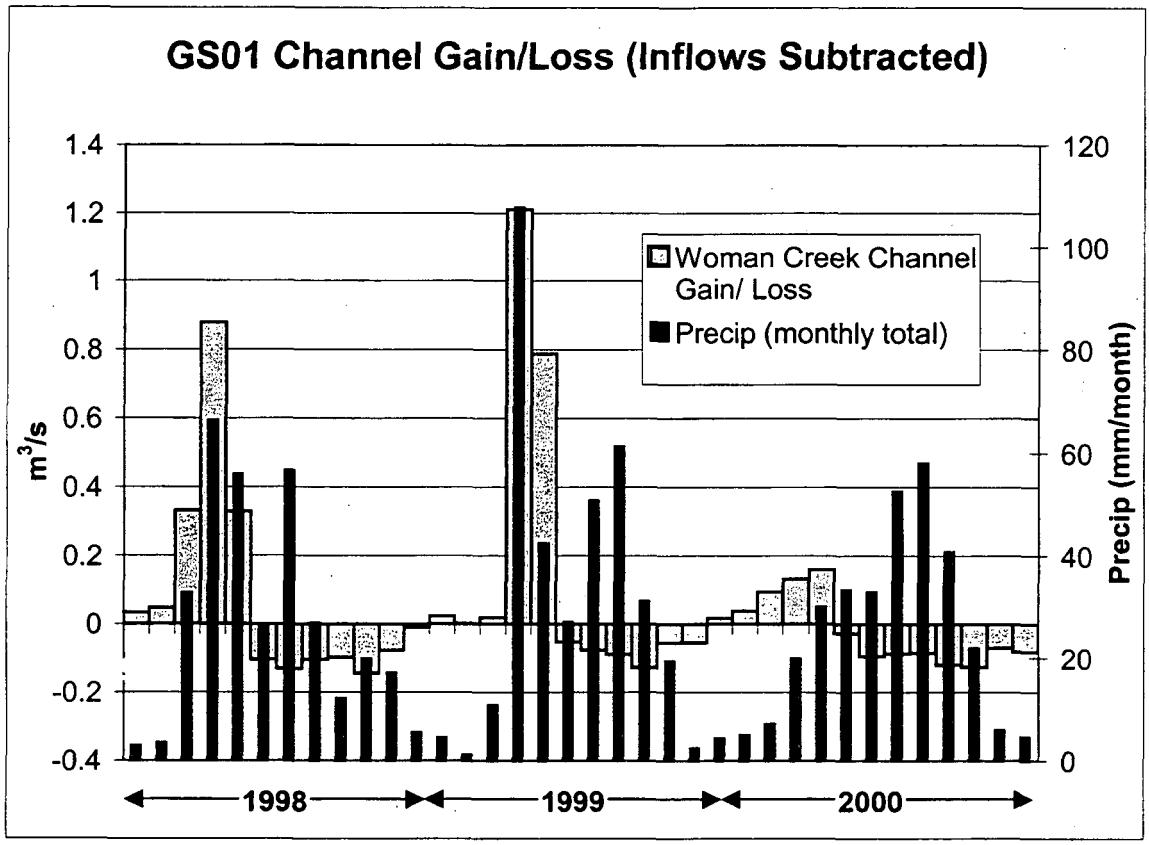


Figure B-37. Seasonal Trends of Gain/ Loss in Woman Creek



An average of 390,000 m^3 (14 million cf) are measured at GS01 annually (averaged data from 1997 through 2001). In WY2000, 150,000 m^3 (5.3 million cf) were measured, which is 62 percent below the 5-year average. Typically (averaged data from

97 through 2001), the volume measured at the discharge point for the Pond C-2 is 70 percent of the volume observed at GS01. As mentioned previously, however, Pond C-2 was not discharged in WY2000.

B.3.1.3 Ponds

For the purposes of this project, water balances were developed using available observed data for the A-3, A-4, B-5 and the Present Landfill Ponds to establish the influence of groundwater on the ponds. Evaporation estimates were applied to fill out data sets including precipitation, inflow volumes, pond levels and discharge volumes. Despite

data availability limitations, the water balances consistently demonstrated that gain or loss of groundwater was not a significant factor determining pond volume. This result is bounded by the error in the depth to volume conversions for the Ponds.

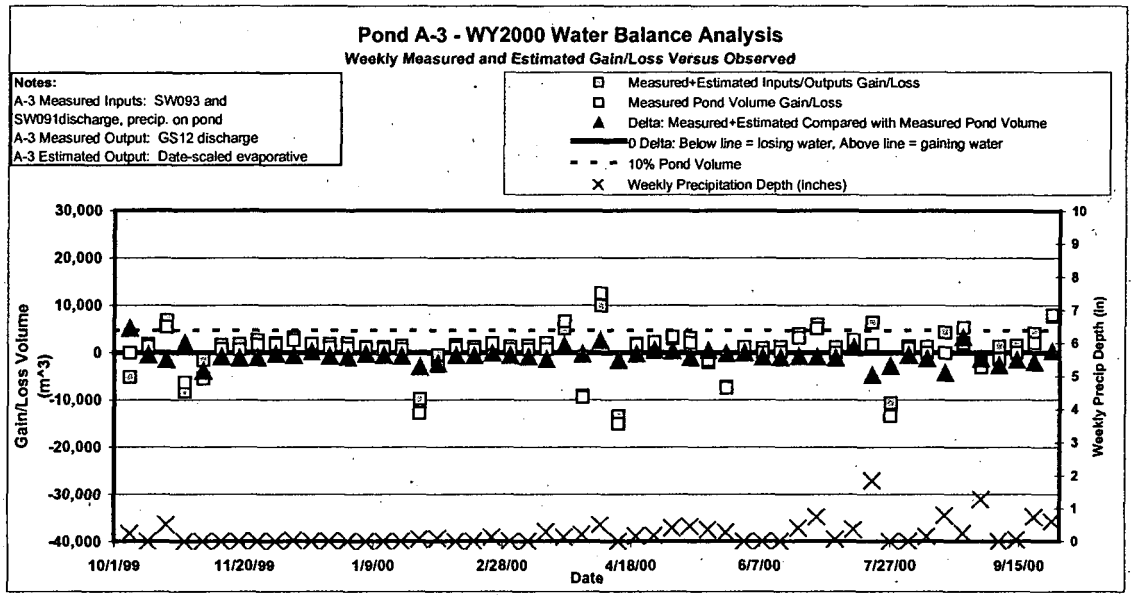
The following images (Figure B-38 through Figure B-42) summarize the results of the pond water balances prepared from observed data. The following data types were applied:

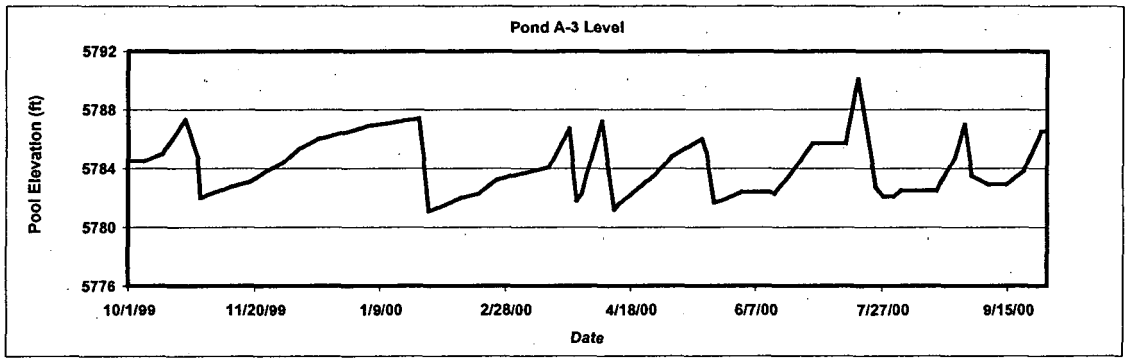
- precipitation;
- inflow volumes;
- discharge volumes;
- pond levels (applying conversions to volume); and
- evaporation (applying evaporation rates based on pond level conversion to surface area).

Pond level data were only available for Ponds A-3, A-4, B-5, C-2 and the Landfill Pond, limiting the study to these water bodies. The greatest error in the applied observed data was in the level measurements as converted to volume.

The two unknowns in the study were overland runoff contributing directly to the ponds and groundwater interaction with the ponds. Based on calibration results, it was assumed that overland runoff contribution to the ponds was negligible. Consequently, the sum of all available water balance components was assumed to be an indicator of the magnitude of groundwater interaction with the ponds. The following charts show this net value to be small.

Figure B-38. Pond A-3 Water Balance from Observed Data





Notes for Interpreting Plots:

Upper Graph

Gray squares - Indicates gain or loss in pond volume based on measured inflows and outflows at gaging stations plus estimated precipitation gain on pond surface minus estimated evaporative losses. Above 0 indicates a gain in pond volume since the previous data point. Below 0 indicates a loss.

White squares - Indicates gain or loss in pond volumes based on pond levels. Above 0 indicates a gain in pond volume since the previous data point. Below 0 indicates a loss.

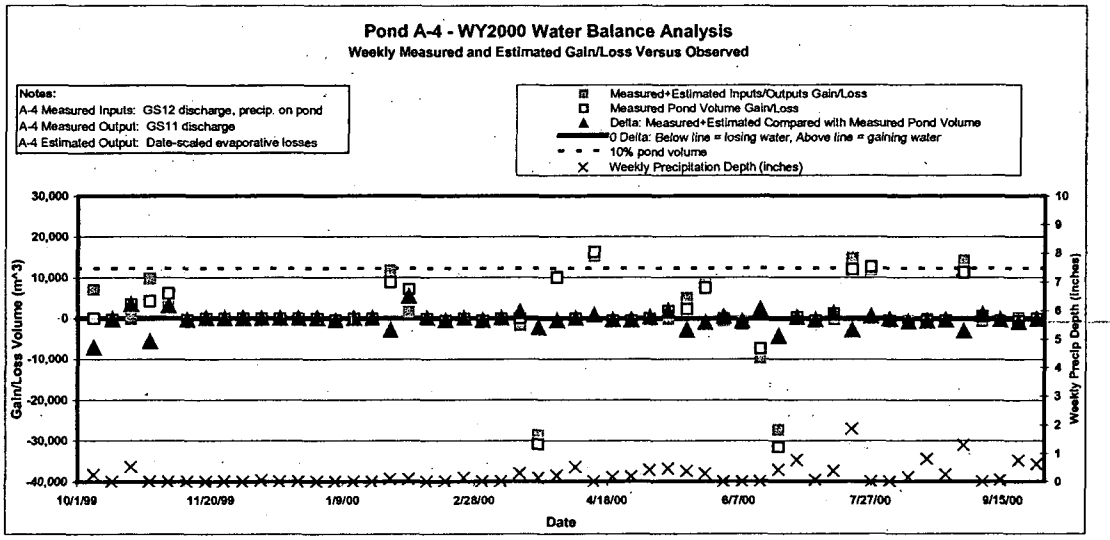
Triangles - Indicate difference between gray squares and white squares. A triangle below 0 indicates (measured + estimated inflows and outflows) is larger than (change in pond volume based on pond level).

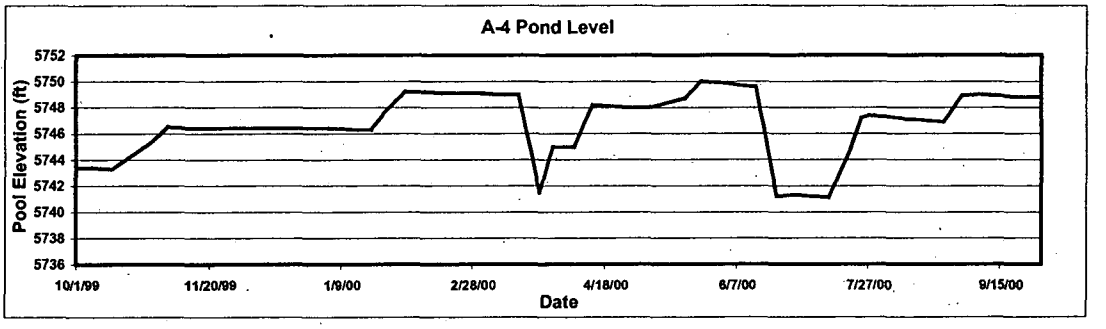
X's - Indicate dates and depths of precipitation events.

Lower Graph

Pond level plotted versus time,

Figure B-39. Pond A-4 Water Balance from Observed Data





Notes for Interpreting Plots:

Upper Graph

Gray squares - Indicates gain or loss in pond volume based on measured inflows and outflows at gaging stations plus estimated precipitation gain on pond surface minus estimated evaporative losses. *Above 0 indicates a gain in pond volume since the previous data point. Below 0 indicates a loss.*

White squares - Indicates gain or loss in pond volumes based on pond levels. Above 0 indicates a gain in pond volume since the previous data point. Below 0 indicates a loss.

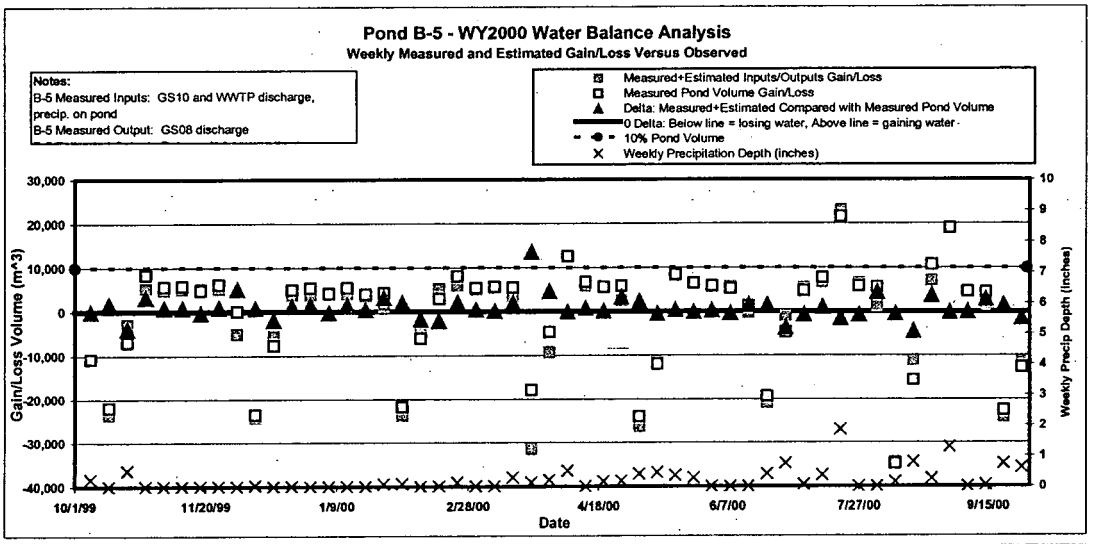
Triangles - Indicate difference between gray squares and white squares. A triangle below 0 indicates (measured + estimated inflows and outflows) is larger than (change in pond volume based on pond level).

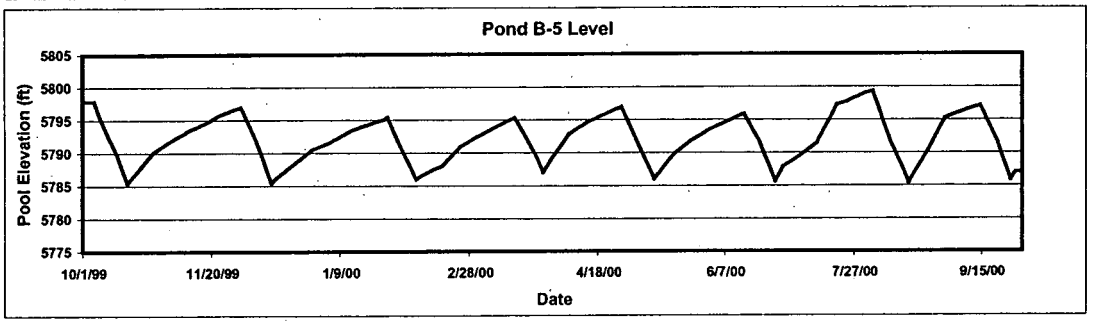
X's - Indicate dates and depths of precipitation events.

Lower Graph

Pond level plotted versus time.

Figure B-40. Pond B-5 Water Balance from Observed Data





Notes for Interpreting Plots:

Upper Graph

Gray squares - Indicates gain or loss in pond volume based on measured inflows and outflows at gaging stations plus estimated precipitation gain on pond surface minus estimated evaporative losses. Above 0 indicates a gain in pond volume since the previous data point. Below 0 indicates a loss.

White squares - Indicates gain or loss in pond volumes based on pond levels. Above 0 indicates a gain in pond volume since the previous data point. Below 0 indicates a loss.

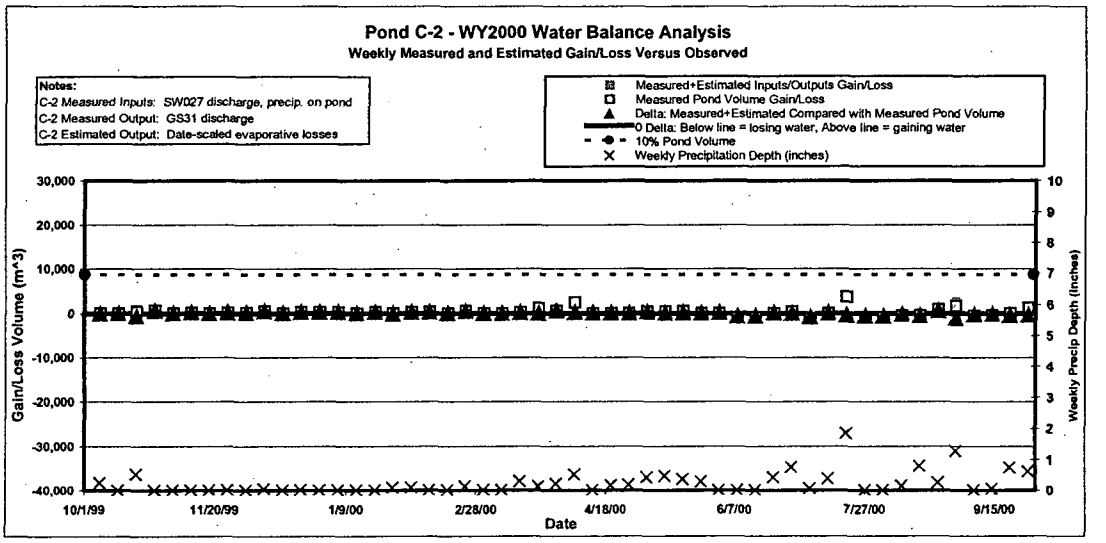
Triangles - Indicate difference between gray squares and white squares. A triangle below 0 indicates (measured + estimated inflows and outflows) is larger than (change in pond volume based on pond level).

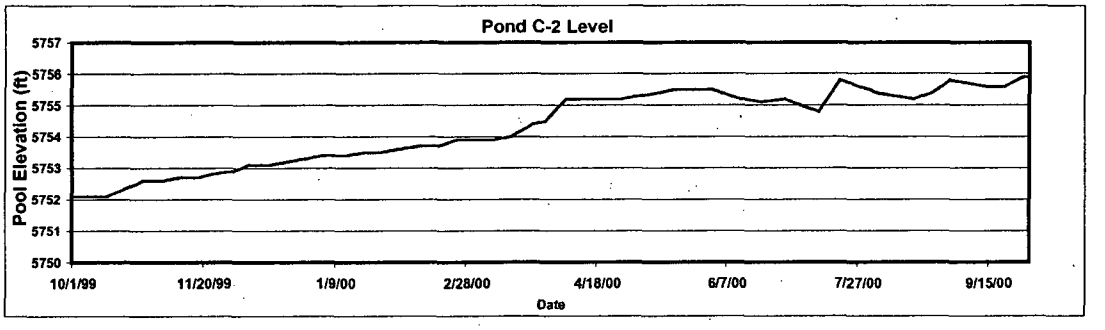
X's - Indicate dates and depths of precipitation events.

Lower Graph

Pond level plotted versus time,

Figure B-41. Pond C-2 Water Balance from Observed Data





Notes for Interpreting Plots:

Upper Graph

Gray squares - Indicates gain or loss in pond volume based on measured inflows and outflows at gaging stations plus estimated precipitation gain on pond surface minus estimated evaporative losses. Above 0 indicates a gain in pond volume since the previous data point. Below 0 indicates a loss.

White squares - Indicates gain or loss in pond volumes based on pond levels. Above 0 indicates a gain in pond volume since the previous data point. Below 0 indicates a loss.

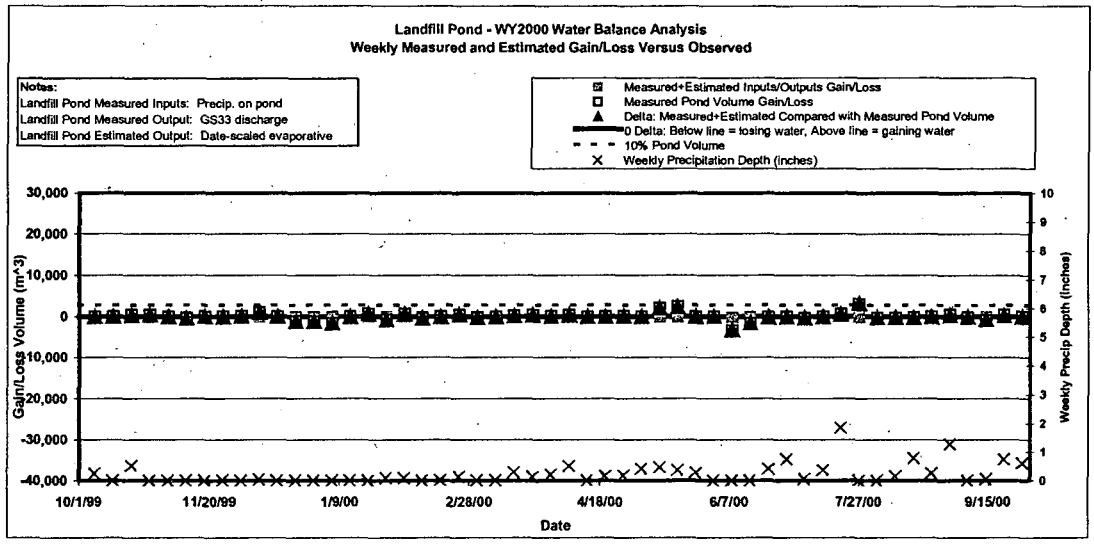
Triangles - Indicate difference between gray squares and white squares. A triangle below 0 indicates (measured + estimated inflows and outflows) is larger than (change in pond volume based on pond level).

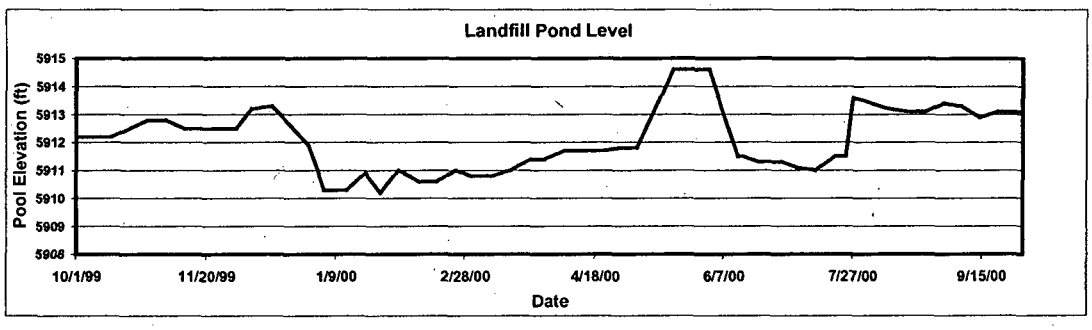
X's - Indicate dates and depths of precipitation events.

Lower Graph

Pond level plotted versus time,

Figure B-42. Landfill Pond Water Balance from Observed Data





Notes for Interpreting Plots:

Upper Graph

Gray squares - Indicates gain or loss in pond volume based on measured inflows and outflows at gaging stations plus estimated precipitation gain on pond surface minus estimated evaporative losses. Above 0 indicates a gain in pond volume since the previous data point. Below 0 indicates a loss.

White squares - Indicates gain or loss in pond volumes based on pond levels. Above 0 indicates a gain in pond volume since the previous data point. Below 0 indicates a loss.

Triangles - Indicate difference between gray squares and white squares. A triangle below 0 indicates (measured + estimated inflows and outflows) is larger than (change in pond volume based on pond level).

X's - Indicate dates and depths of precipitation events.

Lower Graph

Pond level plotted versus time,

These ponds were not lined at the time of construction; however, the assumption of limited groundwater interaction seems reasonable considering recent observations of thick layers of fine sediments (Kaiser-Hill, 2002a). Additionally, a simple pond management model, assuming no groundwater interaction, has been applied at the Site to plan all pond transfers and discharges with good predictive success (Hoffman, 2002).

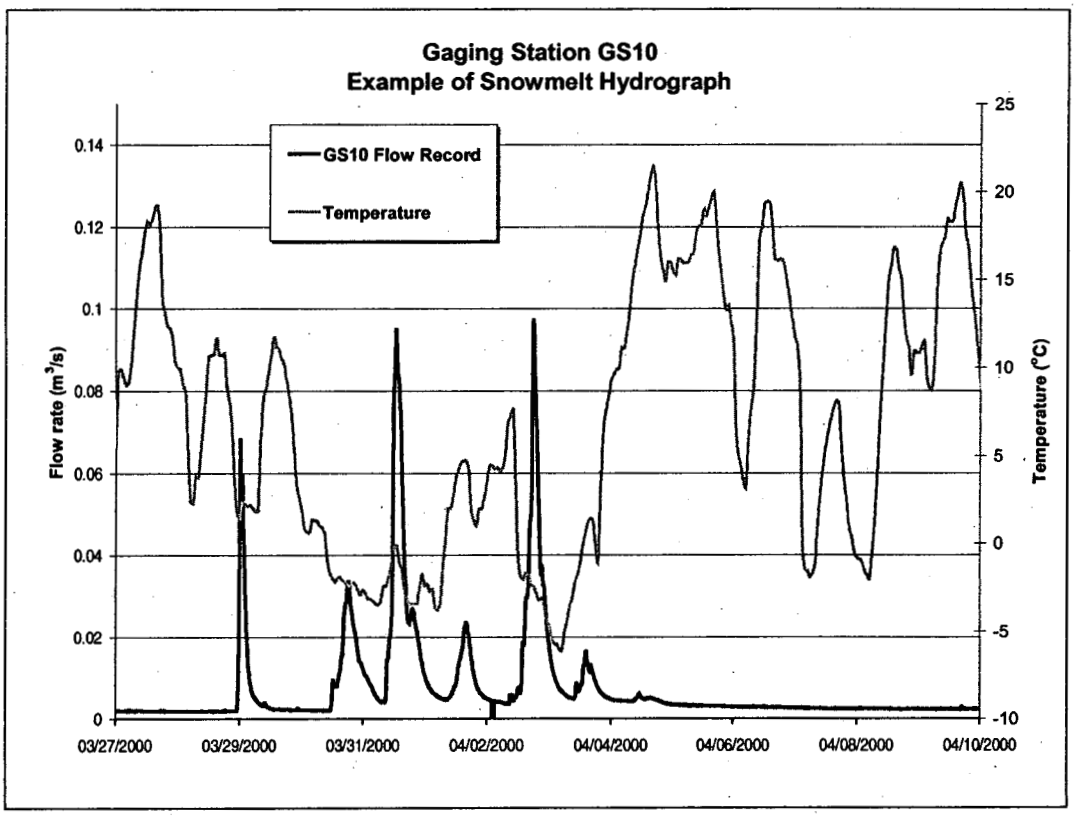
B.3.1.4 Snowmelt

Snowfall is observed during fall, winter and early spring at RFETS. Typically, snowmelt occurs quickly (within 1 to 5 days). Snowmelt events can influence overland runoff directly or can create antecedent conditions of saturated to near-saturated surfaces. Snow depth and water content measurements are not routinely made (but was monitored as part of a study by Moffit [1996]).

Snowmelt was monitored and modeled at RFETS by Moffit (1996). The purpose of the study was to quantify snowmelt rates and to assess potential melt rates from extreme snow events. The US Army Corps of Engineers model, SNTHERM, was used to simulate snowmelt of a snowpack with 9.0-cm Snow-Water-Equivalent (SWE) for a 100-year recurrence. The modeled snowpack melted in 1.8 days. A one-meter snowdrift (30-cm SWE) melted in 5.6 days. This is equivalent to 78 percent of the annual precipitation applied as a localized recharge source. One of the main conclusions is that snowdrifts can result in high melt volumes. The study assumed that the ground was not frozen and readily allowed infiltration of snowmelt, which was locally high in snowdrift areas.

Surface water response to snowfall events is most evident in the Industrial Area subdrainages, where overland runoff is generally observed for most precipitation events. A diurnal-type hydrograph response is typical, coinciding with increased air temperatures and solar radiation during the days following the event. An example hydrograph of snowmelt is shown below in Figure B-43. Complexities such as drifting, salting of roads and plowing patterns can affect subdrainages locally, but they were not specifically considered in this project.

Figure B-43. Snowmelt Response Example at GS10



B.3.2 Subsurface Flow Response

B.3.2.1 Unsaturated Zone Response

Unsaturated zone flow dynamics become increasingly non-linear and complex with increasing aridity because of large temperature ranges. Four fundamental flow processes occur within the unsaturated zone, namely: (1) infiltration; (2) ET; (3) redistribution; and (4) groundwater recharge. ET is described as a model stress in Section 3, while the others are briefly described below in a conceptual manner. The unsaturated zone dynamics are probably the most important to understand because they link the surface flow system with the saturated zone. Of all the hydrologic processes at RFETS, flow response data in the unsaturated zone are limited and only locally available. As such, the unsaturated zone flow response is described mostly in terms of the observed saturated zone and surface flow system responses.

On a regional basis, the effects of local factors (like macropore flow, air entrapment, hysteresis, vapor transport, macropore flow and interflow [Stephens, 1995]) were considered secondary to the unsaturated zone hydraulic properties of the surficial deposits. For example, the noticeable groundwater table response suggested that recharge through the unsaturated zone, regardless of depth, occurred in most pervious areas of the model area (mostly in response to spring precipitation events). Although some studies performed on-Site attempted to describe unsaturated zone processes, none considered this response over the entire model area and focused on local areas (Daniels, 1996).

Ponding occurs by two mechanisms on pervious material, saturation excess and by Horton flow (Chorley, 1978). During extreme events, when precipitation intensities overwhelm soil infiltration capacities, Horton flows will dominate streamflow hydrographs. Saturation excess occurs when groundwater rises and saturates the ground surface, like at seeps located around the Site. The principal area where saturation excess occurs is at gaining sections of streams and at significant seeps, like Antelope Springs, where groundwater discharges to the ground surface. During precipitation events, shallow groundwater levels adjacent to streams, or at seeps, quickly rise and saturate the ground surface. This is an important process because it impacts the streamflow response at RFETS. The saturated zones at the ground surface typically increase up hillslopes during precipitation events causing increasing area for fast runoff. These areas are referred to as Variable Source Areas (VSA). The extent of VSAs at RFETS is unknown, but groundwater levels in wells in near-stream areas exhibit rapid responses. This flow condition probably occurs throughout shallow groundwater-stream areas, and it contributes to streamflow.

B.3.2.2 Saturated Zone Response

Hydrologic response of the saturated zone is described in detail in several reports (EG&G,1995a; RMRS, 1999a). Available RFETS data were reviewed, and the spatial and temporal groundwater response was analyzed. Unpublished data from the Site were also applied to this analysis. General characteristics of the groundwater response are

summarized in the following sections. System response is described in terms of three primary saturated zone datasets, namely: (1) groundwater water levels (heads); (2) groundwater discharge through seeps; and (3) discharge through subsurface drains.

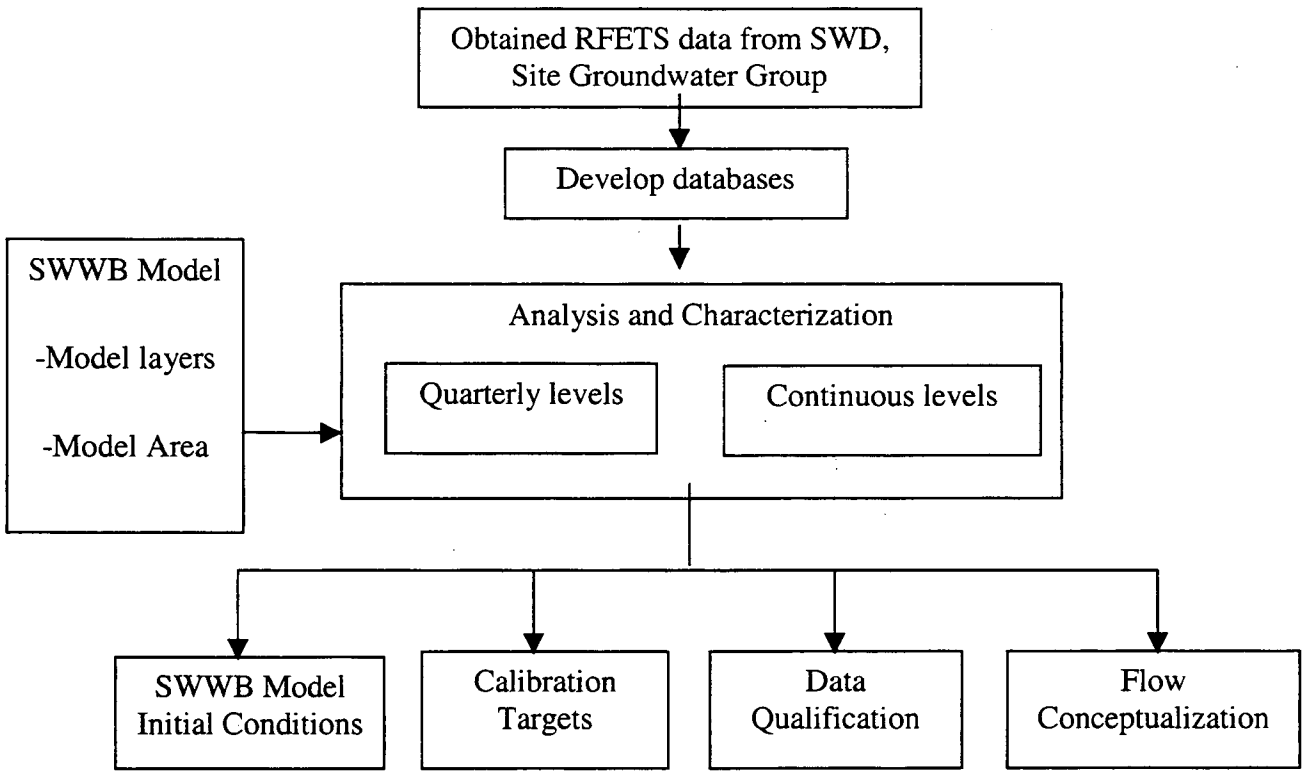
Groundwater flows into the model area along the western boundary and discharges to off-Site along the eastern boundary. Generally, there is no discharge across either the northern or southern boundaries, except for possible short-term response to surface flow in McKay Ditch. Vertical groundwater flow between the UHSU and LHSU is considered negligible. It does not vary much seasonally because groundwater gradients do not change significantly across the boundary.

An analysis of the available groundwater data from 1990 to 2000 was conducted to:

- Identify trends in potentiometric surface depths and elevations;
- Identify outliers or problem data (quality control);
- Identify data gaps and provide estimates for depth/elevation in these areas;
- Evaluate vertical head differences over vertical extent of model layers;
- Provide spatial distribution over model area;
- Identify specific SWWB model calibration targets and develop appropriate datasets;
- Develop appropriate plots where flow directions, gradients and magnitudes are characterized; and
- Evaluate the change in water levels throughout the year throughout the model area (quarterly and continuous).

Figure B-44 outlines the approach taken to analyze the groundwater data.

Figure B-44. Groundwater Analysis Approach



Water levels changes in wells provided useful information on groundwater flow. First, a potentiometric surface was developed by interpolating groundwater levels in wells located within the same hydrostratigraphic unit. The potentiometric surface was then used to infer groundwater flow directions and hydraulic gradients. The change in potentiometric surface over time was estimated from these potentiometric surfaces. This provided useful information on seasonal trends and identified specific areas that experience higher relative changes in water level. Long-term (multi-year), seasonal and short-term response of groundwater levels is described in Section 3.

B.3.2.2.1 Long-Term Response

Data for an approximately eight-year period (January 1, 1992 to November 2, 1999) were queried from the on-Site Soil Water Database (SWD) database. The extracted well data

were grouped by geomorphic location (mesas, hill slopes or stream areas) and examined for long-term responses. Figure B-45 displays the long-term response for wells in each of the three areas. General observations include:

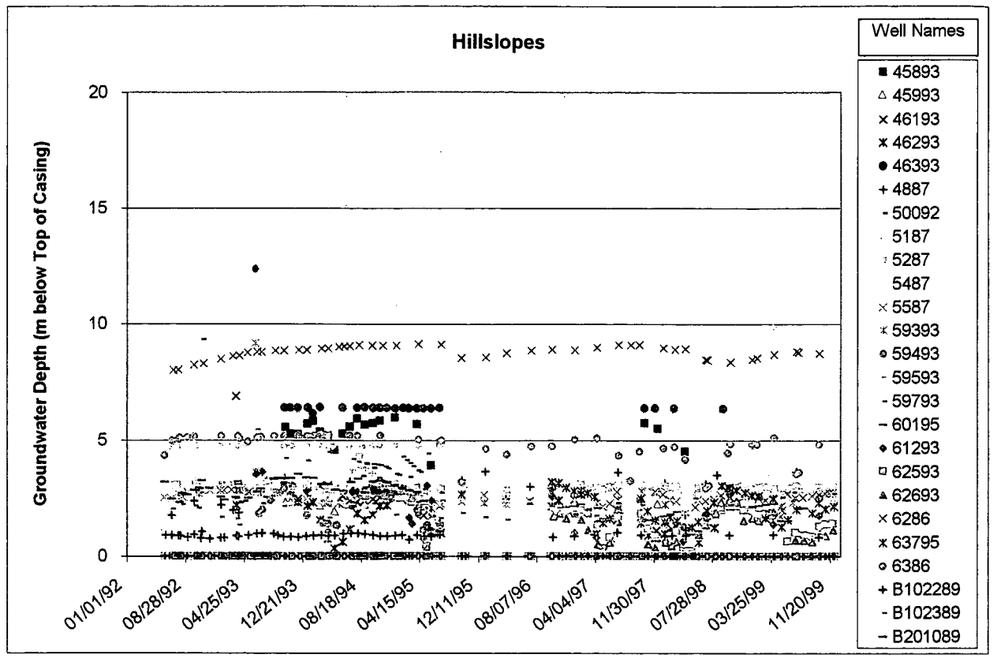
- Groundwater levels at the Site are relatively steady over the last 8 years;
- The variability in individual wells tended to return to the long-term average. This was generally true regardless of location (mesa versus stream areas). However, the mesa areas took longer to recover from seasonal event perturbations; and
- The most important implication is that a single year's precipitation stress signal did not cause long-term perturbation as the system returns to average annual levels.

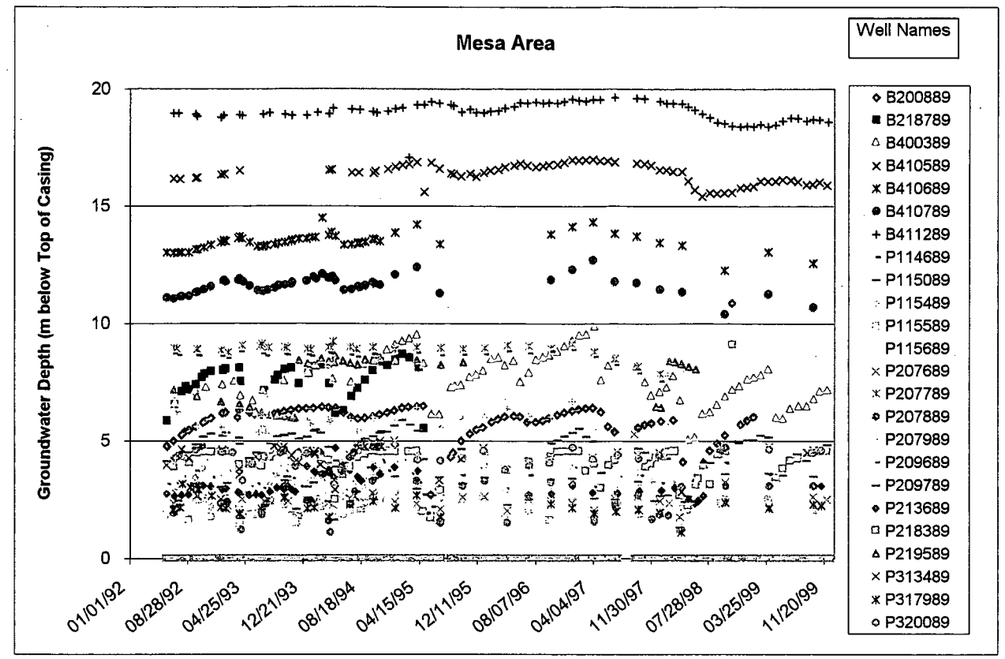
B.3.2.2.2 Potentiometric Surface Characteristics

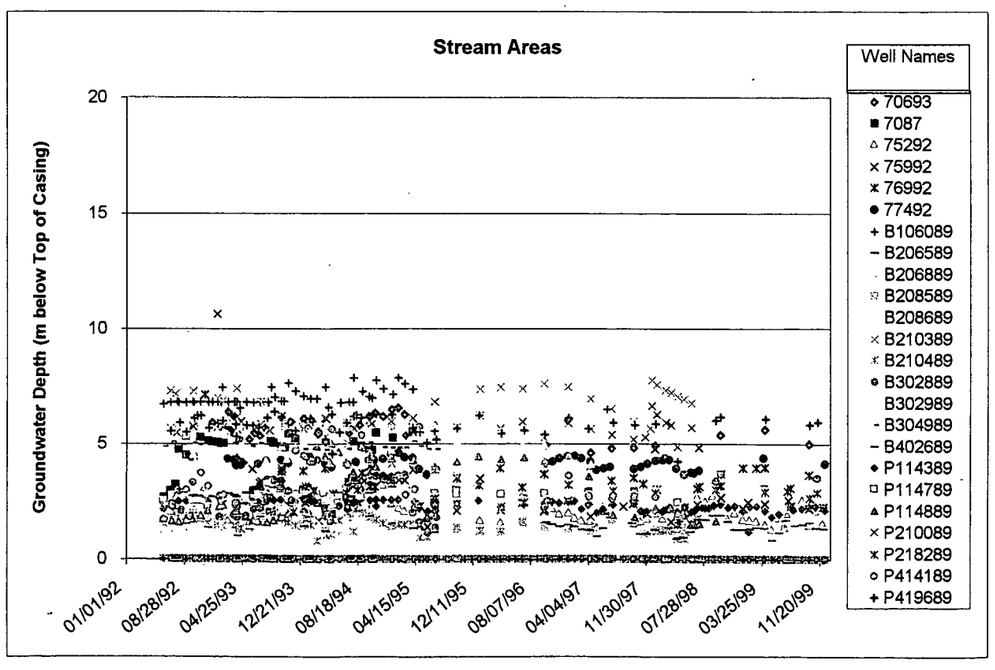
Groundwater table characteristics can be described in terms of a continuous pressure surface (potentiometric surface) or in terms of groundwater depth. The October, 2000 potentiometric surface over the model area presented on Figure B-46. A seasonal analysis of the potentiometric surfaces indicated several notable characteristic including:

- Hydraulic gradients follow topography and weathered bedrock surface closely;
- Regional groundwater flow directions generally change little throughout the year, despite seasonal changes in water table. This is due chiefly to the strong effect of topographic elevation change on groundwater flow (elevation head);

Figure B-45. Long-Term Groundwater Depths







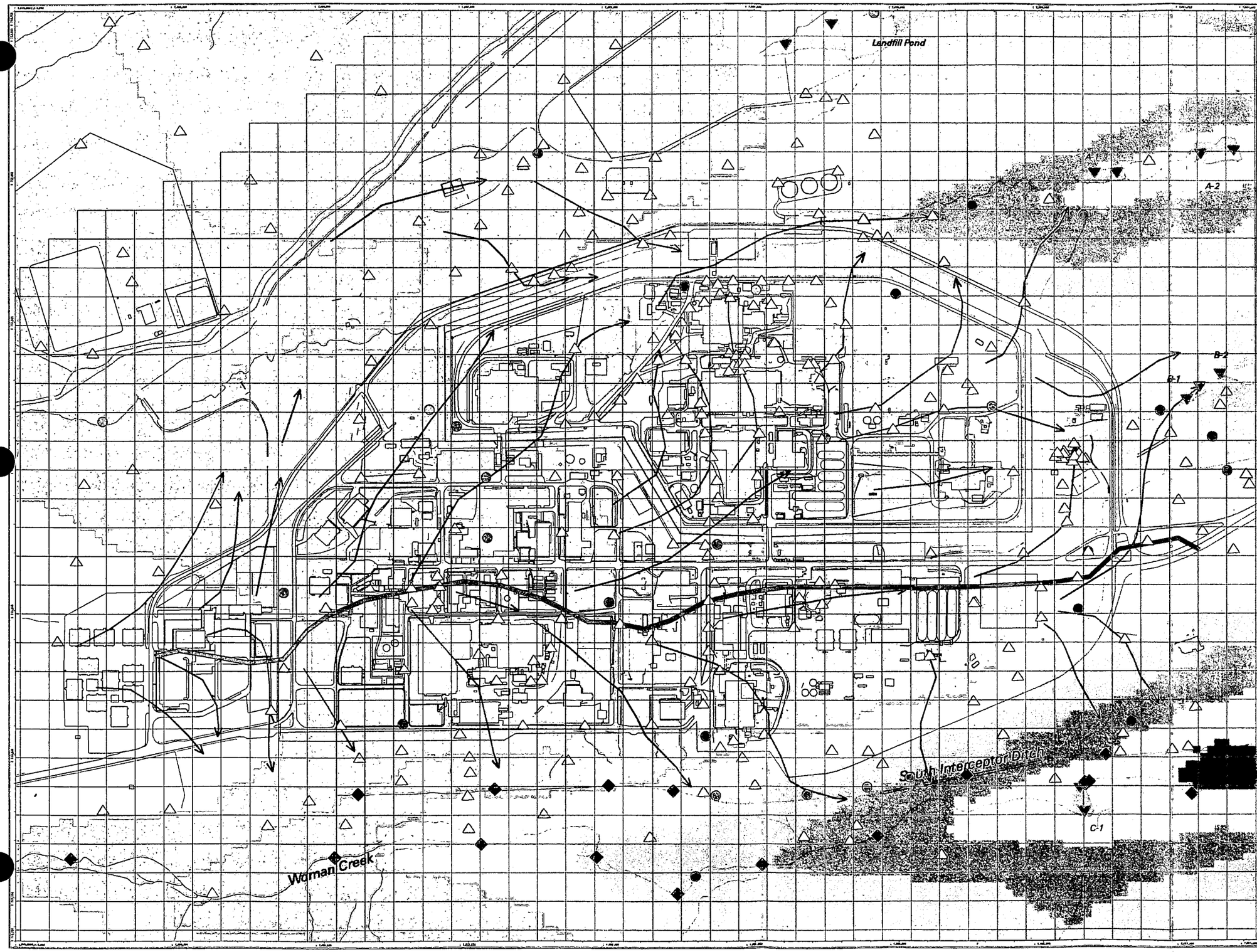


Figure B-46

Site-Wide Water Balance Report

Industrial Area Groundwater Elevations (October 2000)

EXPLANATION

Groundwater Monitoring

- Continuous Groundwater Levels
- Sampling Well
- Pond Control
- Seep Control
- Stream Control
- Monitoring Well

Groundwater Flow

- Approximate Groundwater Flow Directions
- Approximate Groundwater Divide

Groundwater Elevation (ft)

- 6040 - 6080 (1841.0 - 1853.1 m)
- 6000 - 6040 (1828.8 - 1841.0 m)
- 5960 - 6000 (1816.6 - 1828.8 m)
- 5920 - 5960 (1804.4 - 1816.6 m)
- 5880 - 5920 (1792.2 - 1804.4 m)
- 5840 - 5880 (1780.0 - 1792.2 m)
- 5800 - 5840 (1767.8 - 1780.0 m)
- 5760 - 5800 (1755.6 - 1767.8 m)
- Model Grid

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Paved roads

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:
Elevations calculated by nearest neighbor interpolation scheme. No attempt was made to further interpolate to subsurface drains. The purpose of the map is to show approximate elevations.

20 0 40 80m

100 0 200 400ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

U.S. Department of Energy
Rocky Flats Environmental Technology Site

CDS Dept. 303-966-7707

Prepared by: DynCorp — THE ART OF TECHNOLOGY

Prepared for: KAISER-HILL COMPANY

May 14, 2002

NT_Gvr w:/projects/ewwb/fy2002/section_b/oct00_gw-elev.aml

- Groundwater flows diverge towards Woman and Walnut Creeks immediately upstream of the Industrial Area. Therefore, there is effectively no upgradient groundwater inflow to the Industrial Area. This strongly suggests that water table fluctuations in the Industrial Area are primarily controlled by direct infiltration of precipitation and subsequent ET and lateral saturated zone flow;

- Although there are many wells in the Industrial Area, the hydraulic influence of subsurface pipes and structures on the potentiometric surface remains unclear;

- Across the model area, groundwater flows towards streams, rather than from west to east. The flow directions are controlled almost entirely by the local topography and bedrock surface morphometries.

Potentiometric surface maps were constructed from the interpolated groundwater depth surfaces for the six quarters of data. Interpolated depths were subtracted from ground surface topography to generate potentiometric surfaces for each quarter. Only the interpolated October, 2000 potentiometric surface and control points are shown on Figure B-46 because flow directions and gradients do not appear to change significantly because of the large elevation head control (i.e., over 600 ft or 183 m topographic surface elevation loss over model area compared to small aquifer thickness). Approximate groundwater flow directions are also shown. General observations are presented in Section 3.

B.3.2.2.3 Groundwater Depths

Groundwater depth data were interpolated over the model area to determine trends, identify outliers and to avoid overshoot/undershoot interpolation issues using elevation data. Six depth surfaces were created using data from October, 1999 through October, 2000. Water depths measured in the first 15 days of each quarter were queried from the SWD because quarterly measurements are recorded during this period. Levels from continuously-monitored wells were averaged over the first 15 days of each quarter so that this information could also be used to better constrain the interpolated depth surfaces.

Additional depth controls were added for seeps, streams, ponds and hilltop areas to improve the interpolation (Nearest Neighbor method). Figure B-47 shows depths from April, 2000. Results showed the following:

- Groundwater depths varied across the Industrial Area from about 2.5 ft (0.76 m) to greater than 25 ft (7.6 m) and averaging about 11 ft (3.4 m). Shallow groundwater depths generally occurred in areas where depths to weathered bedrock were shallow. Well data densities were not sufficient to confirm whether groundwater depths were controlled by trenches, drains or variations in hydrogeologic properties; and

- Groundwater depths generally increase from west to east.

B.3.2.2.4 Seasonal Groundwater Change

Spatial changes in groundwater levels over the model area were reviewed using available quarterly and continuously-monitored water level data. Data used to evaluate the change in groundwater levels over the model were more comprehensive than prior studies, because continuous groundwater level data were included. Several observations were made on the change in levels from January, 2000 to April, 2000, and from April, 2000 to July, 2000 (based on Figure B-48 and Figure B-49). These include:

- Over the majority of the Industrial Area, groundwater levels increased from January, to April, 2000 about 1 to 2 ft (0.3 to 0.61 m), and then decreased about this same amount from April to July; and

- Within these two periods, greater groundwater level changes occurred in hillslope areas adjacent to the Industrial Area. In these areas, groundwater flow velocities increased due to higher bedrock surface gradients and likely caused more rapid change in groundwater levels compared to flatter mesa or stream areas. Groundwater level changes ranged from -8 ft to 9 ft (-2.4 to 2.7 m). In some instances, the change was attributed to concentrated snowmelt (southwestern Industrial Area adjacent to pavement).

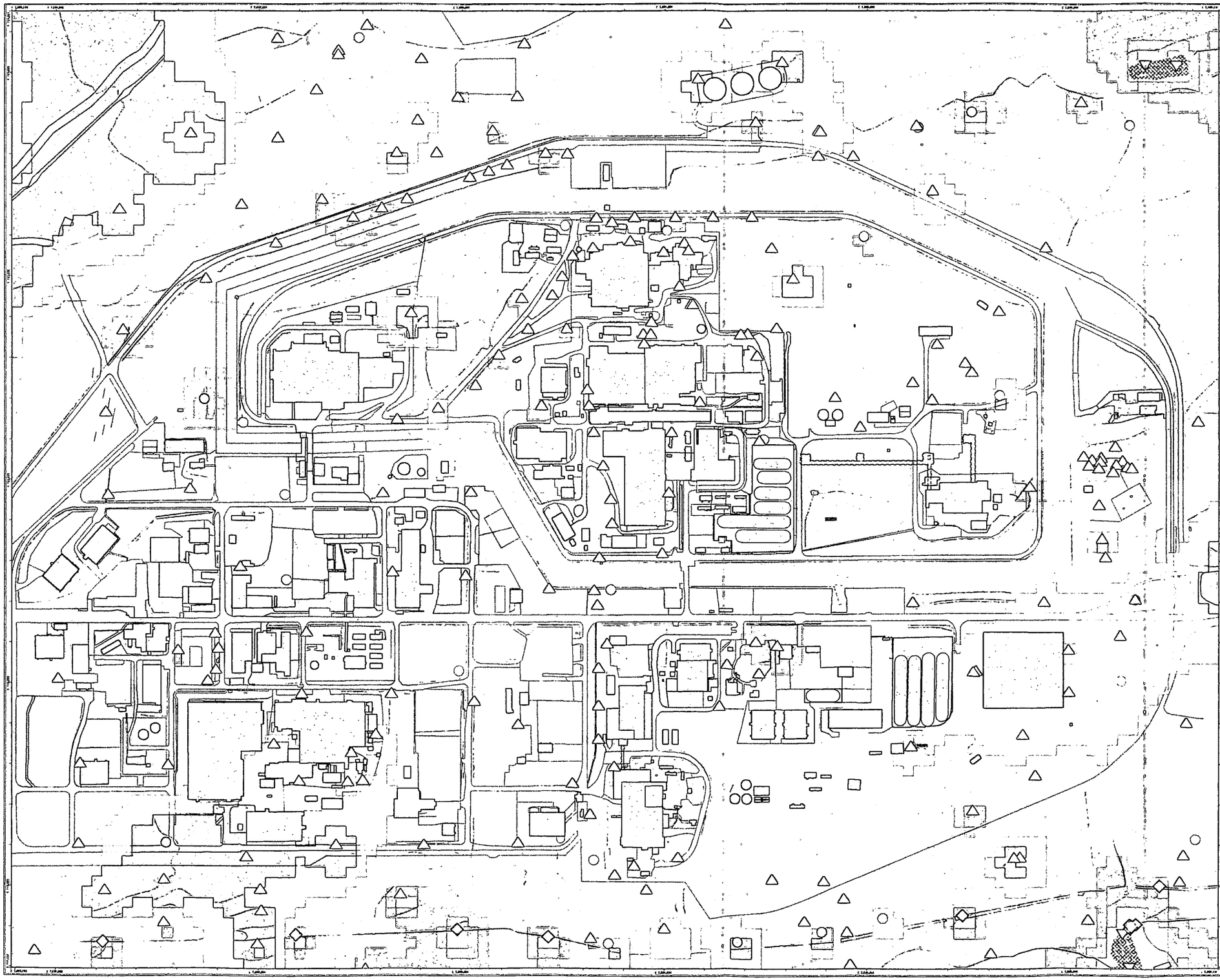


Figure B-47

Site-Wide Water Balance Report

Groundwater Depths (April 2000)

EXPLANATION

Control Points

- Continuous GW Levels
- Sampling Well
- Pond Control
- Seep Control
- Stream Control
- Monitoring Well

Approximate April 2000 Groundwater Depth Below Ground Surface (ft)

- 0 - 1 (0 - 0.3 m)
- 1 - 2 (0.3 - 0.6 m)
- 2 - 4 (0.6 - 1.2 m)
- 4 - 6 (1.2 - 1.8 m)
- 6 - 8 (1.8 - 2.4 m)
- 8 - 10 (2.4 - 3.0 m)
- 10 - 15 (3.0 - 4.6 m)
- 15 - 20 (4.6 - 6.1 m)
- 20 - 30 (6.1 - 9.1 m)
- 30 - 40 (9.1 - 12.2 m)
- 40 - 60 (12.2 - 18.3 m)

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Topographic Contour (20-Foot)
- Paved roads
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

Topographic contours were derived from digital elevation model (DEM) data by Morrison Knudson (MK) using ESRI Arc TIN and LATTICE to process the DEM data to create 5-foot contours. The DEM data was captured by the Remote Sensing Lab, Las Vegas, NV, 1994 Aerial Flyover at ~ 10 meter resolution. DEM post-processing performed by MK, Winter 1997.

NOTES:

Depths calculated by nearest neighbor interpolation scheme. No attempt was made to further interpolate to subsurface drains. The purpose of the map is to show approximate depths.

20 0 40 80m

100 0 200 400ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

U.S. Department of Energy
Rocky Flats Environmental Technology Site

GIS Dept. 303-966-7707

Prepared by: DynCorp — THE ART OF TECHNOLOGY

Prepared for: KAISER-HILL COMPANY

May 14, 2003

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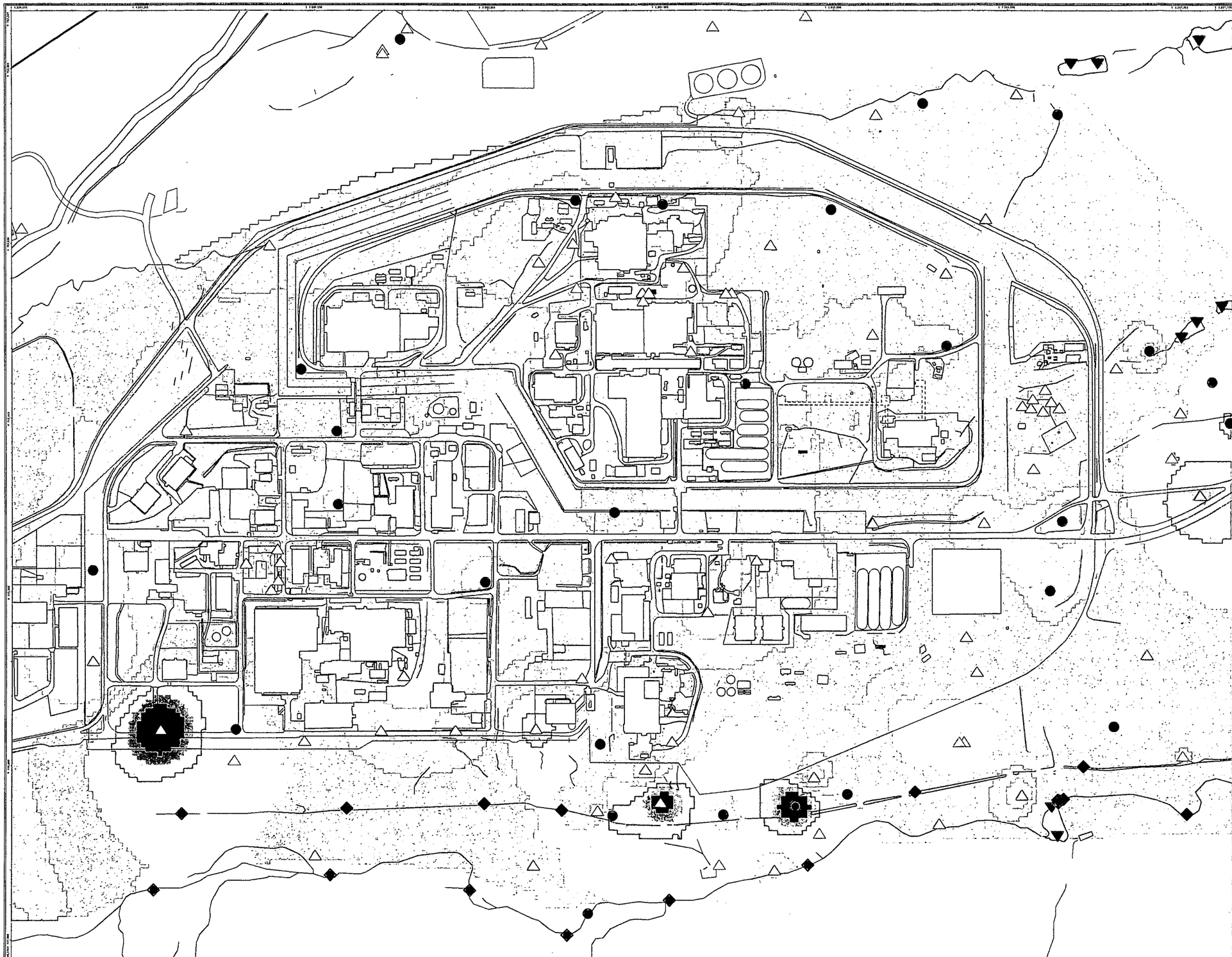

Figure B-48

Site-Wide Water Balance Report

January 2000 to April 2000 Groundwater Level Change

EXPLANATION

Control Points for April & January 2000

- Continuous Groundwater Levels
- Sampling Well
- Pond Control
- Seep Control
- Stream Control
- Monitoring Well

Approximate Change in Groundwater Elevation April minus January 2000 (ft)

- -15 to -7 (-4.6 to -2.1 m)
- -7 to -5 (-2.1 to -1.5 m)
- -5 to -3 (-1.5 to -0.9 m)
- -3 to -2 (-0.9 to -0.6 m)
- -2 to -1 (-0.6 to -0.3 m)
- -1 to 0 (-0.3 to 0 m)
- 0 to 1 (0 to 0.3 m)
- 1 to 2 (0.3 to 0.6 m)
- 2 to 3 (0.6 to 0.9 m)
- 3 to 5 (0.9 to 1.5 m)
- 5 to 19 (1.5 to 5.8 m)

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Paved roads
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:

Control points used to help constrain interpolation.

Elevations calculated by nearest neighbor interpolation scheme. No attempt was made to further interpolate to subsurface drains. The purpose of the map is to show approximate elevations.

20 0 40 80m

100 0 200 400ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

U.S. Department of Energy
Rocky Flats Environmental Technology Site

GIS Dept. 303-966-7707

Prepared by: DynCorp THE ART OF TECHNOLOGY

Prepared for: KAISER-HILL COMPANY

May 14, 2000

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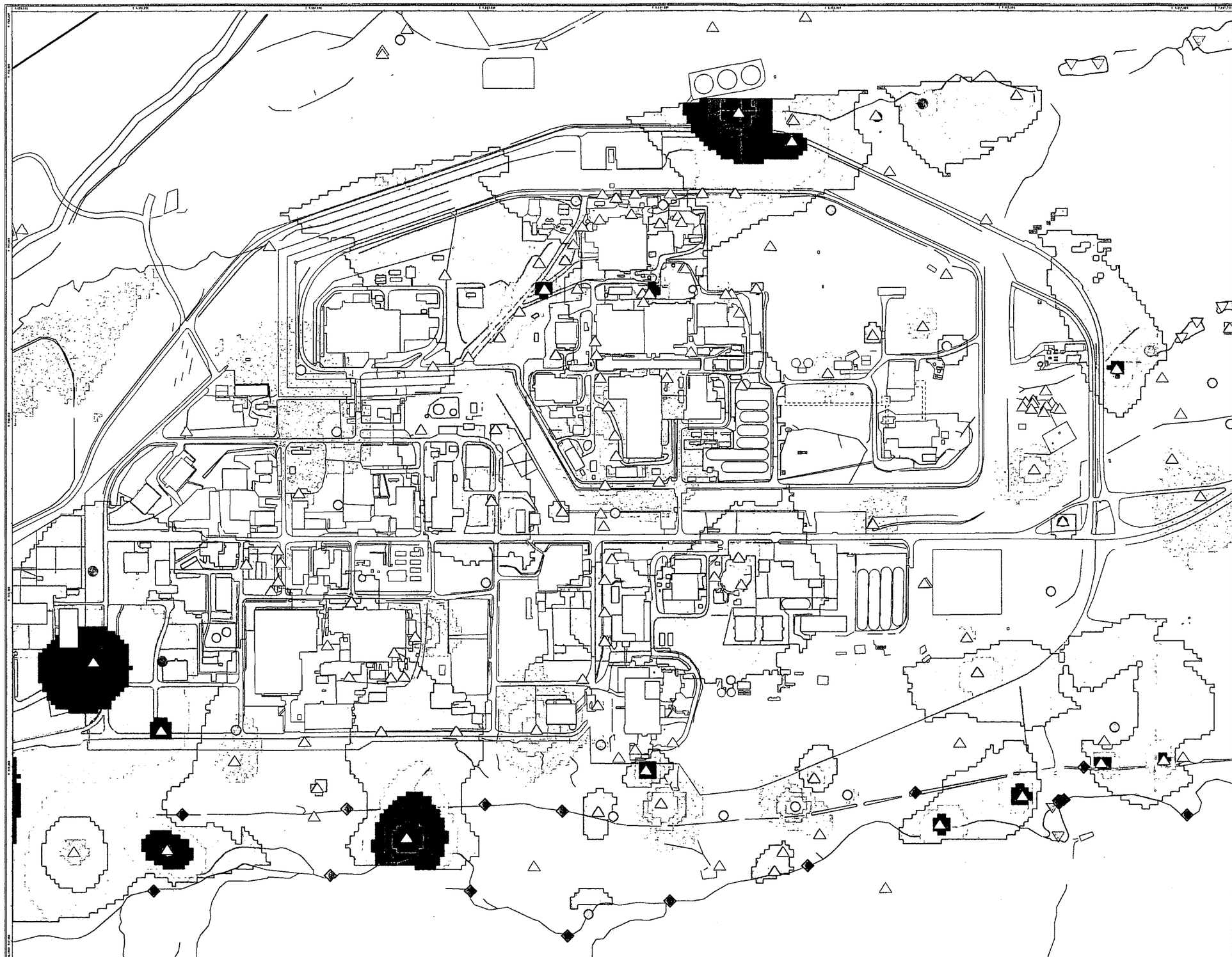

Figure B-49

Site-Wide Water Balance Report

April 2000 to July 2000 Groundwater Level Change

EXPLANATION

Control Points for July & April 2000

- Continuous GW Levels
- Sampling Well
- Pond Control
- Seep Control
- Stream Control
- Monitoring Well

Approximate Change in Groundwater Elevation July minus April 2000 (ft)

- -15 to -7 (-4.6 to -2.1 m)
- -7 to -5 (-2.1 to -1.5 m)
- -5 to -3 (-1.5 to -0.9 m)
- -3 to -2 (-0.9 to -0.6 m)
- -2 to -1 (-0.6 to -0.3 m)
- -1 to 0 (-0.3 to 0 m)
- 0 to 1 (0 to 0.3 m)
- 1 to 2 (0.3 to 0.6 m)
- 2 to 3 (0.6 to 0.9 m)
- 3 to 5 (0.9 to 1.5 m)
- 5 to 19 (1.5 to 5.8 m)

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Paved roads
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:

Control points used to help constrain interpolation.

Elevations calculated by nearest neighbor interpolation scheme. No attempt was made to further interpolate to subsurface drains. The purpose of the map is to show approximate elevations.

20 0 40 80m

100 0 200 400ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

U.S. Department of Energy
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Prepared by: DynCorp THE ART OF TECHNOLOGY

Prepared for: KAISER-HILL COMPANY

May 14, 2002

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The quarterly change in the groundwater levels was determined by subtracting the earlier quarter from the following one (i.e, April, 2000 minus January, 2000). The change in groundwater levels from January, 2000 to April, 2000 is shown on Figure B-48, and the change in groundwater levels from April, 2000 to July, 2000 is shown on Figure B-49.

B.3.2.2.5 Short-Term Response

Data from the 42 continuous well locations at the Site (monitored every four hours) were examined. Locations for these wells are shown in Figure B-50. Additional continuous wells monitored for the SWWB project were differentiated from the existing continuous wells. These wells were grouped into four distinct subsets based on the local geology, namely:

- Colluvium;
- Valley-Fill Alluvium;
- Rocky Flats Alluvium; and
- Rocky Flats Alluvium in the Industrial Area.

Continuous groundwater well data from March, through May, 1999 are shown on Figure B-51 to illustrate differences in short-term saturated resopnse. The data were normalized as the difference from the average depth to water in the well over the time period minus the measurement at any one time. Wells are also differentiated on the basis of geologic formation (i.e., Rocky Flats Alluvium, Colluvium and Valley-Fill Alluvium). Wells are also shown with different symbols on each graph based on average annual groundwater depth. General observations included:

- All monitoring wells responded to an April, 2000 recharge event;
- Most wells showed daily effects of ET and barometric pressure changes over the Site;

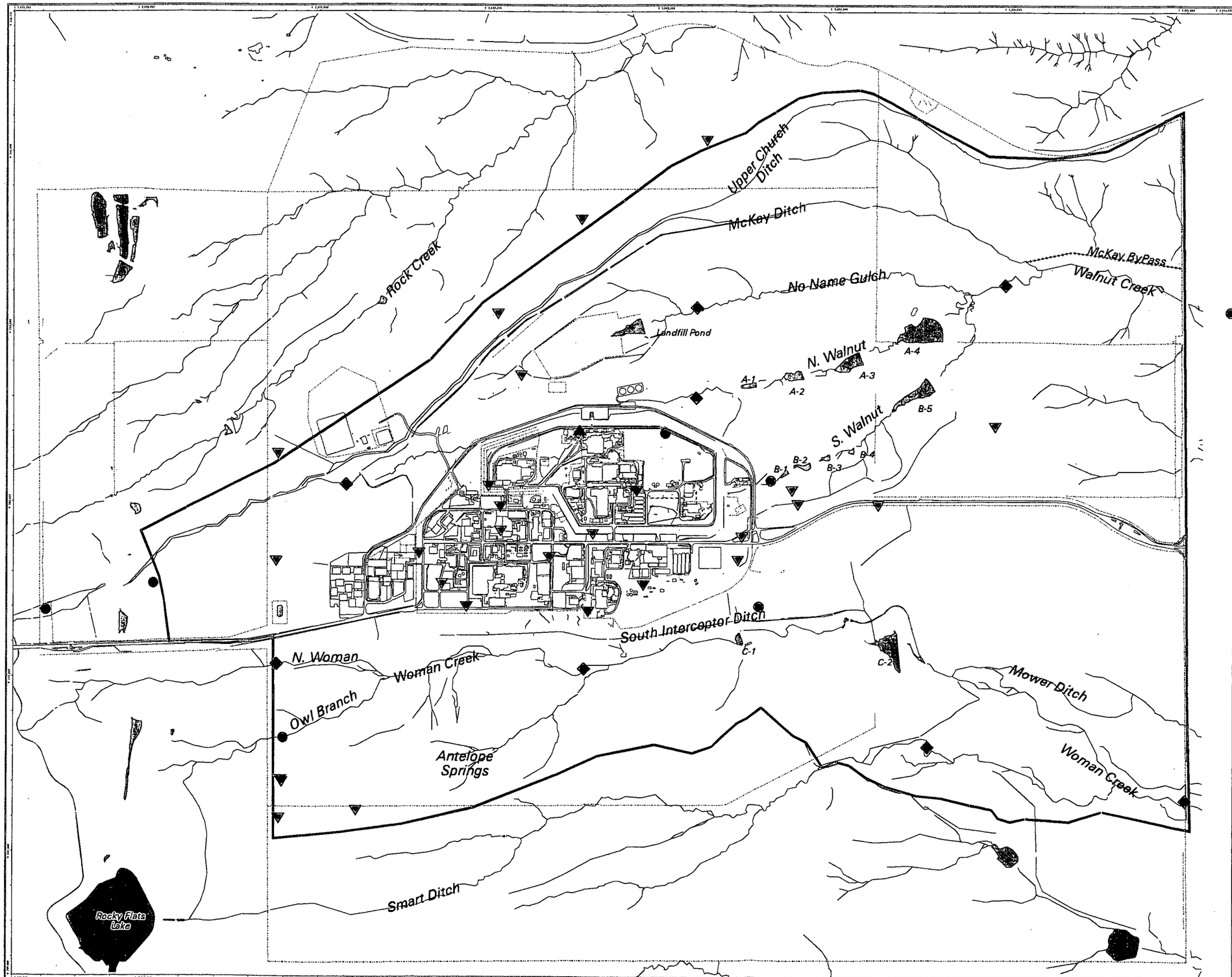

Figure B-50

Site-Wide Water Balance Report

Continuously Monitored Groundwater Well Locations

EXPLANATION

- Colluvium
- Fill
- Offsite
- Rocky Flats Alluvium
- Valley Fill Alluvium

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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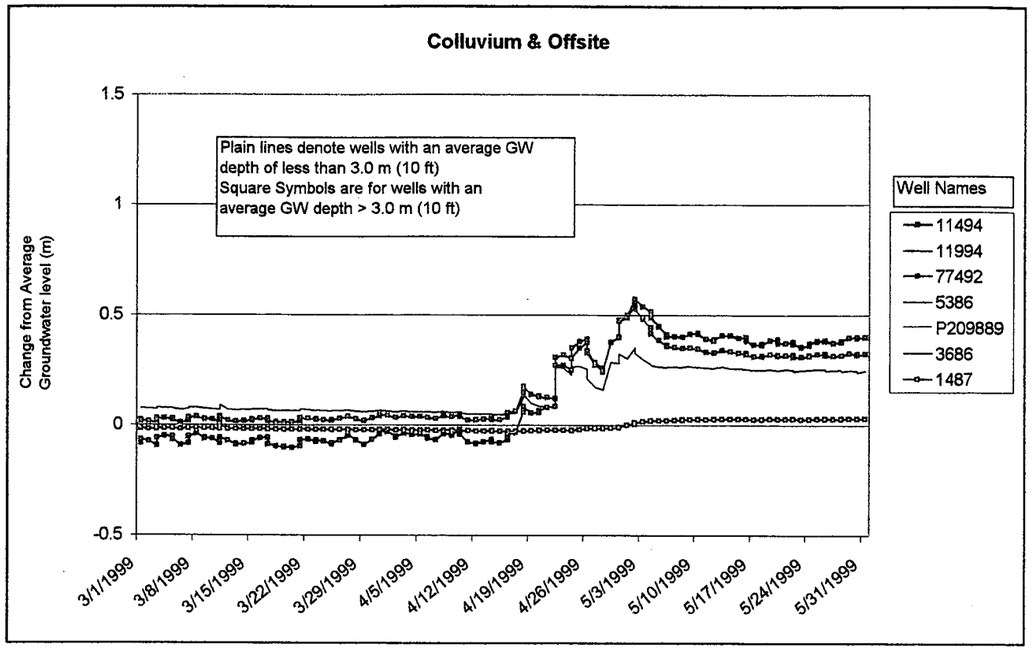
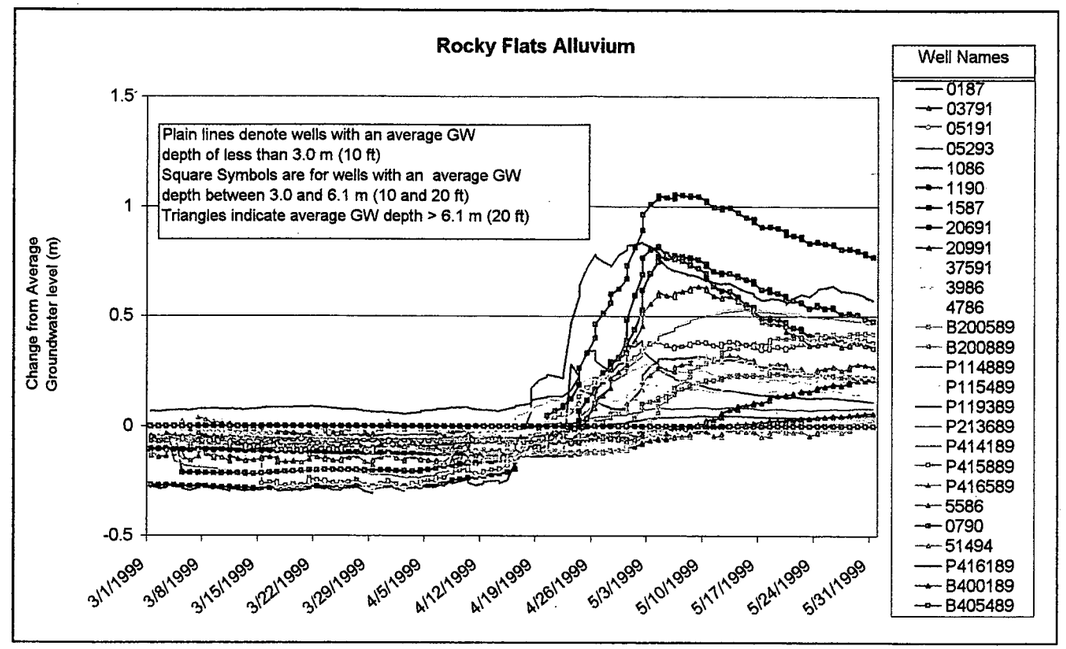
Prepared for: KAISER-HILL

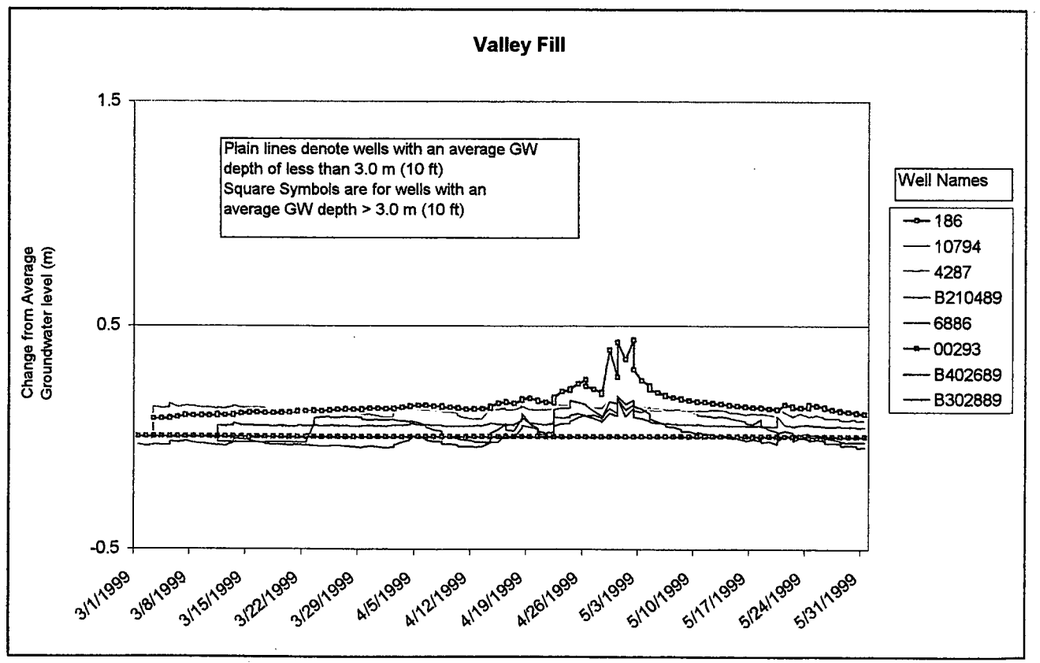
May 14, 2002

NT_Svr w:/projects/swwb/fy2002/section_b/cont_gw_wells.aml

Figure B-51. Continuous Groundwater Well Data







- Most shallow wells near streams responded rapidly, either due to streamflow or because groundwater levels are shallow and recharge occurred shortly after precipitation began;
- The magnitude of change due to the April, 2000 recharge event occurred in shallow in moderate depth wells;
- Deeper unsaturated zone columns showed the least response to recharge. It took up to six months for these wells (western model area) to reach peak groundwater levels in response to the April, 2000 recharge event; and
- Evaluation of 1998 through 2000 continuous well data showed the same significant spring recharge event, event though its impact differed every year.

B.3.2.3 Seeps

RFETS seep flow data were generally unavailable and difficult to measure. Antelope Springs, located south/southwest of the Industrial Area, continuously-discharges groundwater over several acres throughout the year. Otherwise, few if any other seeps within the model boundary discharge continuously throughout the year. Instead, some were activated by seasonal increases in the groundwater table; these discharges, were not recorded.

B.3.2.4 Subsurface Utilities

Flow estimates for East Trenches, Mound Plume and Solar Ponds Plume Remediation Systems were based on 15-minute flow record. These flow systems were calibrated infrequently and exhibited frequent malfunctions; however, the data set provided a reasonable estimate of annual discharge. Discharge estimates for the 881-Hillside French Drain system were based on previous years of flow record, when flows were diverted to a treatment facility. Flows were directed to the SW027 drainage toward the end of WY2000. Estimates of flow for the Present Landfill were prepared by Site Geologist (Smith, 2000), based on quarterly flow estimates recorded by field personnel.

Hydrologic response data for subsurface utilities were largely unavailable because they have not been monitored. Only rough flow estimates existed for each of the four primary pipe flow utilities. These are reported in Table B-6.

Table B-6. Subsurface Pipe Flows

Utility	Annual GW Discharge (ac-ft/yr)	Annual GW Recharge (ac-ft/yr)	Reference
Sanitary Sewer	13.6	7.5	Zero-Off-Site Water-Discharge Study (ASI, 1991a)
Storm Sewer	80.4		Zero-Off-Site Water-Discharge Study (ASI, 1991c)
Footing Drains	40.0	0	Estimated from limited monitoring data. See Section B.3.2.4.1 below for more details.
Water Supply	0	32.9	SWWB Work Plan (2000) estimate based on typical urban loss from water supply lines.

Pipeflow from individual buildings was not monitored and flows were assumed to be relatively constant in time based on trends observed in the WWTP outflow record.

B.3.2.4.1 Footing Drain Flows

Six surface water monitoring locations were identified which monitor footing drain flow: GS22, GS40, GS43, GS44, 371Subb and 371 Bas. These gages capture the majority of footing drain discharge to the surface. The remaining known discharges (unmonitored) of footing drain flow originated from Buildings 779, 771, 774, 881, 883 and 850. These drains have been observed to flow, but are expected to represent a small portion of the total footing drain flow.

Of the monitored gages, only 371Subb and 371Bas monitor footing drain discharge directly. The other gages also record local surface runoff and may include other sources of low flow (e.g., groundwater leak to surface water not via footing drains).

Estimates for drain flow for gages GS22, GS40, GS43 and GS44 were developed by modifying observed 15-minute record during precipitation events. This approach provided a rough estimates of baseflow at these gages for each month in WY2000. All estimates for GS44 were from WY2001 as the gage was not installed until September, 2000. Estimates for flow for October through December at GS22 were also from WY2001 because this gage was not installed until January, 2000.

Data sets from 371Subb and 371Bas exhibited significant problems. First, data were collected at these locations by radio telemetry only. With poor notes collected by the operator for WY2000, there was significant uncertainty that the correct conversion was being applied for the pressure transducer translation to telemetry record. Additionally, the narrow weirs were frequently clogged with algae and other debris, which was infrequently cleared (field visits frequency every 1 to 4 weeks). Based on these sources of error, an extensive effort was made to work up the available data. Efforts resulted in large (several months) periods of estimated data. Finally, it was determined by professional judgement that a simple constant estimate of flow rate would be the best product from this problematic data set. The following estimates were made from field observations. These values obviously do not capture the seasonality of flow rates; however, this was the best information available.

The resulting estimate is likely to be an overestimate of the contribution of footing drain flow to each of these monitoring locations; however, as discussed, these gages did not include all outfall locations. In short, the error is uncertain and cautiously expected to be +/- 50 percent. The resulting monthly estimates are summarized below in Table B-7 and on Figure B-52. The annual estimate is 49,000 m^3/yr (1.7 million ft^3/yr, 40 ac-ft/yr).

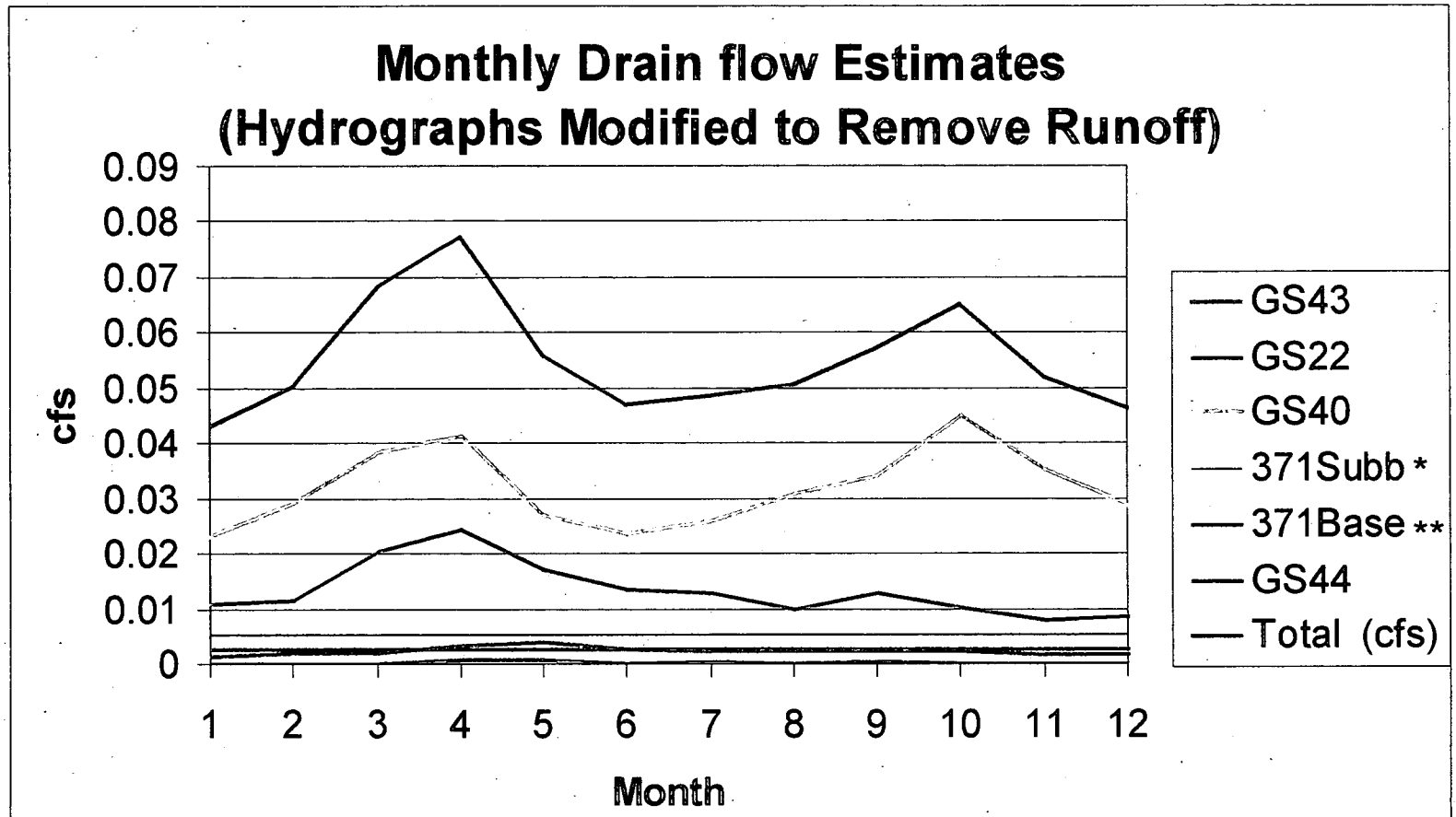
Table B-7. Estimates of Footing Drain Discharge

Month	GS43 cfs	GS22 cfs	GS40 cfs	371Subb cfs	371Base cfs	GS44 cfs	Total (CF)
1	0.00E+00	1.09E-02	2.29E-02	5.18E-03	2.56E-03	1.31E-03	1.150E+05
2	6.34E-05	1.16E-02	2.90E-02	5.18E-03	2.56E-03	1.81E-03	1.257E+05
3	4.86E-05	2.04E-02	3.82E-02	5.18E-03	2.56E-03	1.92E-03	1.831E+05
4	8.11E-04	2.43E-02	4.12E-02	5.18E-03	2.56E-03	3.22E-03	2.003E+05
5	5.79E-04	1.70E-02	2.67E-02	5.18E-03	2.56E-03	3.86E-03	1.495E+05
6	0.00E+00	1.36E-02	2.33E-02	5.18E-03	2.56E-03	2.48E-03	1.220E+05
7	3.61E-04	1.27E-02	2.55E-02	5.18E-03	2.56E-03	2.42E-03	1.305E+05
8	5.61E-05	9.84E-03	3.05E-02	5.18E-03	2.56E-03	2.42E-03	1.353E+05
9	2.39E-04	1.30E-02	3.37E-02	5.18E-03	2.56E-03	2.42E-03	1.480E+05
10	4.52E-05	1.03E-02	4.47E-02	5.18E-03	2.56E-03	2.42E-03	1.746E+05
11	1.39E-05	7.87E-03	3.48E-02	5.18E-03	2.56E-03	1.54E-03	1.348E+05
12	5.20E-05	8.68E-03	2.84E-02	5.18E-03	2.56E-03	1.50E-03	1.242E+05
Annual Average	1.89E-04	1.34E-02	3.16E-02	5.18E-03	2.56E-03	2.28E-03	1.743E+06

B.3.2.4.2 Remediation Systems

Table B-8 summarizes annual discharge rates observed or estimated for the five different remediation systems. All values presented represent estimates. Observed 15-minute flow records were available for WY2000 for the East Trenches, Solar Ponds and Mound plume remediation system outfalls. Historical records of treated volumes were used to generate the 881 Hillside French Drain estimate. Historical quarterly flow-rate measurement data were applied to develop the Landfill Interceptor Trench estimate.

Figure B-52. Monthly Estimates of Footing Drain Discharge



*371Subb refers to the drain outlet from the sub-basement.
**371Base refers to the drain outlet from the basement.

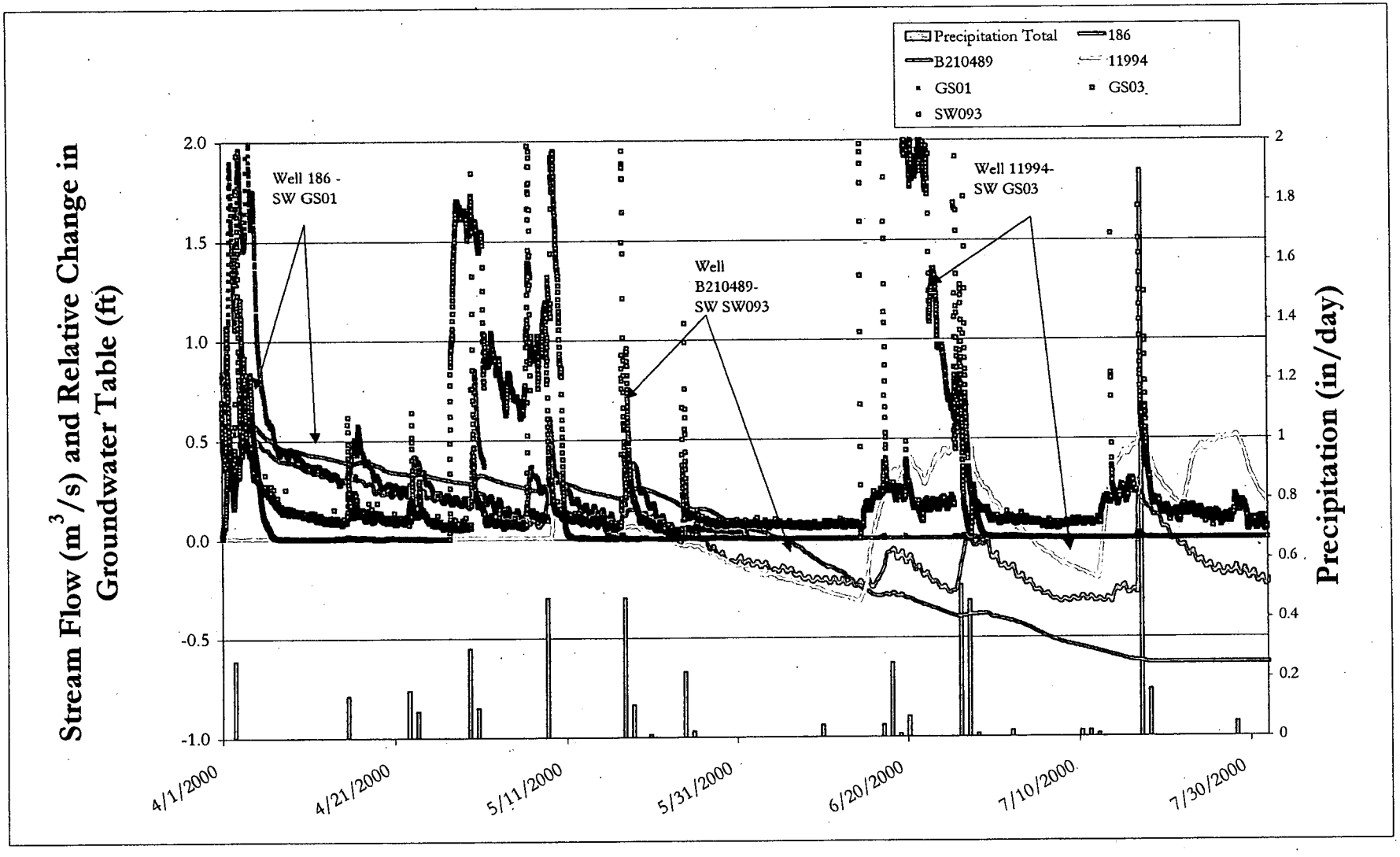
Table B-8. Approximate Annual Discharge – Remediation Systems

Treatment System	Annual GW Discharge (ac-ft/yr)	Annual GW Discharge (m^3/yr)
881 Hillside French Drain	0.2	246.7
Landfill Interceptor Trench	3.8	4687.2
East Trenches Remediation System	4.7	5797.3
Mound Plume Remediation System	0.8	1233.5
Solar Ponds Remediation System	0.7	863.4

B.3.3 Integrated System Response

The integrated response of the system can be described in terms of groundwater-surface water interactions shown on Figure B-53. Also included on the graph are daily precipitation amounts to show how surface and subsurface conditions were affected. Groundwater wells 186, 11994 and B210489 are located near surface gages, GS01 (East Woman Creek), GS03 (East Walnut Creek) and SW093 (northern Industrial Area), respectively. It is clear from all three well-surface gage pairs that the hydrologic response was strongly integrated. Precipitation events drove most of the responses, though at GS03, larger flow events were due to pond discharges. Groundwater in these stream areas appeared to respond almost immediately, and mirror most stream flow hydrograph peak responses. Along Woman Creek, effects of precipitation events, or surface flow on groundwater levels appeared to dampen out by the end of July, 2000. This is mostly due to ET effects becoming more dominant than in cooler months.

Figure B-53. Integrated System Response Figure



Notes: 1. 186, 11994, and B210489 indicate groundwater levels at these wells
2. GS01, GS03, and SW093 are surface flow gages.

Site-Wide Water Balance Model Report

Appendix C

Modeling Approach

May 2002

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C.1 Integrated Model Boundary Definition C-1

C APPENDIX: MODELING APPROACH

C.1 INTEGRATED MODEL BOUNDARY DEFINITION

The western boundary extends about one mile from north to south, in three separate segments. The boundary follows the RFETS western property boundary for 0.65 miles (1.04 km) south of the West Access Road, 0.33 miles (0.53 km) along the West Access Road and 0.33 miles (0.53 km) north of the West Access Road (see Figure 2-1). From this point, it extends northward roughly parallel to the groundwater potentiometric contour lines. This boundary is just east of the Laramie-Fox Hills Aquifer outcrop. Specifying the boundary at this location, rather than further west, avoided simulating losses to the Laramie-Fox Hills Aquifer. Furthermore, the western boundary was adequately monitored for both surface and subsurface conditions. Although current upgradient mining and water management operations did not appear to affect hydrologic conditions within the model boundary, future conditions may require adjustments to this boundary.

Only groundwater and channelized surface water were assumed to flow into the model along the entire western boundary. Very little overland flow is expected to flow across either the southern or northern segments of the western boundary because of low topographic gradients. Some overland flow may have occurred across the southern portion of the western boundary due to flood irrigation on the McKay property west of the RFETS property boundary, but no data were available to confirm this. Although the groundwater level configuration varied in response to direct recharge and lateral inflow, the groundwater flow direction remained relatively unchanged throughout the year.

Surface flow entering the western boundary along McKay and Upper Church Ditches typically occurred during spring or summer months. Notable losses to the groundwater occurred, as a result of these ditches being unlined (Wright Water Engineers, 1995). This may affect the local groundwater gradients at this boundary. These temporary conditions were considered small compared to the entire western boundary.

The eastern boundary is defined as the eastern RFETS boundary (Indiana Street). This boundary extends approximately 2.3 miles from north to south. The principal drainages across this boundary are Woman and Walnut Creeks. Minor drainage features also cross this boundary (i.e., Mower Ditch, Badger Ditch, Kestrel Gulch and three other unnamed features). Each minor drainage feature is routed through culverts beneath Indiana Street. Topographic depressions route surface water along Indiana Street between these culverts. Flows along the minor drainages were negligible year round except during significant precipitation or snowmelt events. Because Indiana Street is situated above for the majority of the eastern boundary, no overland flow crosses this boundary.

Groundwater flow across the eastern boundary was specified in the model based on continuous groundwater monitoring data. Most of the groundwater flow at the eastern boundary is within the alluvium of Walnut and Woman Creeks. The groundwater flow across the boundary between Walnut and Woman Creek originates from direct precipitation recharge within the area east of the Industrial Area and between the two Creeks. The total groundwater flow across the eastern boundary is very low compared to surface flow and therefore, was not critical for simulating the total flow across this boundary.

The north and south boundaries of the model were defined based on surface water divides, which are for the most part coincident with topographic divides (highs). The northern boundary was a no-flow surface water boundary and a specified-head type boundary for groundwater flow. This groundwater flow boundary was specified as a constant head boundary in previous modeling efforts (Roberts, 1997; CDPHE, 1994). However, since the SWWB will be simulating time-varying conditions, the northern groundwater boundary may experience a gradient change in this location due to flows in the McKay Bypass Ditch during the months when this water right is exercised. Therefore, this boundary was a time-varying head boundary condition based on nearby continuously-monitored groundwater elevation data.

The southern model boundary represents a no-flow boundary condition for both surface and groundwater. South Woman Creek normally does not receive flow from the Smart

Ditch (see Figure 2-1). However, at higher flow rates, some flow from Smart Ditch apparently overtopped the diversion structure used to prevent flow from Smart Ditch from entering South Woman Creek. According to the RFETS Surface Water Group, this location, and another location downstream on Smart Ditch, do not contribute significantly to the annual surface water flows recorded at GS01, on Woman Creek, which receives surface flow from South Woman Creek. Therefore, the southern boundary was defined to include overland flow contributions to South Woman Creek, but not from the Smart Ditch. The southern boundary was defined similarly by Kaiser-Hill (2000d).

Site-Wide Water Balance Model Report

Appendix D

Numerical Model Design

May 2002

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D APPENDIX: NUMERICAL MODEL DESIGN

D.1 MIKE SHE CODE

MIKE SHE is a deterministic, dynamic, fully-distributed hydrologic model, which simulates all major hydrologic processes and interrelationships. MIKE SHE comprises a number of hydrological flow components, which in combination simulates the entire land-based part of the hydrological cycle.

The core of MIKE SHE is the water movement module, which includes a distributed watershed definition, interception, evapotranspiration (ET), overland and channel flow, unsaturated/saturated zone flow and snowmelt. MIKE SHE has a flexible modular structure where any combination of flow components may be set up depending on the actual application or as intermediate steps of building a fully integrated model.

The saturated zone component (MIKE SHE SZ) solves the Boussinesq equation in two-dimensions/three-dimensions or, as an alternative, a linear reservoir description is available. The groundwater component include a selection of boundary condition types, a sheet piling module, a drainage component and facilitates incorporation of time-varying distributed groundwater withdrawals. The groundwater component is dynamically coupled to the unsaturated zone, river and surface water bodies included in the surface water model and the overland flow component. The main inputs for the groundwater component are geological layering, associated hydraulic conductivities and storage coefficients.

The unsaturated zone component (MIKE SHE UZ) solves the Richard's equation, a reduced gravity flow version of the Richard's equation or applies a lumped two-box unsaturated zone model. It is assumed that one-dimensional vertical flow is dominant and horizontal unsaturated zone flow is negligible. The unsaturated zone model simulates infiltration, the time varying soil moisture content and percolation. The unsaturated zone is dynamically coupled to the overland component, the ET component and the saturated zone. Input to the unsaturated zone component includes soil physical properties in terms of retention curve and a hydraulic conductivity curve.

The ET component (MIKE SHE ET) simulates distributed actual rates of ET. Interception by vegetation, free water surface evaporation, soil evaporation and transpiration by plants is included in the Kristensen and Jensen method. The ET sink terms are extracted from the overland component, the root zone of the unsaturated zone or from the groundwater (if the groundwater table is within the root zone). The actual ET rates depend on the input time series from the following: (1) potential ET [typically derived from Pennmann estimates]; (2) the vegetation stage and seasonal variation expressed through leaf are index (LAI) and root depth (RDF); and (3) the water content of the soil.

MIKE11 is a dynamic hydraulics model, which solves the Saint-Venant equations for a kinematic, diffusive or fully-dynamic wave approximation. MIKE11 includes various hydraulic structures and structure operation features. MIKE11 is in itself used for a wide range of river hydraulics applications applying simple rainfall-runoff models to generate lateral inflow. When coupled with MIKE SHE lateral inflows from overland flow, drains and baseflow are distributed along the individual river reaches depending on overland and groundwater levels.

MIKE SHE has been applied at various spatial scales ranging from basin-wide regional studies to local, detailed applications. A typical approach is first to establish a regional coarse scale model and subsequently zoom in to a local area of particular interest applying a finer grid. Tools to generate boundary conditions from the coarse to the fine scale model support the telescoping feature.

The surface and subsurface components of the hydrological system operates at different temporal scales. To capture the dynamics of the respective components, increasing time steps are applied in the numerical solution of the surface domain down through the unsaturated and saturated components. Automatic time step control is used to reduce time steps when rapid changes occur (e.g., high intensity rainfall events following a dry period). The fully-dynamic behavior of the system is described while maintaining a numerically stable solution.

A number of add-on component exist for integrated solute transport and water quality applications considering mass transport and chemical/biological degradation in surface water, groundwater or in the entire hydrological system.

MIKE SHE is a versatile hydrological tool, which covers a wide range of potential applications. It has been used world wide under different climatic conditions and is a well-proven water management tool (http://www.dhisoftware.com/mikeshe).

D.2 INTEGRATED NUMERICAL FLOW MODEL – SURFACE FLOW

D.2.1 Additional Information on Cross-section Refinement

As discussed in the Main Report, channel cross-section data from Site surveys were applied to the model. In applying the full set of surveyed cross-sections, it was determined that some modifications to the data set were required to run the model. The following paragraphs describe these special cases and the modification applied.

In some cases, cross-section survey data lacked the resolution to identify the low point in the channel, resulting in a flat-bottom type cross-section, which did not handle low flow rates well. Where necessary (due to observed instability problems), a central low-point was added to these cross-sections, always honoring the surveyed thalweg elevation. Any resulting effects on channel conveyance and dynamics were not apparent in the resulting hydrographs.

In other cases, cross-section data extended well beyond the surrounding 200ft x 200ft (~61 m x 61 m) grid cells. Because MIKE SHE places a channel between grid cells, this occasionally created situations where the channel banks extended up higher than the topography of the adjacent grid cell. As a result, overland flow could not freely enter the channel. This occurred primarily on the eastern end of Woman Creek, where the basin flattens out and cross-sections were surveyed to include the entire flood plain. To fix this problem, cross-section banks were trimmed to meet the elevation of the adjacent grid cells. This did not limit the capacity of the channels because the MIKE 11 program assumes infinite vertical channel banks at the end of the designated cross-sections.

Although this may affect flow dynamics at very high flow rates, the model was not designed to accurately predict flood-flows (i.e., no designation of flood coding to allow for accurate interaction of the flooded area with the unsaturated zone).

Occasionally, cross-sections were added to better define the channel profile. Cross-sections were often collected for other, non-integrated modeling projects, where inconsistency with topography was not a critical problem. When too few cross-sections were applied, the interpreted part of channel profile can appear to the integrated model to cut deep into the ground surface on a convex change in topography or even be raised above the ground surface on a concave change in topography. As a result, a minimum number of additional cross-sections were applied, recognizing that the model is only a mathematical representation of the Site.

Occasionally, cross-sections were removed to help stabilize the solution. Some areas had many cross-sections available for a small area, perhaps due to focus areas of precious modeling efforts. The solution stability was often challenged by sharp changes in the solution interval, which can be caused by increased density of cross -sections. Removal of cross-sections was only permitted when it did not significantly impact the representation of the channel profile.

Where cross-section data were not available, cross-sections were applied based on topography and field observations of channel geometry. In the Industrial Area, simple triangular cross-sections were applied, recognizing the primary focus of simply routing the water and the challenge of generating a stable solution with sharp changes in slope. Through calibration, it was determined that accurate timing and shape of hydrographs could be simulated using this approach.

To provide accurate stream profiles in pond areas, detailed topographic information was gathered from engineering drawings of ponds. This information was applied to accurately produce cross-sections for spillways and ponds.

D.2.2 Numerical Model Surface Flow Figures (Figures D-1 through D-5)

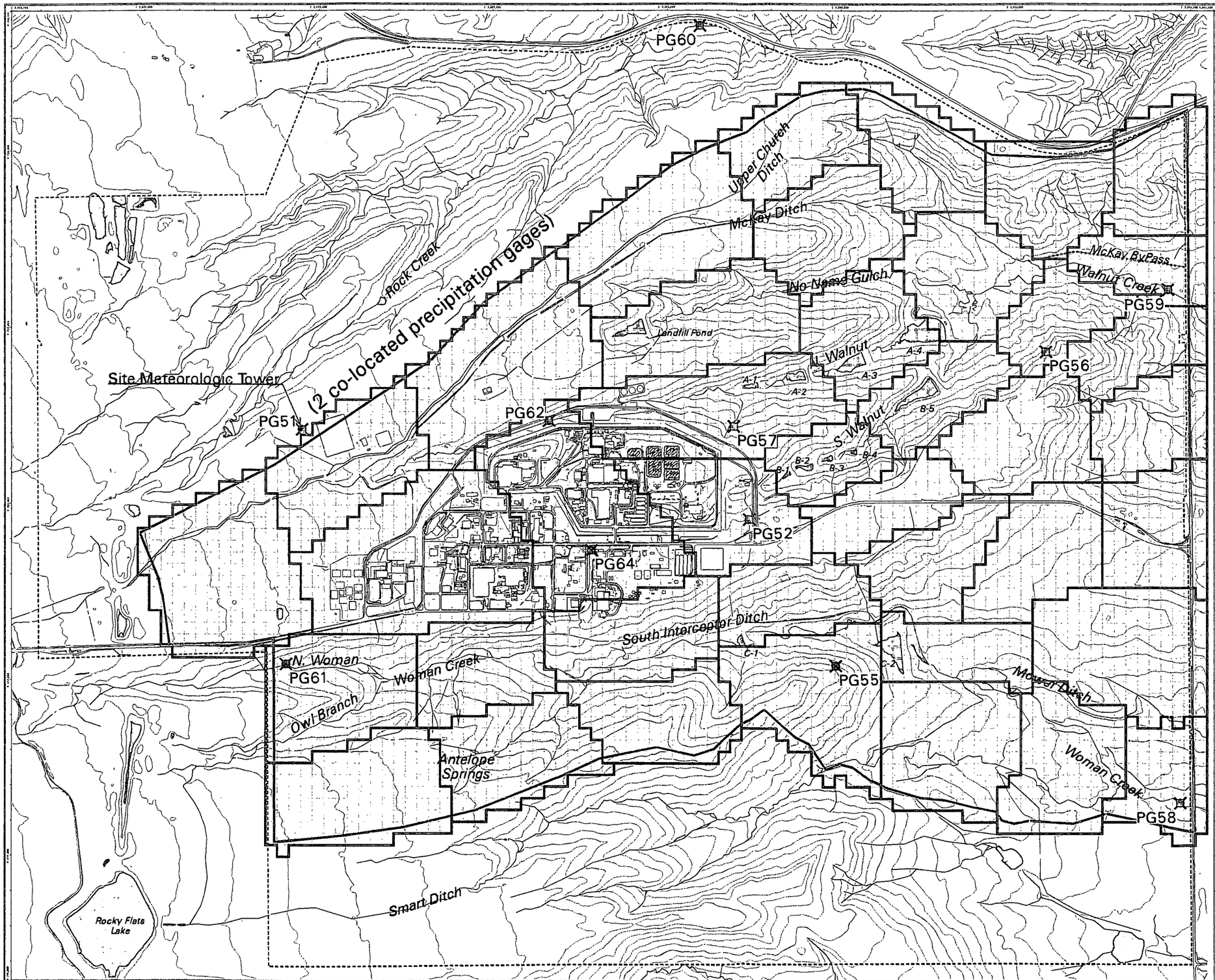

Figure D-1

Site-Wide Water Balance Report

Precipitation Zones (Numerical Model Grid)

EXPLANATION

- Precipitation Zone Boundary
- Catchment Grid
- Precipitation Gage
- Site Meteorologic Tower

Standard Map Features

- Buildings and other structures
- Paved roads fill
- Solar Evaporation Ponds (SEPs)
- Lakes and ponds
- Streams, ditches, or other drainage features
- Topographic Contour (20-Foot)
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95 Topographic contours were derived from digital elevation model (DEM) data by Morrison Knudson (MK) using ESRI Arc TIN and LATTICE to process the DEM data to create 5-foot contours. The DEM data was captured by the Remote Sensing Lab, Las Vegas, NV, 1994 Aerial Flyover at ~ 10 meter resolution. DEM post-processing performed by MK, Winter 1997.

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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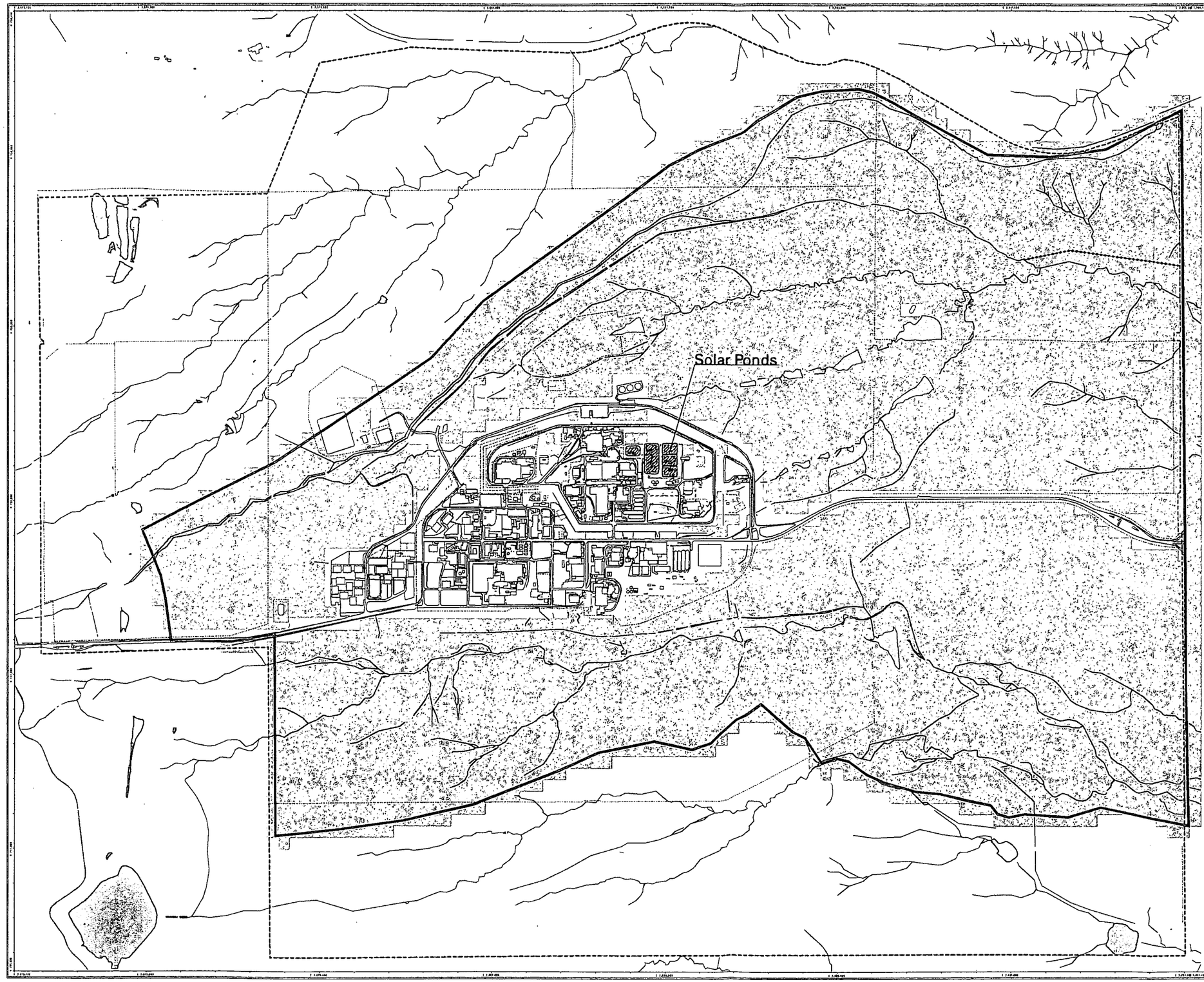

Figure D-2

Site-Wide Water Balance Report

Surface Detention Storage (Numerical Model Grid)

EXPLANATION

Detention Storage (m)

- 0
- 0.001
- 1

Standard Map Features

- Buildings and other structures
- Solar Evaporation Ponds (SEPs)
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

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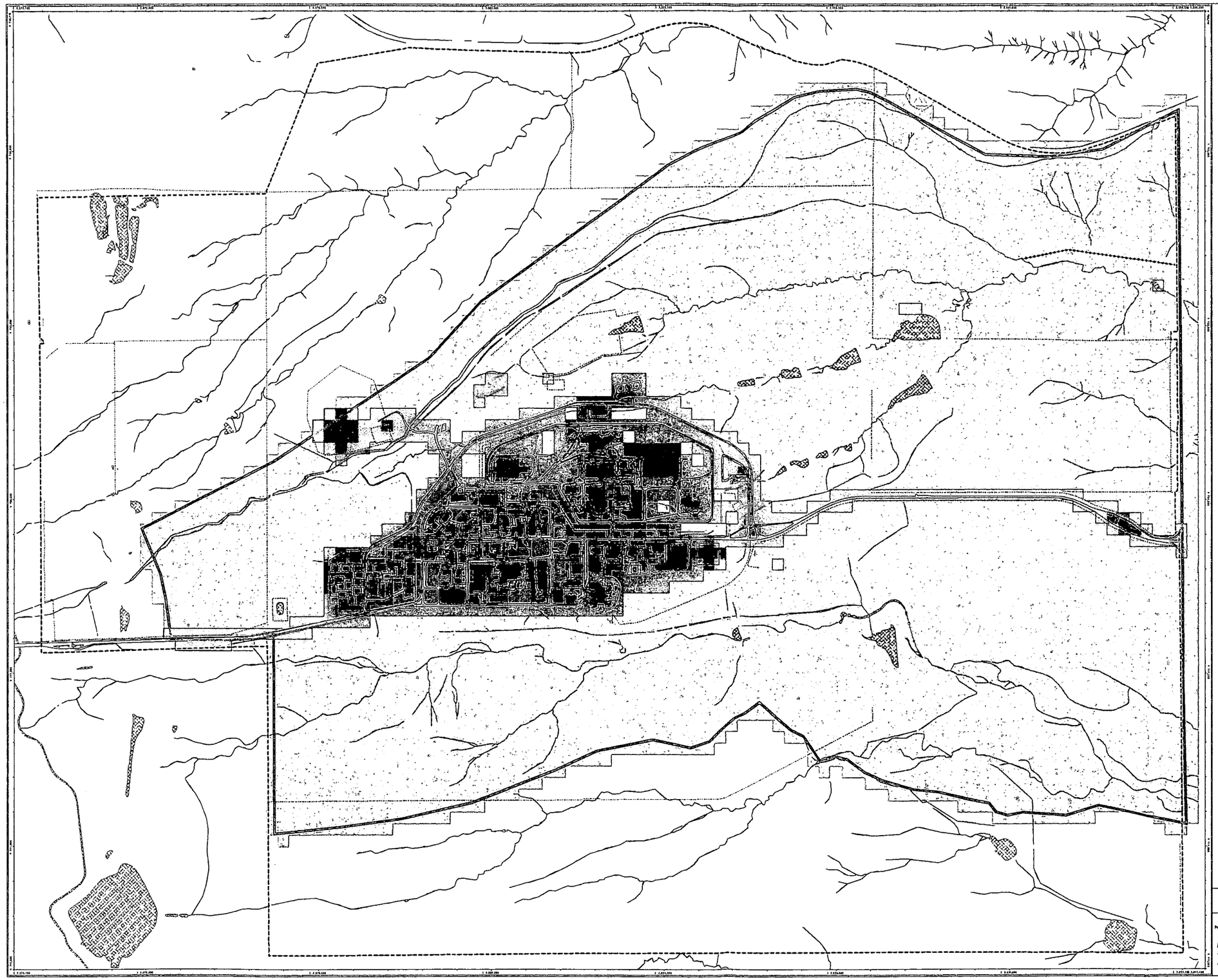

Figure D-3

Site-Wide Water Balance Report

Distribution of Overland Resistance - Manning Number (Numerical Model Grid)

EXPLANATION

Manning Number (M)*

- 3
- 5
- 20
- Outside of Model Boundary

Standard Map Features

- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:

* M equals 1/n

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

U.S. Department of Energy

Rocky Flats Environmental Technology Site

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May 14, 2002

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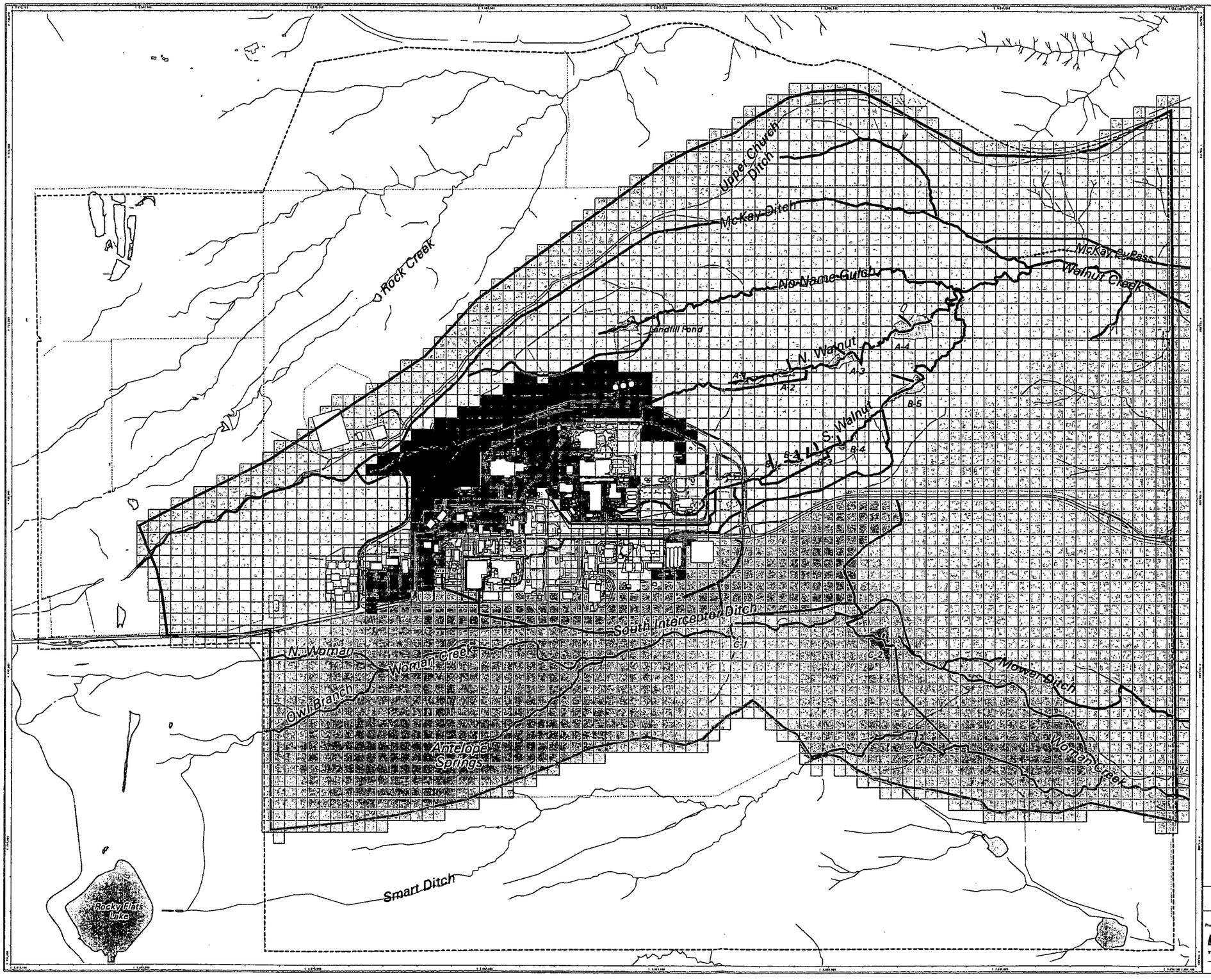

Figure D-4

Site-Wide Water Balance Report

Overland Flow Boundaries and Surface Channel Network (Numerical Model Grid)

EXPLANATION

Surface Flow Channel Network

- Aboveground Pipe
- Belowground Pipe
- Pond Evaporation Structure
- Surface Channel

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:
Overland flow is not simulated across the boundaries in the MIKE SHE model.

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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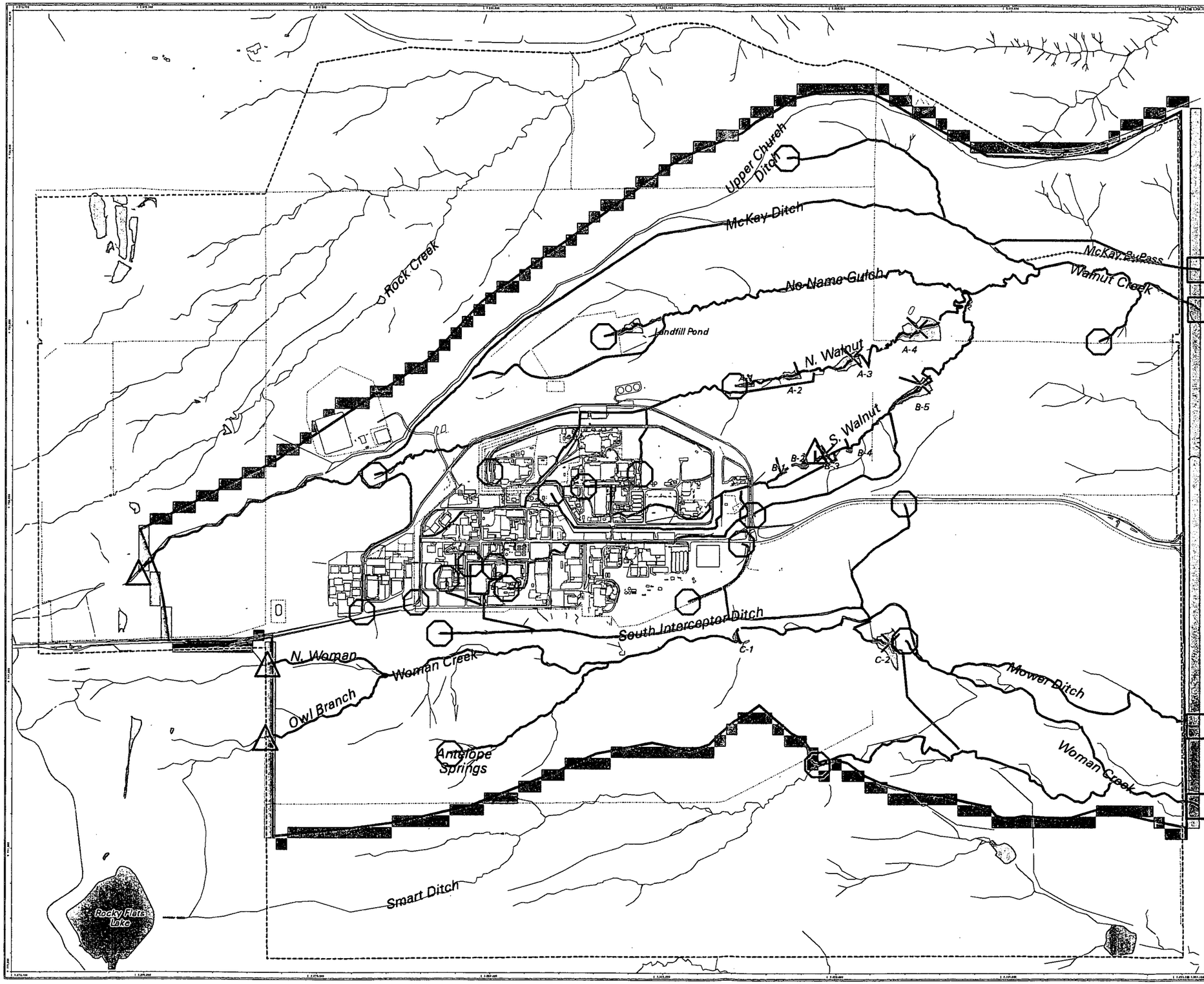

Figure D-5

Site-Wide Water Balance Report

Surface and Groundwater Boundary Conditions

EXPLANATION

- Surface Water Channel Network

Groundwater Boundary Conditions

- No Flow
- Constant Pressure
- Surface Water Inflow Boundary Condition
- Surface Water Zero Flow Boundary Condition
- Surface Water Constant Stage Boundary Condition
- Pond Discharge/Transfer Boundary Condition

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:

1) See discussion of groundwater boundary conditions in Appendix C.

2) Surface water boundary conditions are discussed in section 5.1.2

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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D.3 INTEGRATED NUMERICAL FLOW MODEL – SUBSURFACE

Figure D-6 through Figure D-11 present the grid distribution of geologic parameters applied to the model, including thickness of the unconsolidated material, thickness of the weathered bedrock and the hydraulic conductivities for all four layers.

D.3.1 Subsurface Utility Specification in MIKE SHE

This section describes how the subsurface utility trenches and fluid-flow pipes are numerically implemented in MIKE SHE.

D.3.1.1 Trench Description in MIKE SHE

To simulate the effect of utility trenches on groundwater flow, hydraulic conductivities, and model layers were adjusted. The approach used is described in the following steps:

- The total linear length of the nine utility lines summarized Appendix B was determined within each model cell using a GIS technique;
- Because the backfill material of trenches is assumed to be more permeable than the surrounding native material, cell conductivities were increased. The total length of utility lines was used to determine the relative increase in hydraulic conductivities for a given cell;
- An algorithm was developed to determine the average hydraulic conductivity of the model cell. Within a given cell, it was not possible to determine the average orientation of all utility trenches with respect to the average groundwater flow direction. Therefore, because the hydraulic conductivity is dependent on the flow direction (tensor), an average value was determined by calculating the geometric mean of average hydraulic conductivities determined from parallel and perpendicular flow;

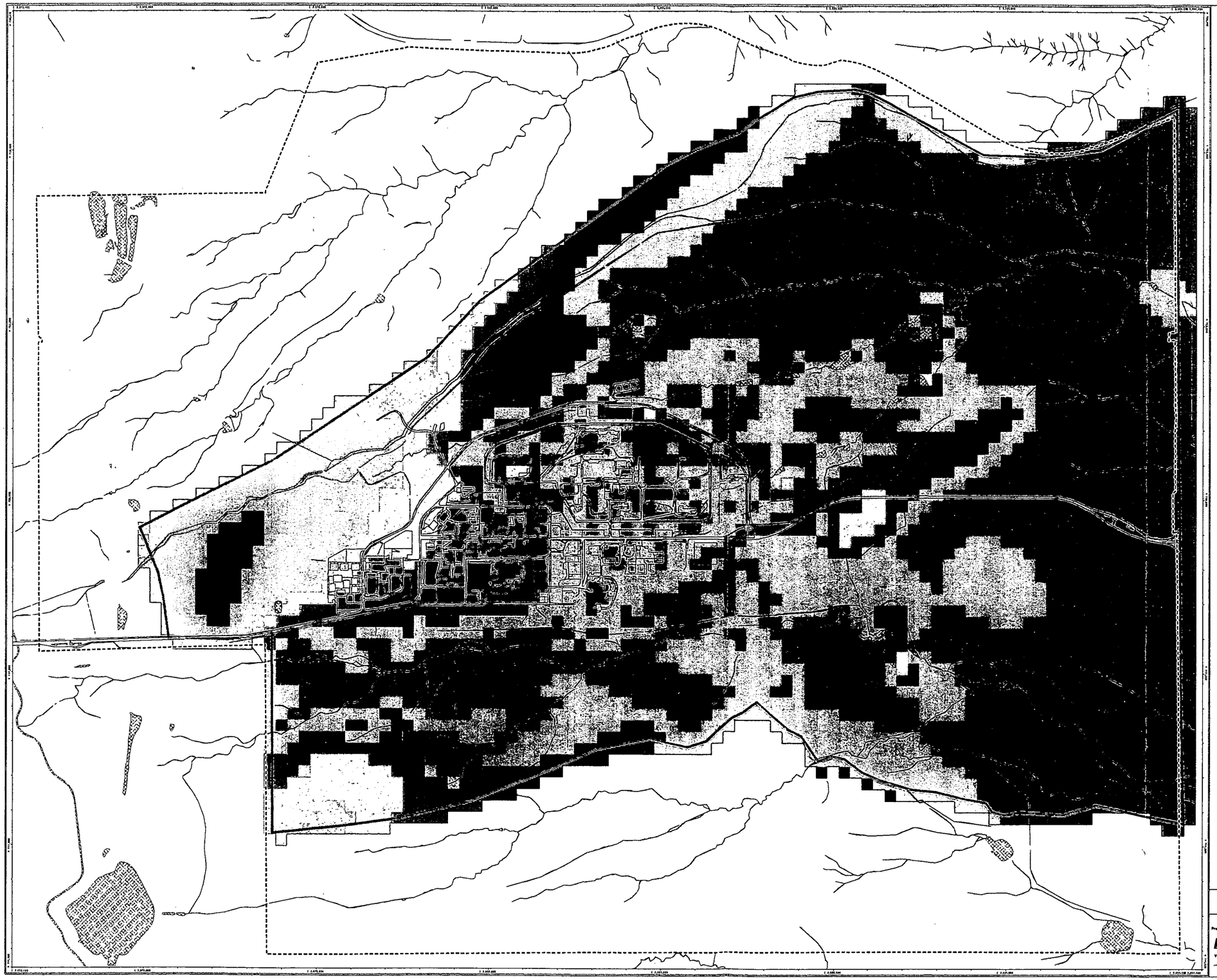

Figure D-6

Site-Wide Water Balance Report

Unconsolidated Thickness (Numerical Model Layers 1 & 2)

EXPLANATION

Thickness (ft)

- 1 to 10 (0.3 to 3.0 m)
- 10 to 20 (3.0 to 6.1 m)
- 20 to 30 (6.1 to 9.1 m)
- 30 to 40 (9.1 to 12.2 m)
- 40 to 50 (12.2 to 15.2 m)
- 50 to 60 (15.2 to 18.3 m)
- 60 to 70 (18.3 to 21.3 m)
- 70 to 80 (21.3 to 24.4 m)
- 80 to 90 (24.4 to 27.4 m)
- 90 to 100 (27.4 to 30.5 m)
- Outside of Model Boundary

Standard Map Features

- Lakes and ponds
- Streams, ditches, or other drainage features
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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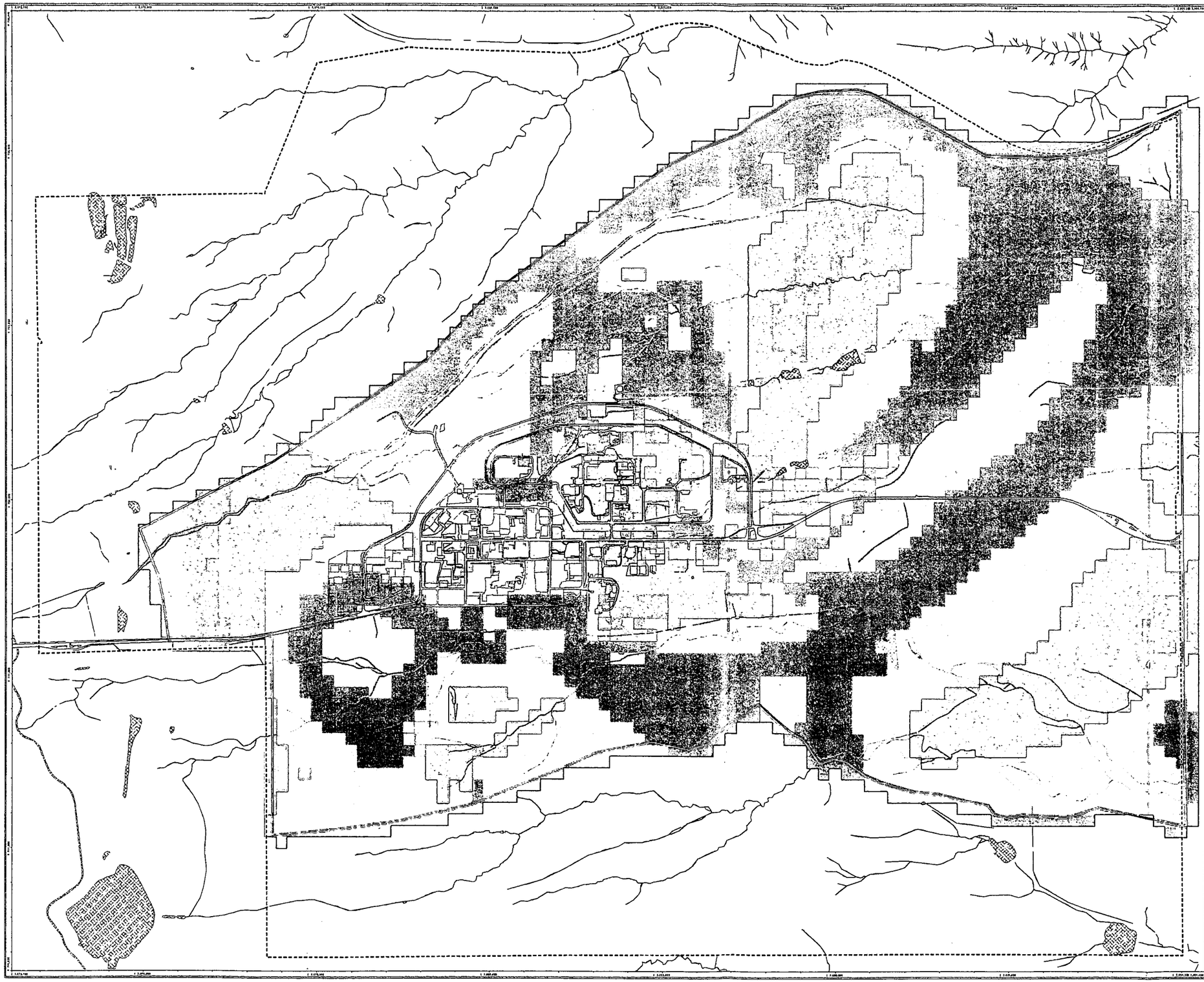

Figure D-7

Site-Wide Water Balance Report

Weathered Bedrock Thickness (Numerical Model Grid)

EXPLANATION

Thickness (ft)

- 1 to 10 (0.3 to 3.0 m)
- 10 to 20 (3.0 to 6.1 m)
- 20 to 30 (6.1 to 9.1 m)
- 30 to 40 (9.1 to 12.2 m)
- 40 to 50 (12.2 to 15.2 m)
- 50 to 60 (15.2 to 18.3 m)
- 60 to 70 (18.3 to 21.3 m)
- Outside of Model Boundary

Standard Map Features

- Lakes and ponds
- Streams, ditches, or other drainage features
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
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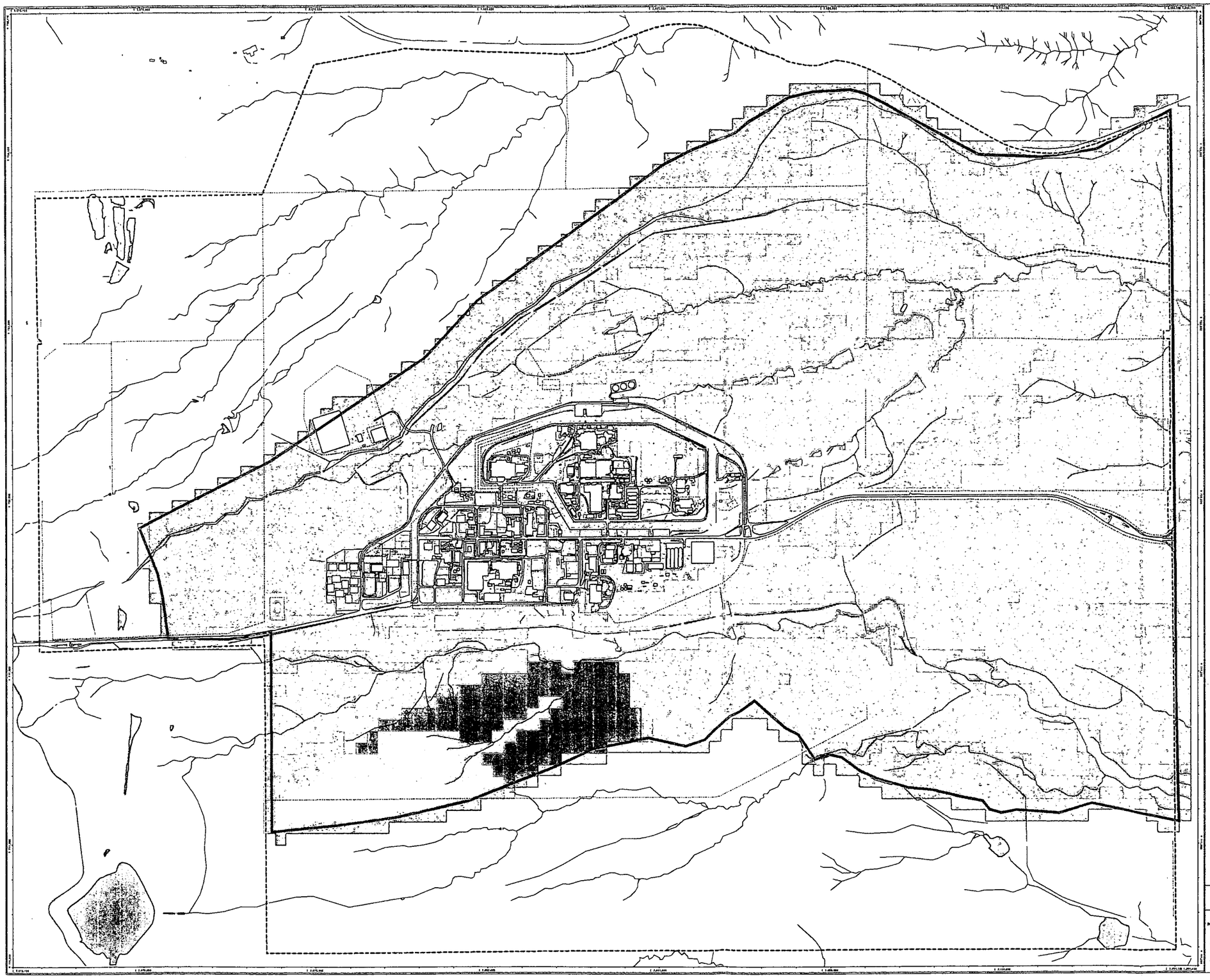

Figure D-8

Site-Wide Water Balance Report

Model Layer 1 Hydraulic Conductivity Distribution (Numerical Model Grid)

EXPLANATION

Layer 1 Hydraulic Conductivity (m/s)

- 1e-10 to 1e-9
- 1e-9 to 1e-8
- 1e-8 to 1e-7
- 1e-7 to 1e-6
- 1e-6 to 5e-6
- 5e-6 to 1e-5
- 1e-5 to 1e-4
- 1e-4 to 2e-4
- Not Active

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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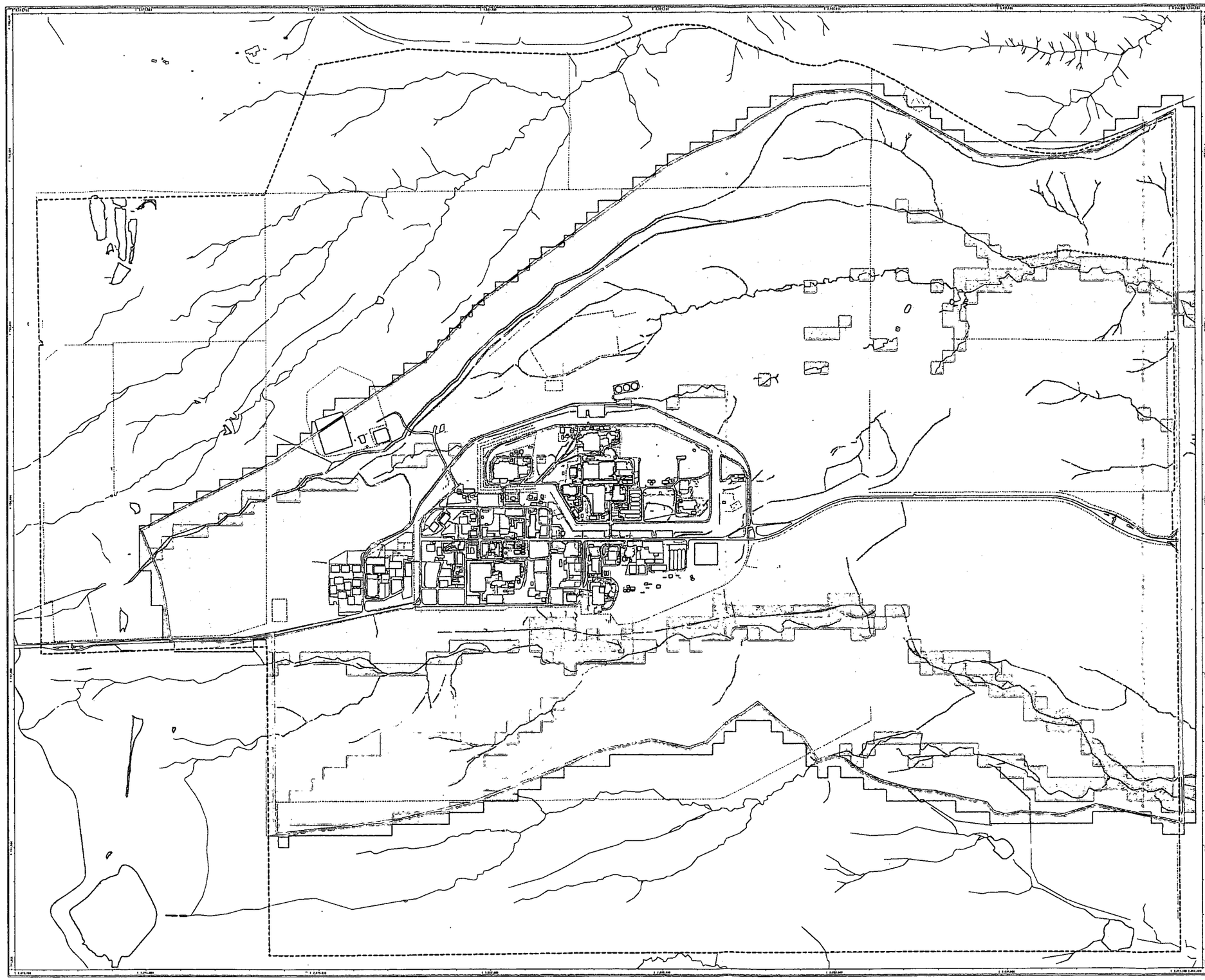

Figure D-9

Site-Wide Water Balance Report

Model Layer 2 Hydraulic Conductivity Distribution (Numerical Model Grid)

EXPLANATION

Layer 2 Hydraulic Conductivity (m/s)

- 1e-10 to 1e-9
- 1e-9 to 1e-8
- 1e-8 to 1e-7
- 1e-7 to 1e-6
- 1e-6 to 5e-6
- 5e-6 to 1e-5
- 1e-5 to 1e-4
- 1e-4 to 2e-4
- Not Active

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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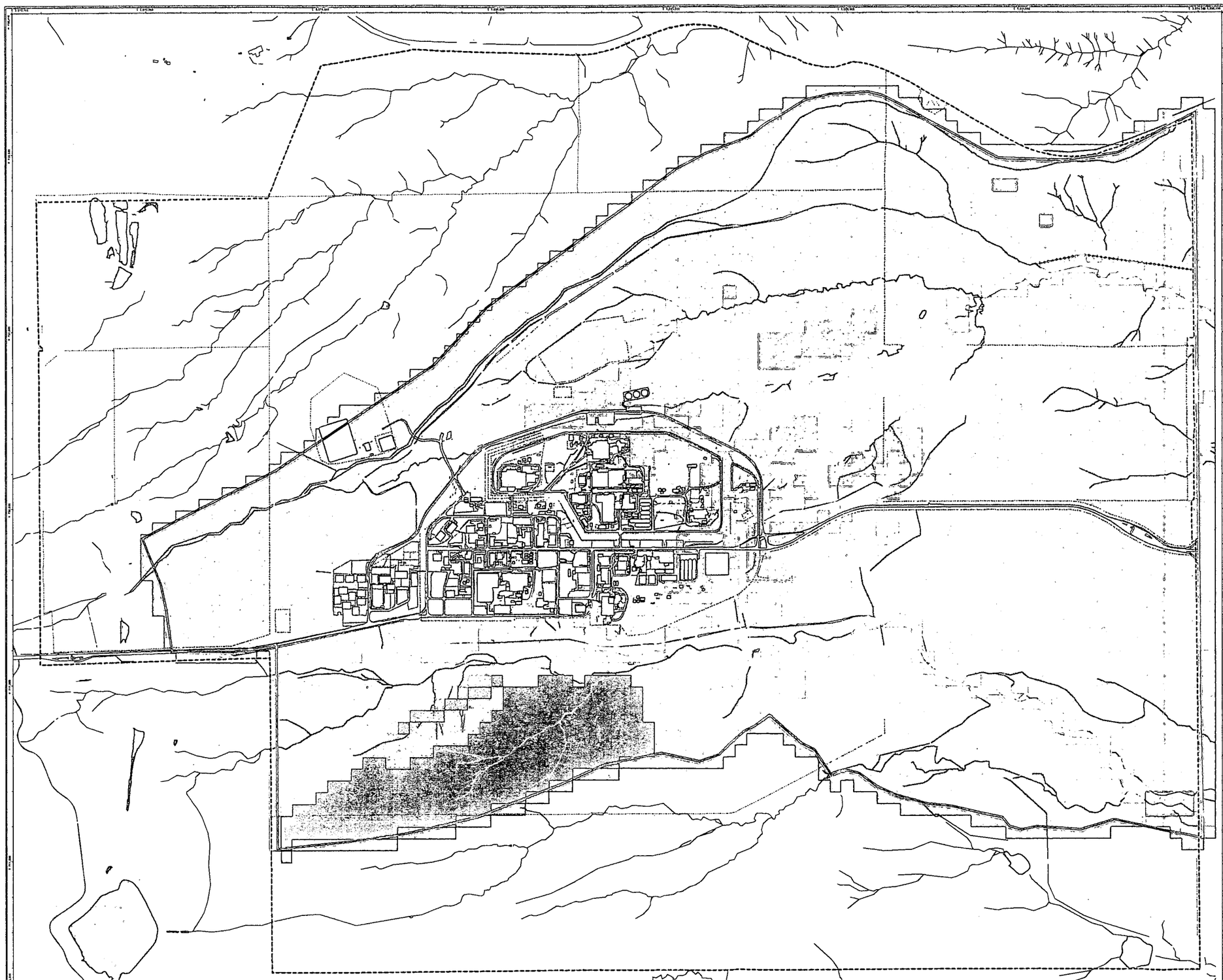

Figure D-10

Site-Wide Water Balance Report

Model Layer 3 Hydraulic Conductivity Distribution (Numerical Model Grid)

EXPLANATION

Layer 3 Hydraulic Conductivity (m/s)

- 1e-10 to 1e-9
- 1e-9 to 1e-8
- 1e-8 to 1e-7
- 1e-7 to 1e-6
- 1e-6 to 5e-6
- 5e-6 to 1e-5
- 1e-5 to 1e-4
- 1e-4 to 2e-4
- Not Active

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

U.S. Department of Energy
Rocky Flats Environmental Technology Site

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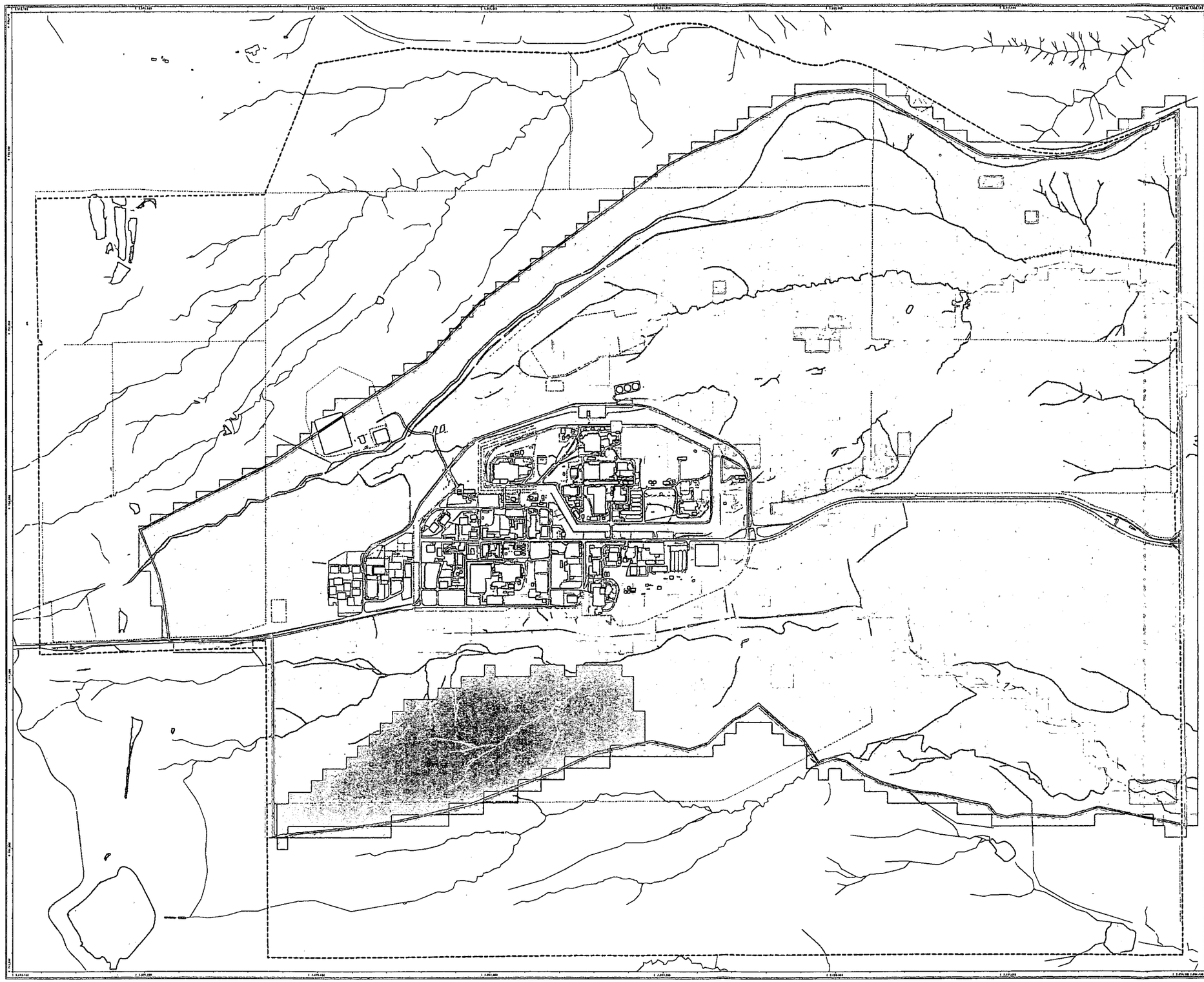

Figure D-11

Site-Wide Water Balance Report

Model Layer 4 Hydraulic Conductivity Distribution (Numerical Model Grid)

EXPLANATION

Layer 4 Hydraulic Conductivity (m/s)

- 1e-10 to 1e-9
- 1e-9 to 1e-8
- 1e-8 to 1e-7
- 1e-7 to 1e-6
- 1e-6 to 5e-6
- 5e-6 to 1e-5
- 1e-5 to 1e-4
- 1e-4 to 2e-4
- Not Active

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

U.S. Department of Energy

Rocky Flats Environmental Technology Site

GIS Dept. 303-966-7707

Prepared by: DynCorp — THE ART OF TECHNOLOGY

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May 12, 2000

NT_Svr w:/projects/swwb/fy2002/section_d/hod_layer4.aml

- In addition to adjusting model cell hydraulic conductivity values, the utility trenches were also used to define the bottom of model layers where they occur. Because the depths of trenches and the top of the weathered bedrock surface both vary over the model area, effective depths had to be determined for each model cell first, prior to specifying the new model layer depths. To determine effective trench depths, the total linear length of trench line within any model cell was determined. Since the inverts of each utility are different, the average trench depth for each cell was determined based on the assumed depths of each utility and individual lengths of each utility within each cell. Therefore, within cells where a relatively high density of deeper utility lines is present, a greater average depth was assigned. Discharge will not occur until groundwater levels exceed this average depth, but the MIKE SHE code only allows specification of a single elevation for a given model layer; and

- The model layer elevations in cells with trenches used averaged trench depths determined in the previous step. If the trench bottom extended into the unweathered bedrock material, or was within 0.5 meters (1.6 ft) of the bottom of this contact, the model layer was assumed to be at the contact to avoid modifying the underlying geologic information. Specification of Model Layer 3 was flexible; if the trench depth extended beyond 0.5 meters (1.6 ft) below the top of the weathered bedrock surface, Model Layer 3 was defined at the bottom of the trench.

D.3.1.2 Pipeflow Description

This section describes how the water supply, sanitary sewer, footing drain and storm sewer were described in the SWWB MIKE SHE model. Invert elevations for the last three drain types were determined using available information from engineering drawings or other data supplied from on-Site personnel (Woods, 2001).

The locations of drain cells specified in the MIKE SHE model are shown on Figure D-12. Drain leakance values specified for these drain cells are shown on Figure D-13. Values

shown on Figure D-12 indicate where drain flows were directed (e.g. negative numbers represent sanitary sewer lines). In the model, groundwater discharge from these cells were removed from the system. In reality, their flows become part of the WWTP discharge to Pond B-3 (this water was accounted for in the model by applying the actual WWTP discharge record as the effluent value from the WWTP). Positive drain values on Figure D-12 represent footing drains, storm sewers, or remediation systems that discharged water to adjacent Industrial Area streams (SW093, GS10 and SW027).

A detailed approach, similar to that described above for determining average trench hydraulic conductivities and invert elevations, was used to determine average invert and leakance values for each of the subsurface drain types modeled. The approach used to define invert elevations was slightly different. Instead of adjusting trench inverts to estimated geologic layers, the subsurface geologic surfaces were adjusted to inverts at subsurface drains. Subsurface drains are believed to have a larger impact on groundwater than trench backfill material because they actually remove groundwater. Leakance values for each cell were determined based on the total length of each drain pipe and individual leakance values.

D.3.1.2.1 Footing and Storm Drains

Footing drain leakance values were given the highest values of any of the subsurface drains because they were designed to extract groundwater. Average invert elevations were specified using information from available engineering drawings.

D.3.1.2.2 Water Supply Lines

Water supply lines were specified in MIKE SHE as a source of constant recharge (i.e., negative abstractions). The rate of recharge to each cell was specified based on the relative density of water supply pipeline in each model cell. It was assumed that 10 percent of the total imported DWB water (329 ac-ft/yr), 32.9 ac-ft/yr (40,581 m^3/yr) leaked from the distribution system to the subsurface. This volume of water was distributed in the model based on the relative density of pipes in each cell.

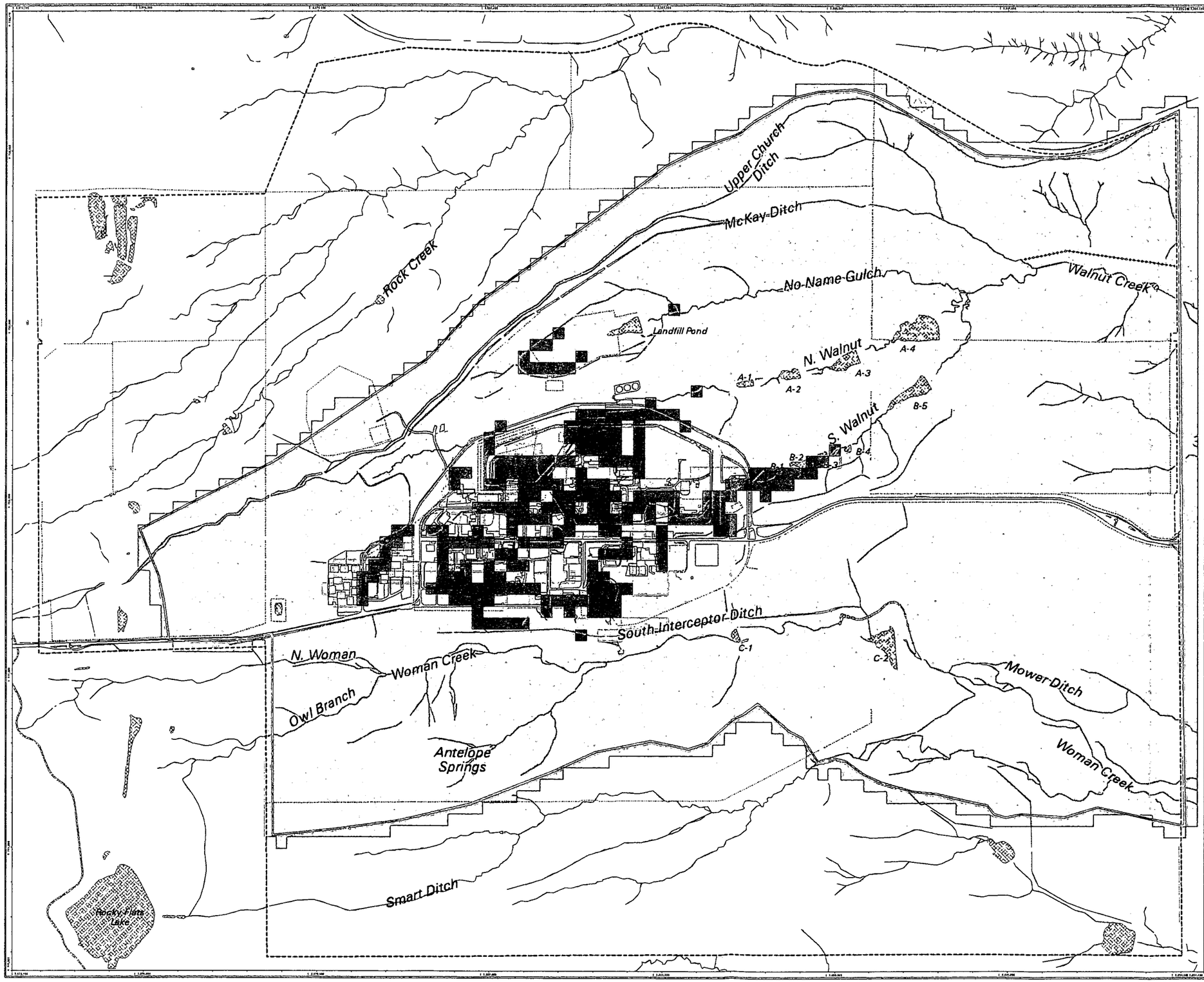

Figure D-12

Site-Wide Water Balance Report

Subsurface Drain Cells (Numerical Model Grid)

EXPLANATION

Model Drains

- Discharge to Model Boundary
- No Drains
- Discharge to Local Streams
- Outside of Model Boundary

Standard Map Features

- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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Prepared for: KAISER-HILL

May 14, 2002

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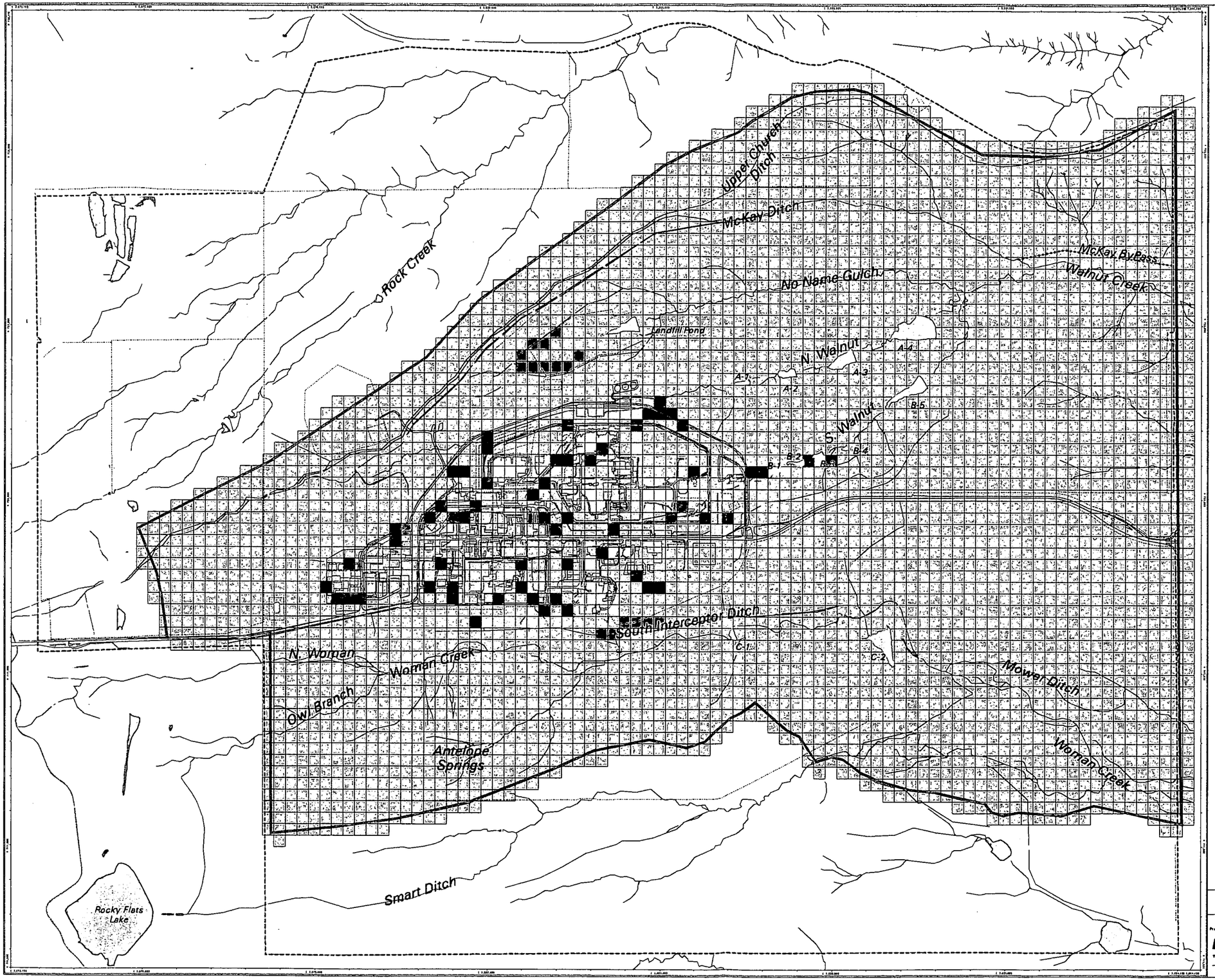

Figure D-13

Site-Wide Water Balance Report

Drain Leakance (Numerical Model Grid)

EXPLANATION

Leakance (1 / s)

- No Leakance
- 1e-10 to 1e-9
- 1e-9 to 1e-8
- 1e-8 to 1e-7
- 1e-7 to 1e-6
- 1e-6 to 1e-5
- 1e-5 to 1e-4
- 1e-4 to 1e-3
- 1e-3 to 1e-2
- 0.01 to 0.1
- 0.1 to 1
- Outside Model Boundary

Standard Map Features

- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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May 13, 2002

NT_Svr w:/projects/swwb/fy2002/section_d/drain_leakance.aml

D.3.1.2.3 Sanitary Sewer Lines

Sanitary sewers were specified as drain cells in the MIKE SHE model, because there appears to be a net discharge from the groundwater to these pipelines. Specification of a drain cell requires four types of information in MIKE SHE, including: (1) drain code specification; (2) invert elevations; (3) leakance values; and (4) discharge points. Within one MIKE SHE model cell, only a single drain can be specified. Therefore, if both sanitary and storm sewer lines occur in one cell, the line type with greater extent of pipeline was assigned to the cell. This is important in the model, because if the cell was specified as a sanitary sewer cell, its discharge was not returned to the system.

D.3.1.3 Remediation/Collection Systems

Remediation/collection systems were conceptually similar to the building footing drains. They were designed to efficiently extract groundwater. Groundwater discharged from the five remediation/collection systems was routed to nearby streams or ponds. For the Present Landfill, a hypothetical slurry wall was simulated using a feature in MIKE SHE that controls lateral flows between adjacent horizontal model cells. Low leakance values were assigned to cells adjacent to the north and south slurry walls to prevent any flow from crossing these cells.

D.4 SUB-REGIONAL SCALE MODELS AND PARTIALLY-COUPLED PROCESS MODELS

This section briefly summarizes setup and results obtained from sub-regional scale models and partially-coupled process models. Sub-regional models for the Antelope Springs, the SW027 drainage basin, the Industrial Area, the GS01 drainage basin and GS03 drainage basin were developed primarily to help parameterize both surface and subsurface processes. The sub-regional scale models simulated local conditions much more efficiently than the fully integrated model. Simple boundary conditions were specified for surface and subsurface conditions (i.e., groundwater boundary conditions). Partially-coupled process models were developed for single-columns located at continuous groundwater well locations, hillslopes and for the full RFETS model area.

This was done to improve computational efficiencies and to help parameterize and understand fundamental flow processes.

Results of the sub-regional scale modeling were incorporated into the fully integrated model. Conclusions for the Antelope Springs model include:

- Conceptual model for Antelope Springs is valid. A shallow bedrock surface forced upgradient groundwater to discharge at the ground surface;
- It is possible to match seeps flow reasonably well, but this system was very non-linear and sensitive to parameters like the saturated hydraulic conductivity of soils and saturated zone;
- Higher "effective" vertical saturated hydraulic conductivities of soil were required to match the surface water response at Antelope gage. This resulted in higher local recharge rates; and
- The saturated area of the spring increased in aerial extent during precipitation, which caused proportionally larger surface runoff (saturation excess - variable source area [VSA]).

The following conclusions were drawn from simulating single-column models that included saturated zone, unsaturated zone, ET and snowmelt:

- ET parameters and vertical saturated hydraulic conductivities affected groundwater level fluctuations the most. Very low specific yield values (i.e., 0.01) for the saturated zone were not required to simulate the notable groundwater level fluctuations observed during each spring (April) recharge event.
- Simulating continuously-monitored groundwater levels at specific wells using no-flow boundary conditions for the saturated zone showed that ET accounts for most of the groundwater level response. This occurred even when groundwater levels were well below the root zone. This suggested that direct groundwater recharge and ET dominated local groundwater level response, rather than lateral

readjustments in saturated zone flows. This was further supported by the relatively slow lateral groundwater flow velocities.

- A single set of unsaturated zone and ET parameters were not identified that could simulate the well responses in all wells located within a single soils type, like the Rocky Flats Alluvium. This suggested that it would be difficult to simulate the continuously-monitored groundwater levels in the regional model. Based on this finding, calibration efforts were made to simulate quarterly groundwater levels well instead of both continuous and quarterly levels.

Figure D-14 and Figure D-15 present the soil and vegetation distributions applied in the model to represent the WY2000 Site configuration.

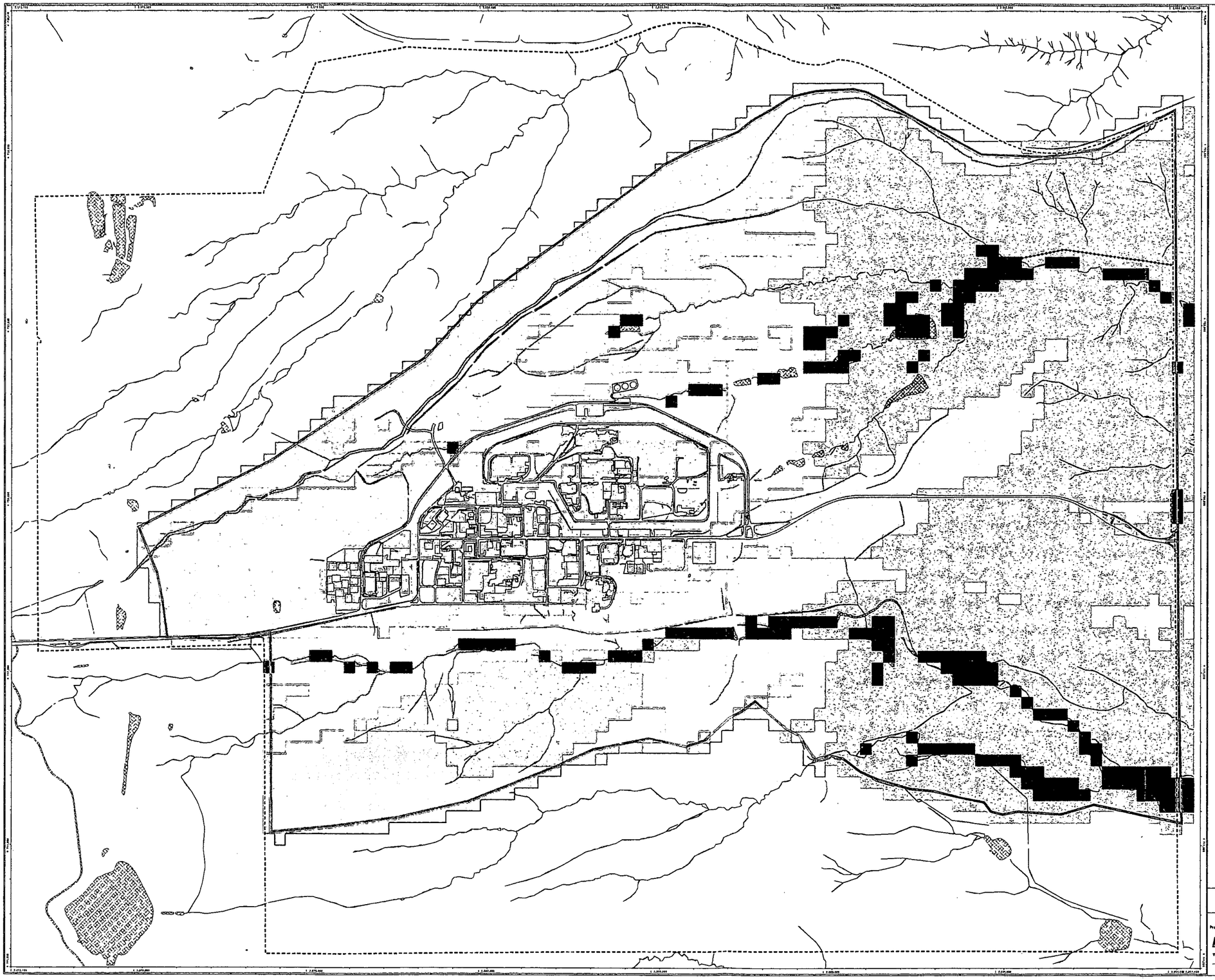

Figure D-14

Site-Wide Water Balance Report

Soils Distribution (Numerical Model Grid)

EXPLANATION

Soil Zones

- Rocky Flats Alluvium
- Colluvium (east)
- Valley Fill
- Bedrock Outcrop
- Pavement
- Colluvium (west)
- Rocky Flats Alluvium (Antelope Springs)
- Colluvium (Antelope Springs)
- Outside of Model Boundary

Standard Map Features

- Lakes and ponds
- Streams, ditches, or other drainage features
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:
Distribution shown derived through model calibration.

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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Rocky Flats Environmental Technology Site

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May 13, 2003

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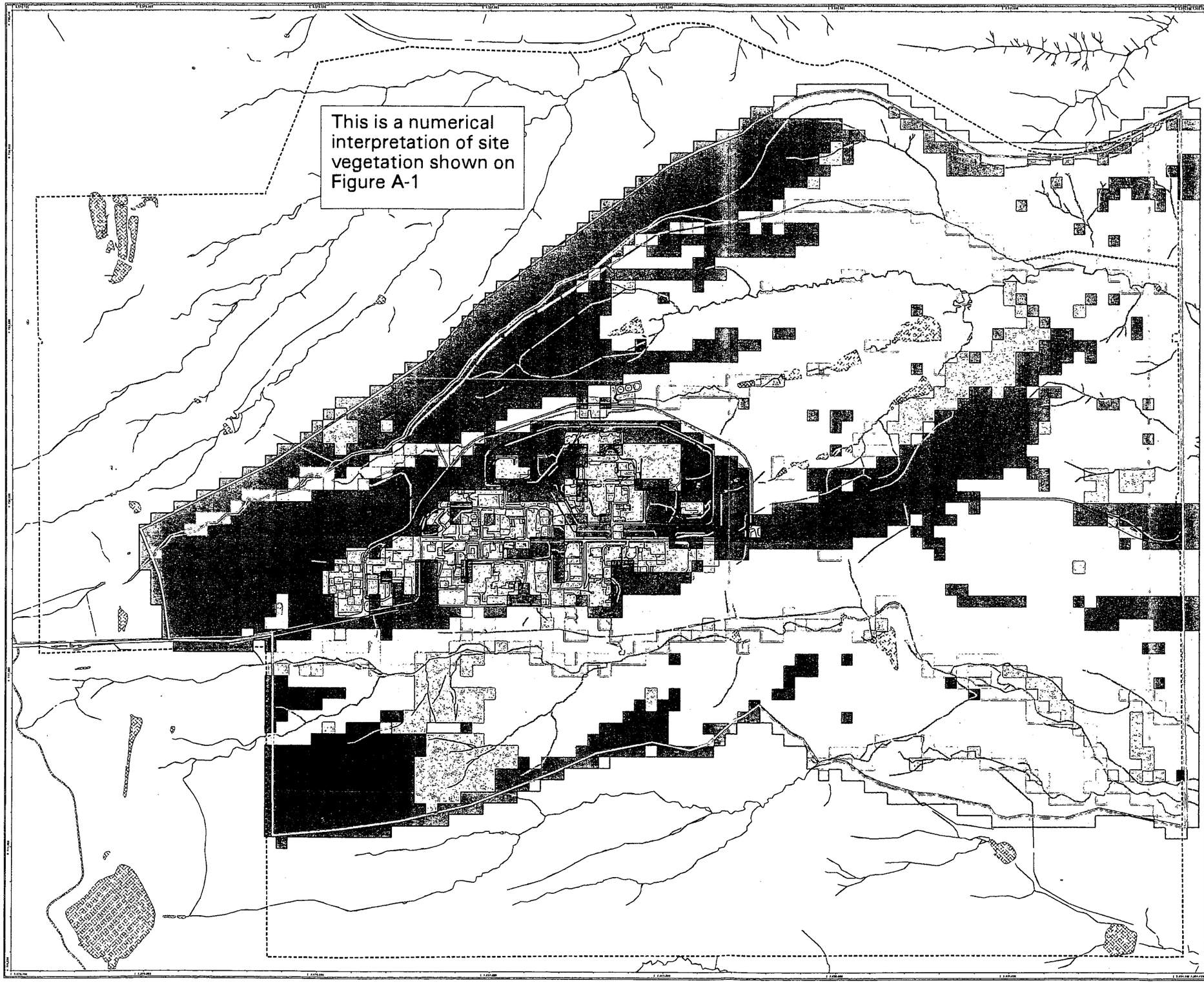

Figure D-15

Site-Wide Water Balance Report

Vegetation Distribution (Numerical Model Grid)

EXPLANATION

- Xeric
- Wetland
- Mesic
- Not Vegetated (paved)
- Riparian Woodland
- 15% Riparian Woodland/85% Mesic
- 37.5% Riparian Woodland/62.5% Mesic
- 15% Riparian Woodland/85% Xerix
- 37.5% Riparian Woodland/62.5% Xeric
- Outside of Model Boundary

Standard Map Features

- Lakes and ponds
- Streams, ditches, or other drainage features
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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Prepared by: DynCorp — THE ART OF TECHNOLOGY

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May 13, 2002

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Site-Wide Water Balance Model Report

Appendix E

Numerical Model Performance

May 2002

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E APPENDIX: NUMERICAL MODEL PERFORMANCE

This appendix contains information to support the Main Report discussion of model performance, including calibration, validation and sensitivity analysis.

E.1 CALIBRATION WY2000

E.1.1 Saturated Zone, Unsaturated Zone and Evapotranspiration

This section presents a series of graphics supporting the Main Report discussion of the model performance for the saturated zone, unsaturated zone and ET. Figure E-1 presents the calibration parameters for the numerical model. Figures E-2 through E-10 present numerical model output, compared to observed data, where available.

E.1.2 Surface Water

E.1.2.1 Additional Images of Surface Flow Calibration

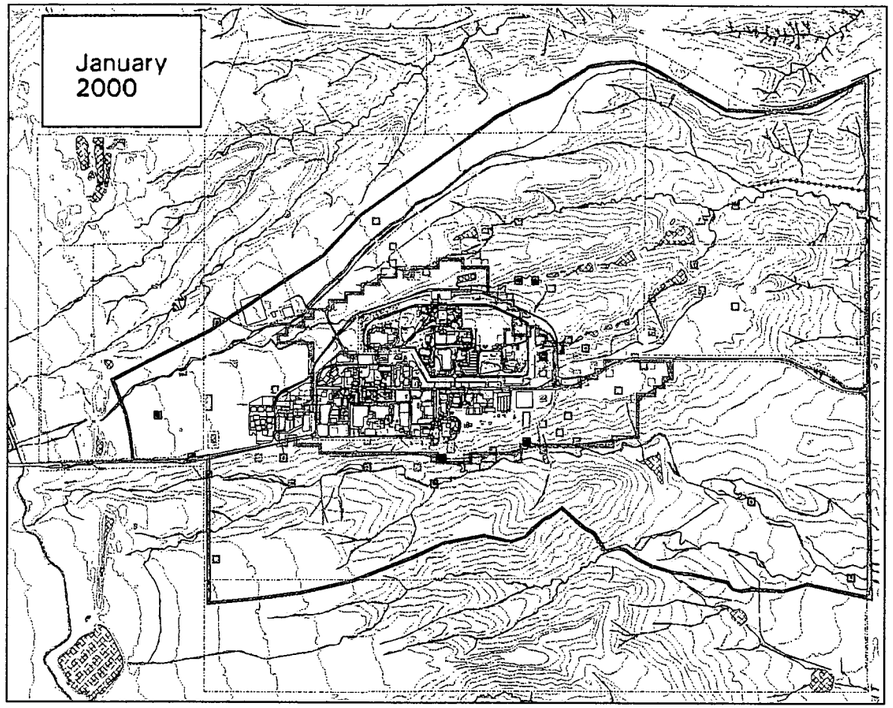
The following images (Figures E-11 through E-14) complete the presentation of the detailed (15-minute interval) assessment of flow rate calibration at gages SW093, GS10, GS22 and SW027. Four types of flow conditions are shown for each gage: baseflow, a large precipitation event, a moderate precipitation event and a snowmelt event.

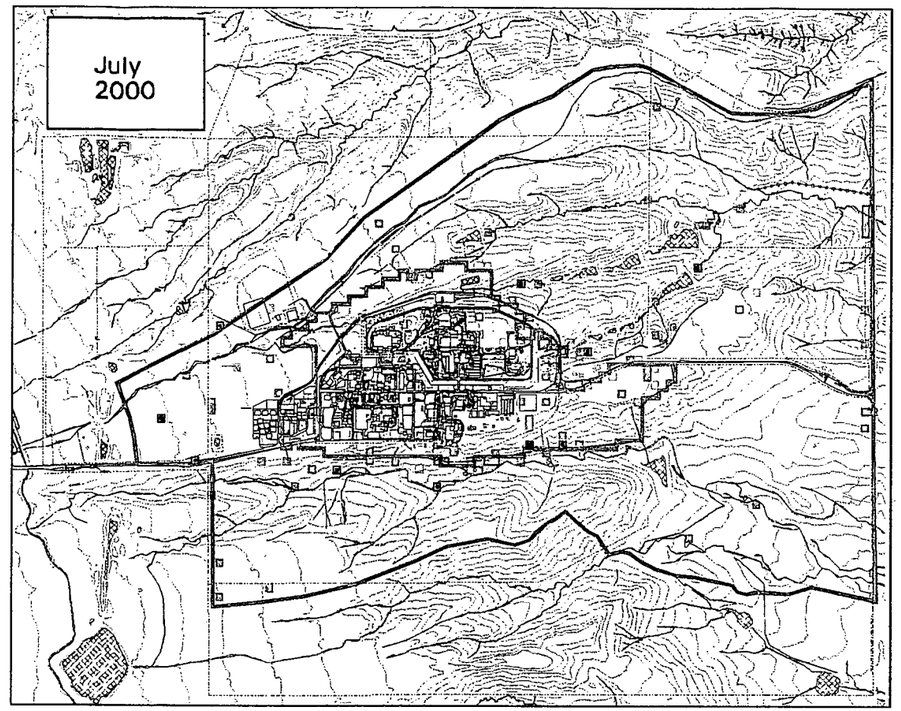
E.1.2.2 Additional Pond Level Calibration Information

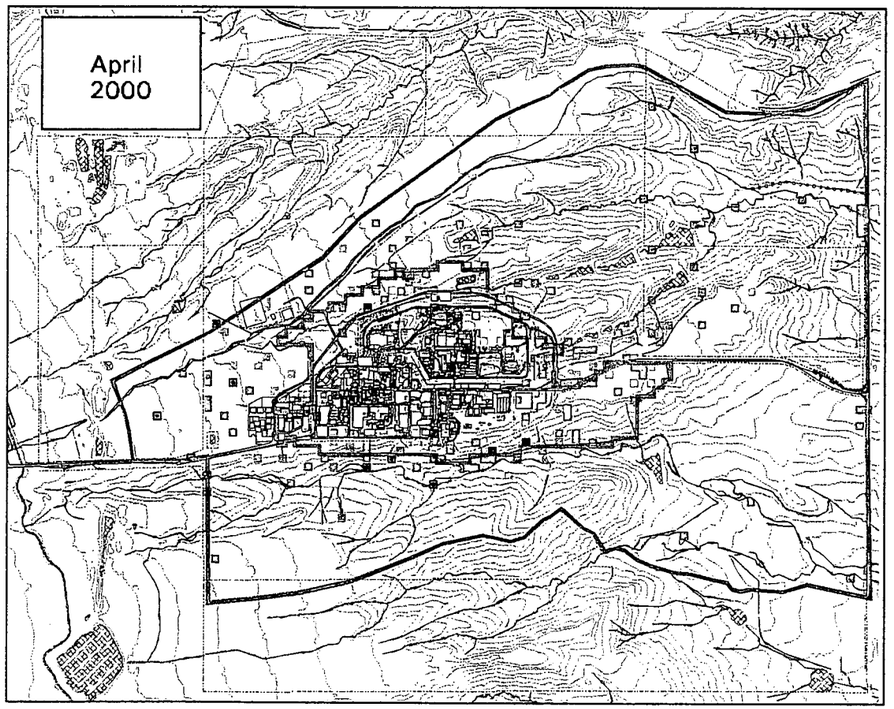
Comparison images of observed and simulated pond levels are presented here for Ponds C-2, B-5 and A-3 (Figures E-15 through E-17) for WY2000. These images are provided as supplemental information for Section 6 of the Main Report (Pond A-4 is presented in the Main Report).

Figure E-1. Calibration Parameters

Processes	General Model Input	Specific Input	Boundary Condition	Parameter	Structure	Calibration Parameter
Saturated Zone						
	Initial heads (each SZ layer)		x			
	Lateral heads	Western Boundary	x			
		Eastern Boundary	x			
	Hydraulic Conductivity					
		Layer 1		x		
		Layer 2		x		
		Layer 3		x		
		Layer 4		x		
	Specific Yield - Unconfined			x		
	Storage Coefficient - Confined			x		
	Footing Drains	Invert elevations	x	x		
		Leakance values		x		
		Drain outflow locations			x	
	Subsurface Drains	Invert elevations			x	
		Leakance values		x		
		Drain outflow locations			x	
	Water Supply Inflow	Abstraction rate	x			
	Trenches	Average Backfill K		x		
		Average trench depth			x	
	Geologic Layer thickness	All Layers			x	
	Geologic Layer Surfaces	All Layers			x	
	Horizontal Grid Resolution				x	
Unsaturated Zone						
	Ksat			x		
	n			x		
	Retention curve			x		
	thetaS			x		
	thetaR			x		
	thetaEFF			x		
	Field Capacity			x		
	Wilting Point			x		
	Soil Profile Vertical Grid			x	x	
	Soil Distribution	Zonations		x		
Climate	Snowmelt	Degree day Factor		x		
		Threshold Temperature		x		
Vegetation						
	C1 - Empirical Parameter			x		
	C2 - Empirical Parameter			x		
	C3 - Empirical Parameter			x		
	Cint - Interception Parameter			x		
	Aroot - Controls root density w/depth			x		
	LAI - Leaf Area Index			x		
	RDF - Root Depth Function			x		
	Kc - Crop Coefficient			x		
Overland Flow						
	Leakance type/rate			x		
	Mannings M			x		
	Detention Storage			x		
	Overland Flow Areas				x	
	Boundary Conditions		x			
Channel Flow						
	Stream Resistance (Mannings M)			x		
	Leakance type/rate w/groundwater			x		
	Cross-sections	Invert Elevations			x	
		Bank Elevations			x	
		Cross-sectional areas			x	
	Structures	Culverts	x			
		Weirs	x			
		Pond Operation	x			
	Specified SW-GW branch interaction		x			
	Inflow/Outflow		x			







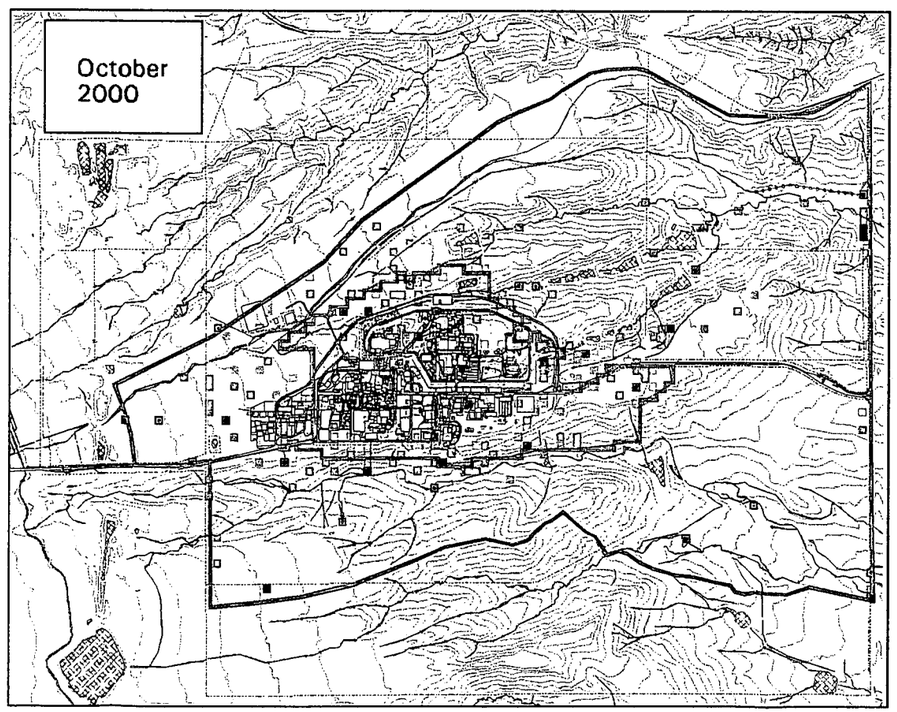


Figure E-2

Site-Wide Water Balance Report

Groundwater Head Residuals

(WY 2000)

EXPLANATION

Groundwater Head Residuals (m)

- Less than -5
- -5 to -2
- -2 to -1
- -1 to 1
- 1 to 2
- 2 to 5
- Greater than 5

Other Features

- Model IA Catchment Boundary

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Topographic Contour (20-Foot)
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the nellisnhighway.w. 1/95

Topographic contours were derived from digital elevation model (DEM) data by Morrison Knudson (MK) using ESRI Arc TIN and LAT LICE to process the DEM data to create 5-foot contours. The DEM data was captured by the Remote Sensing Lab, Las Vegas, NV, 1994 Aerial Flyover at ~ 10 meter resolution. DEM post-processing performed by MK, Winter 1997.

NOTES:

Positive groundwater residuals denote simulated heads greater than observed.

Negative groundwater residuals denote simulated heads less than observed.

200 0 400 800m

500 0 1000 2000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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Prepared by: KAISER-HILL COMPANY

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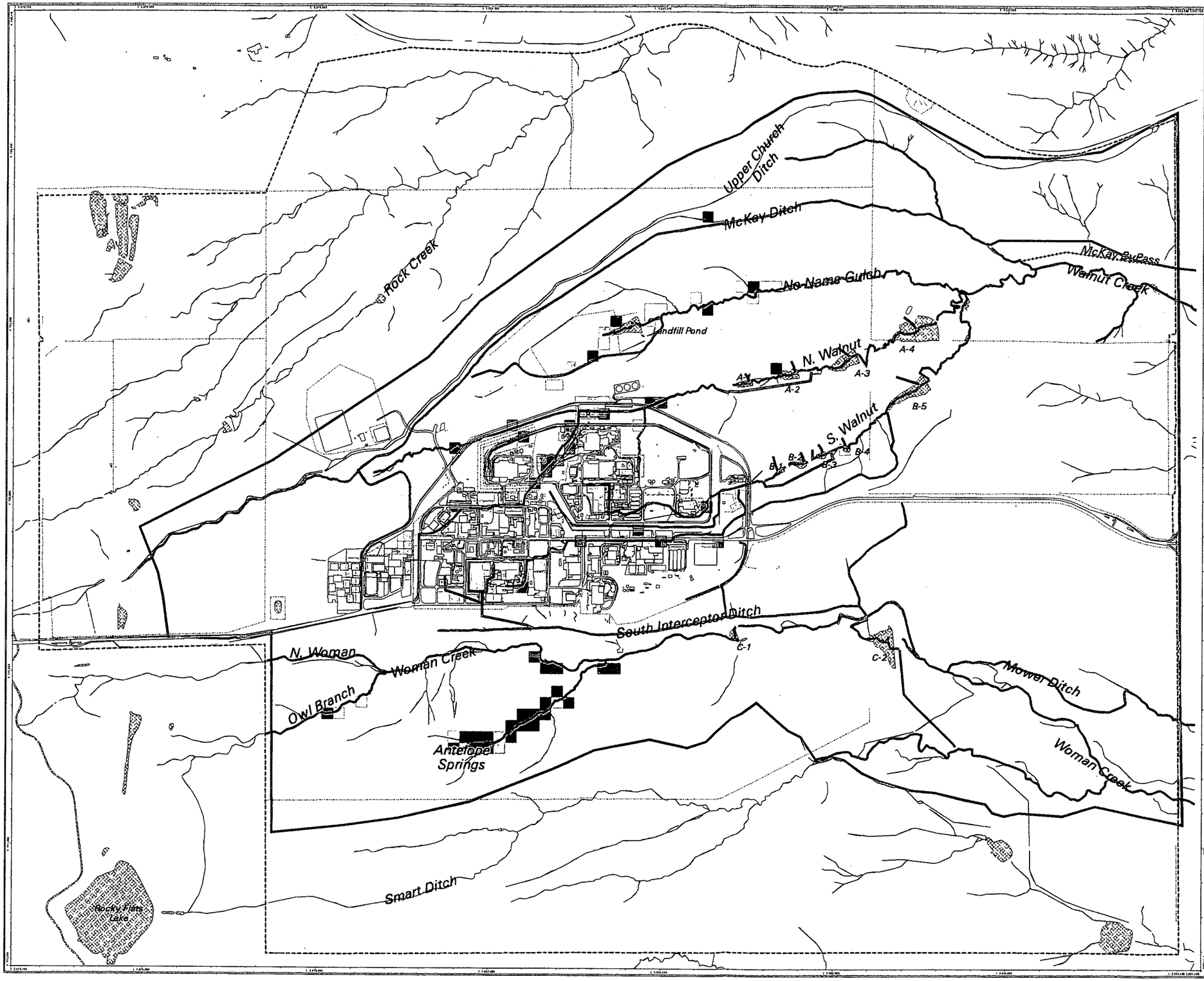

Figure E-3

Site-Wide Water Balance Report

Simulated Annual Overland Flow to Streams (WY 2000) (Numerical Model Grid)

EXPLANATION

Overland Flow to Streams (m^3/yr)

- 0 - 1
- 1 - 10
- 10 - 100
- 100 - 1000
- 1000 - 10000
- > 10000
- Outside of Model Boundary

Surface Flow Channel Network

- Aboveground Pipe
- Belowground Pipe
- Pond Evaporation Structure
- Surface Channel

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:

To convert indicated flow rate to length per time, divide rate by model grid cell area (40,000 square ft).

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

U.S. Department of Energy
Rocky Flats Environmental Technology Site

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Prepared by: DynCorp — THE AGY OF TECHNOLOGY

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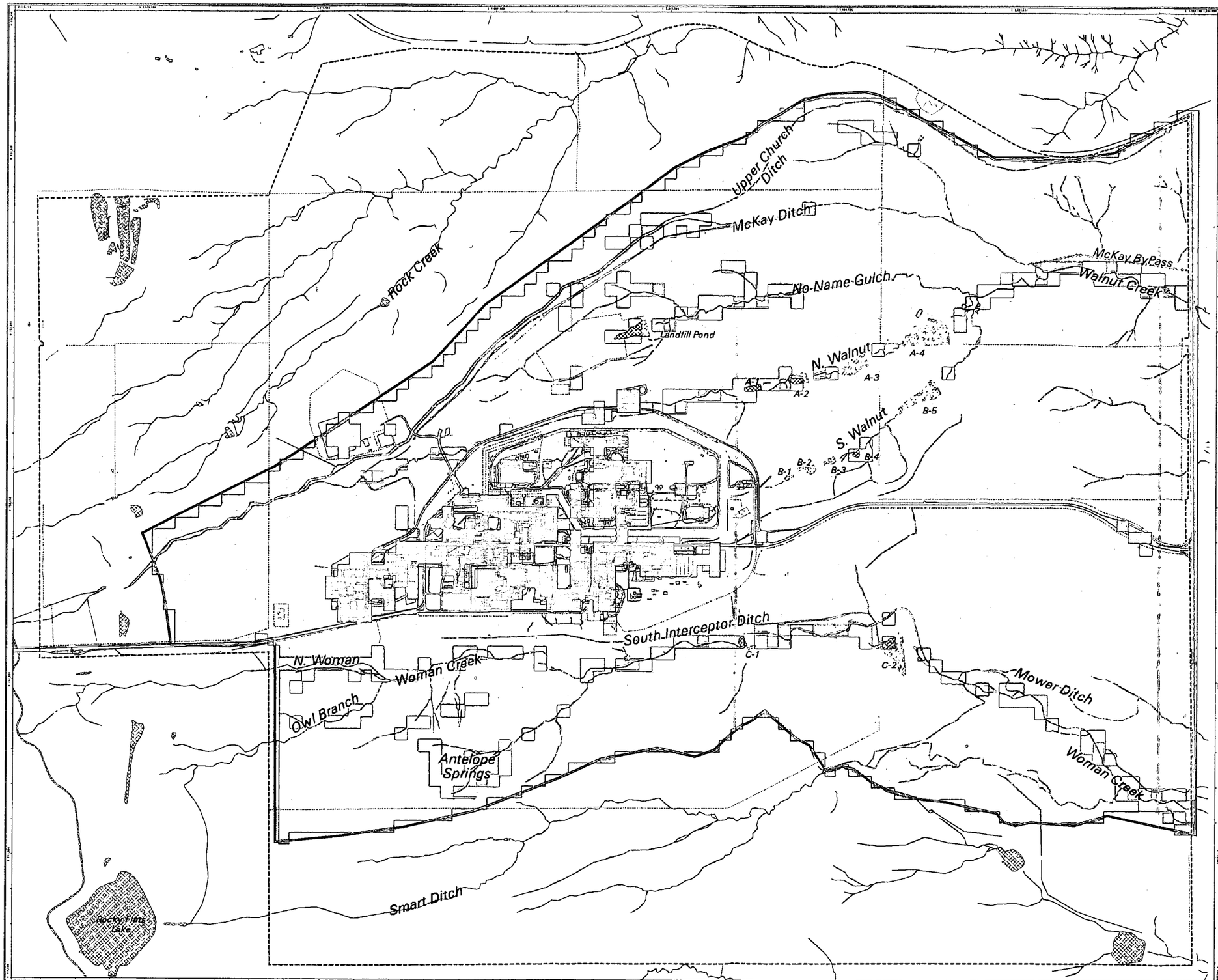

Figure E-4

Site-Wide Water Balance Report

Simulated Annual Evapotranspiration (Numerical Model Grid)

EXPLANATION

Simulated Evapotranspiration (in/yr)

- 0 to 5 (0 to 127 mm/yr)
- 5 to 10 (127 to 254 mm/yr)
- 10 to 20 (254 to 508 mm/yr)
- 20 to 30 (508 to 762 mm/yr)
- 30 to 40 (762 to 1016 mm/yr)
- 40 to 50 (1016 to 1270 mm/yr)
- Outside of Model Boundary

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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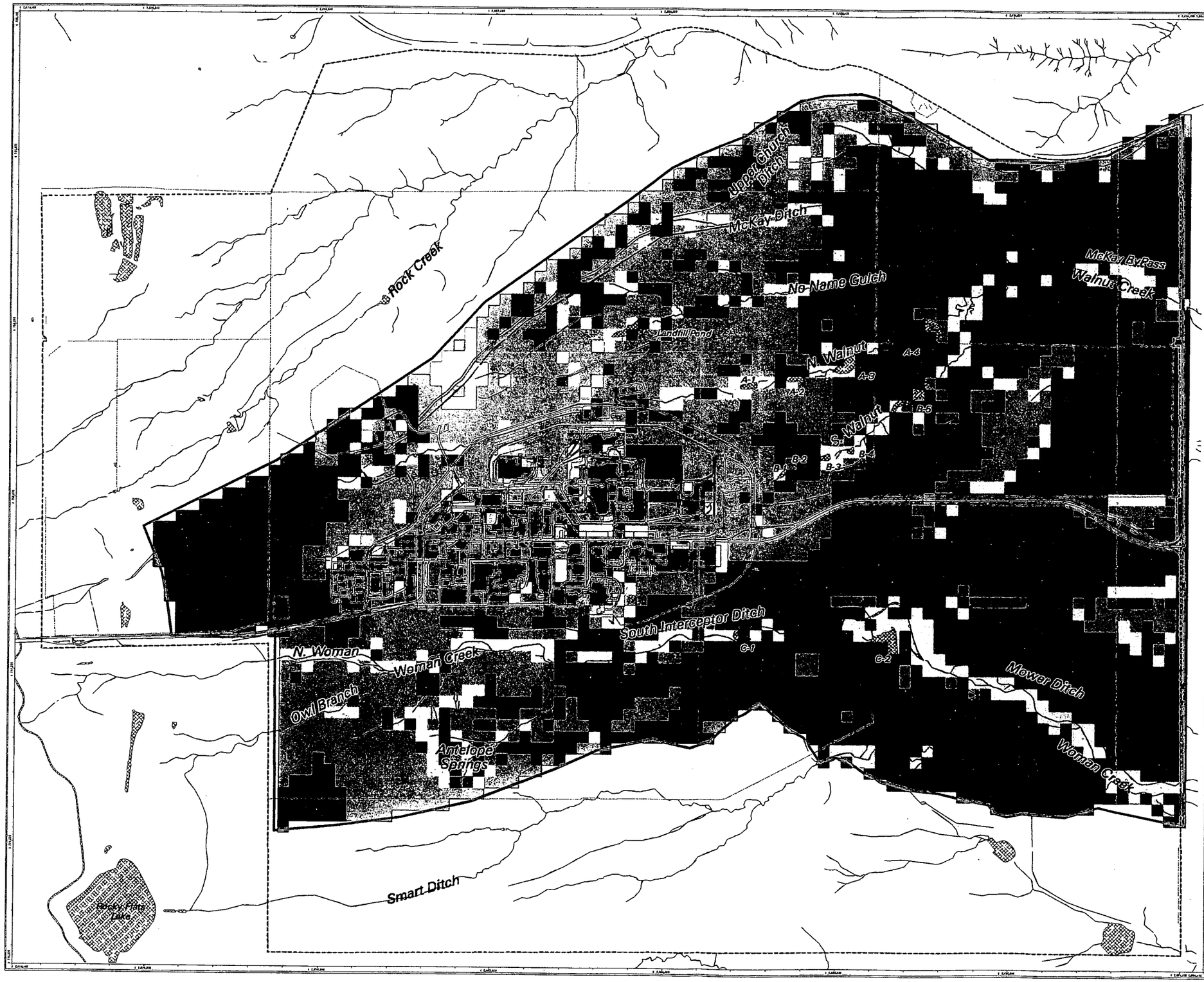

Figure E-5

Site-Wide Water Balance Report

Simulated Distribution of Annual Groundwater Recharge (Numerical Model Grid)

EXPLANATION

Simulated Groundwater Recharge (in/yr)

- < -10 (less than -254 mm/yr)
- -10 to -1 (-254 to -25.4 mm/yr)
- -1 to 1 (-25.4 to 25.4 mm/yr)
- 1 to 5 (25.4 to 127 mm/yr)
- 5 to 10 (127 to 254 mm/yr)
- 10 to 20 (254 to 508 mm/yr)
- > 20 (greater than 508 mm/yr)
- Outside of Model Boundary

Standard Map Features

- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:
Negative recharge denotes actual groundwater loss (no net recharge for year).

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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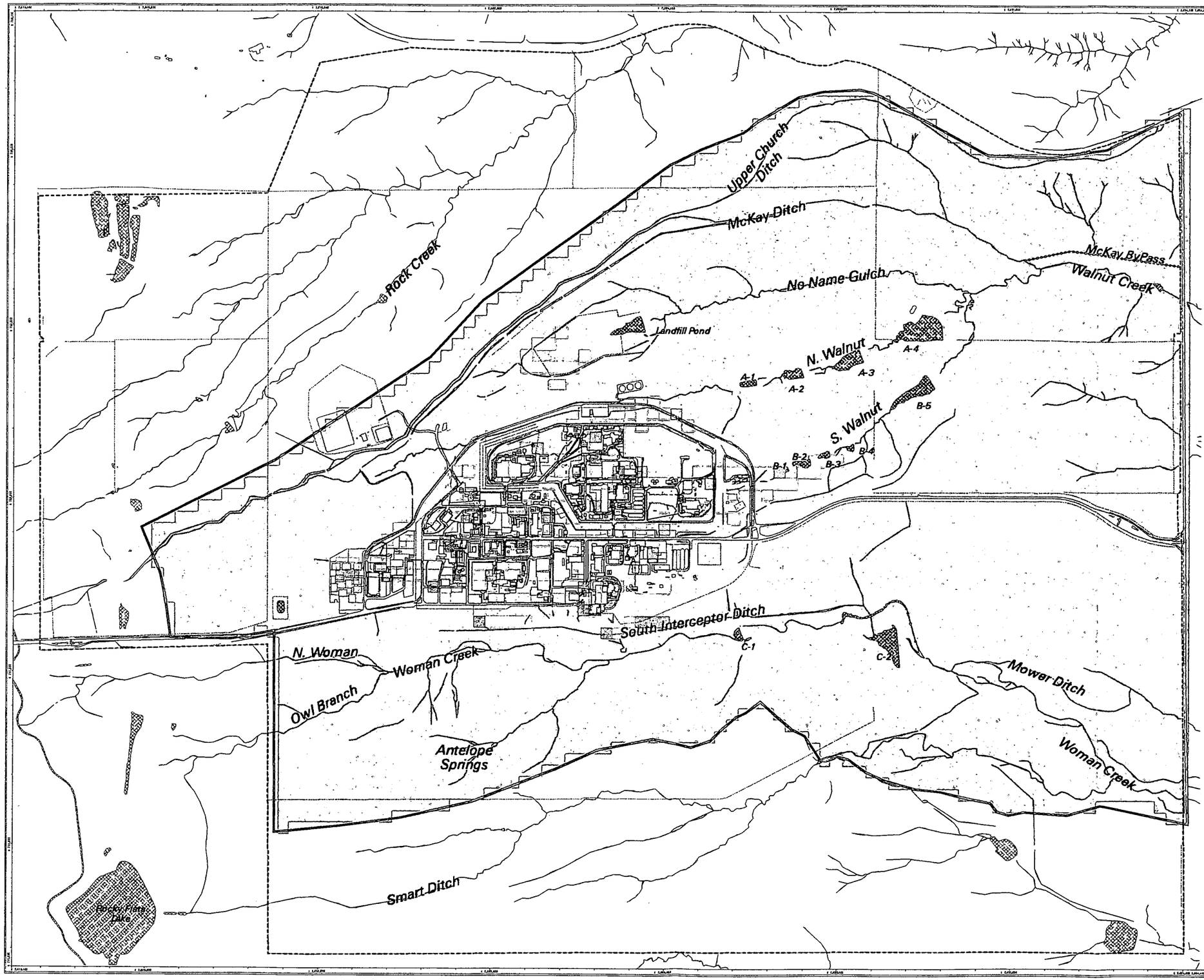

Figure E-6

Site-Wide Water Balance Report

Spatial Distribution of Drain Discharge to Streams (Numerical Model Grid)

EXPLANATION

Simulated Drain Discharge to Streams (m^3/yr)

- 0 to 1
- 1 to 10
- 10 to 100
- 100 to 1000
- 1000 to 10000
- Greater than 10000
- Outside of Model Boundary

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:

To convert indicated flow rate to length per time, divide rate by model grid cell area (40,000 square ft).

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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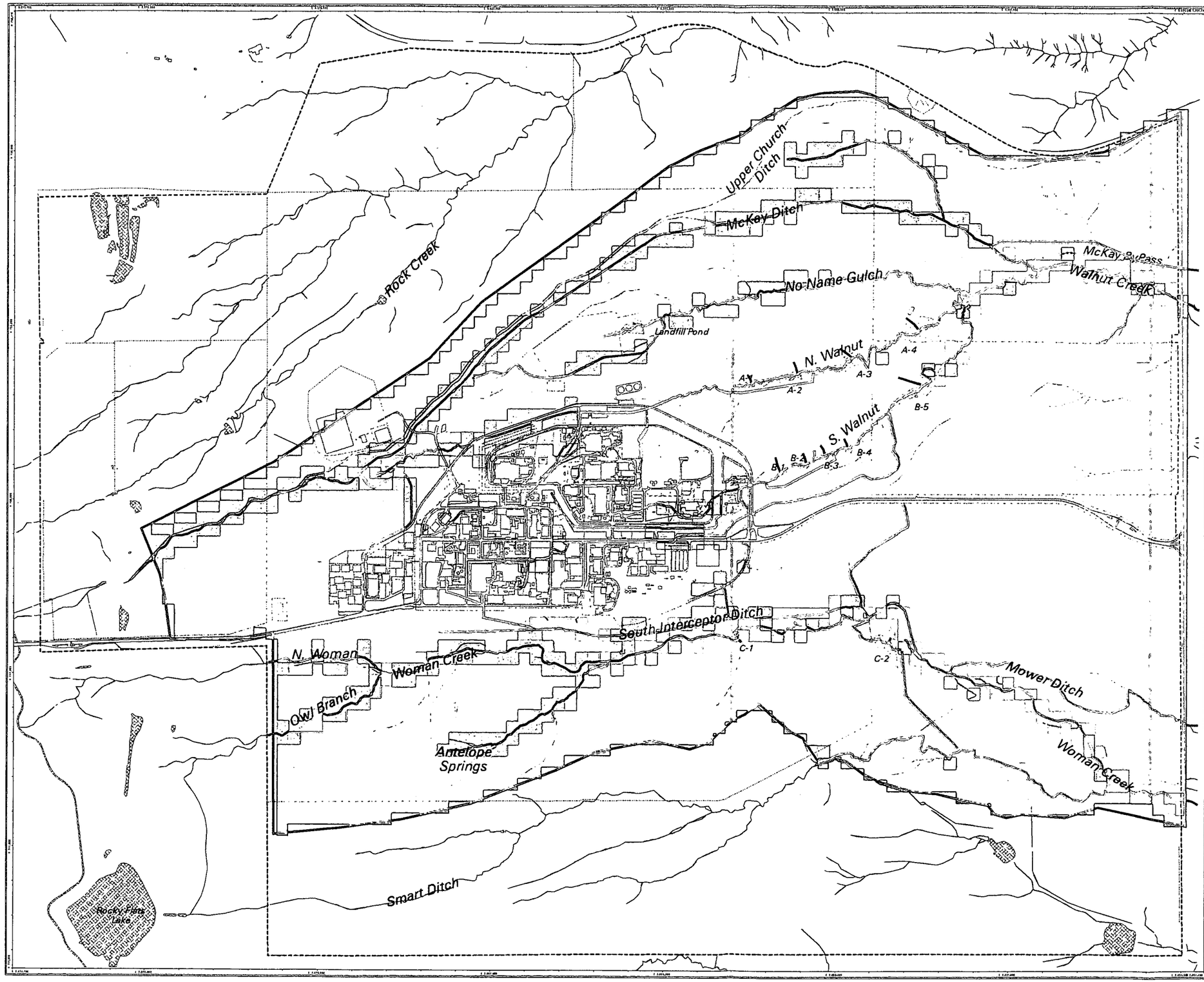

Figure E-7

Site-Wide Water Balance Report

Annual Distribution of Baseflow to Modeled Stream Branches (Numerical Model Grid)

EXPLANATION

Baseflow to Streams (m^3/yr)

- -5000 to -1000
- -1000 to -100
- -100 to -10
- -10 to 10
- 10 to 100
- 100 to 1000
- 1000 to 5000
- Outside of Model Boundary

Surface Flow Channel Network

- Aboveground Pipe
- Belowground Pipe
- Pond Evaporation Structure
- Surface Channel

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:

Negative values indicate net losing reach annually.

To convert indicated flow rate to length per time, divide rate by model grid cell area (40,000 square ft).

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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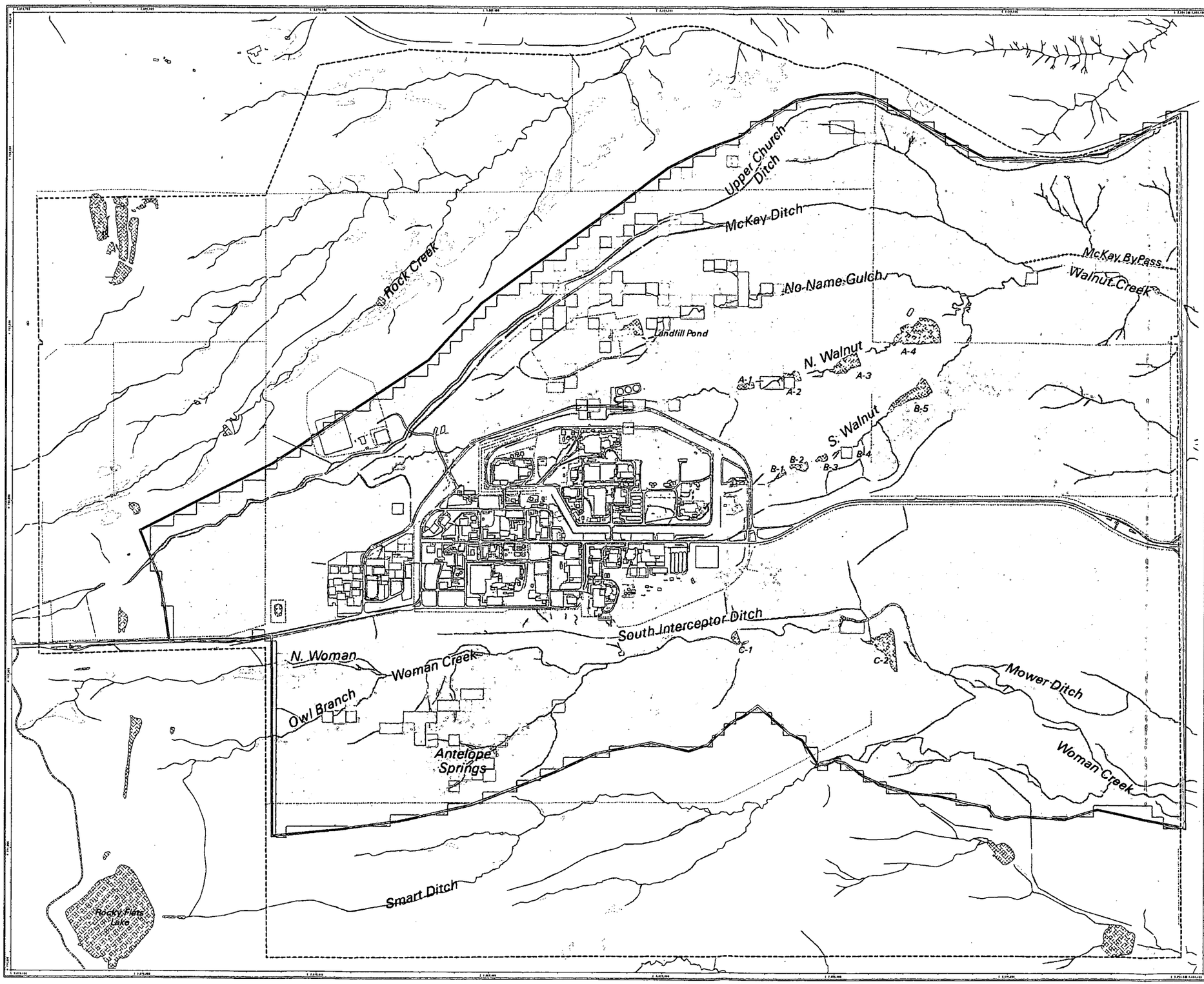

Figure E-8

Site-Wide Water Balance Report

Simulated Annual Saturated Zone Discharge to the Ground Surface (Numerical Model Grid)

EXPLANATION

Simulated Flow (m^3/yr)

- 0 - 1
- 1 - 10
- 10 - 100
- 100 - 1000
- 1000 - 10000
- > 10000
- Outside of Model Boundary

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:
Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:
To convert indicated flow rate to length per time, divide rate by model grid cell area (40,000 square ft).

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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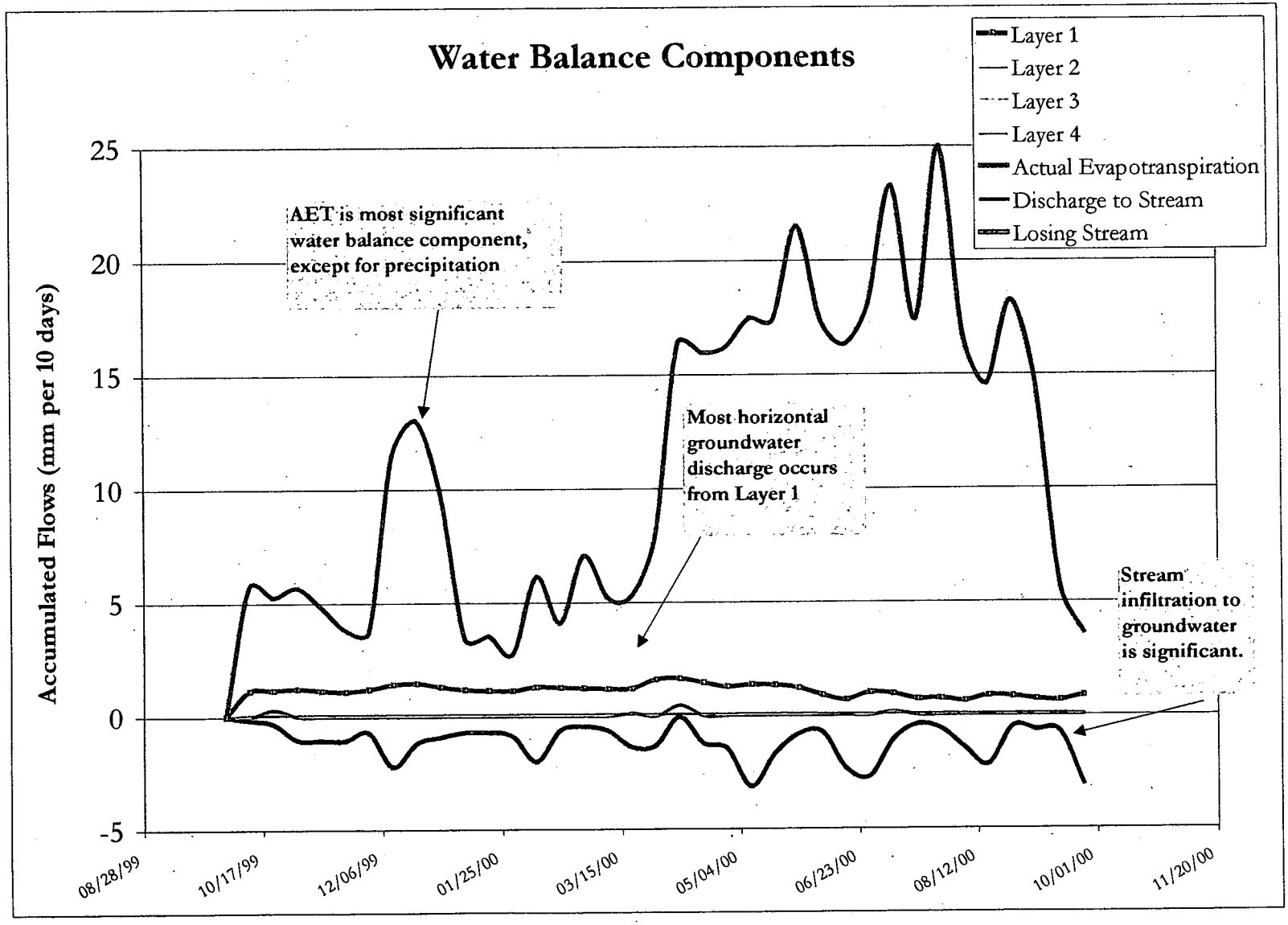
Figure E-9. Simulated Water Balance Time Series – Eastern Model Boundary



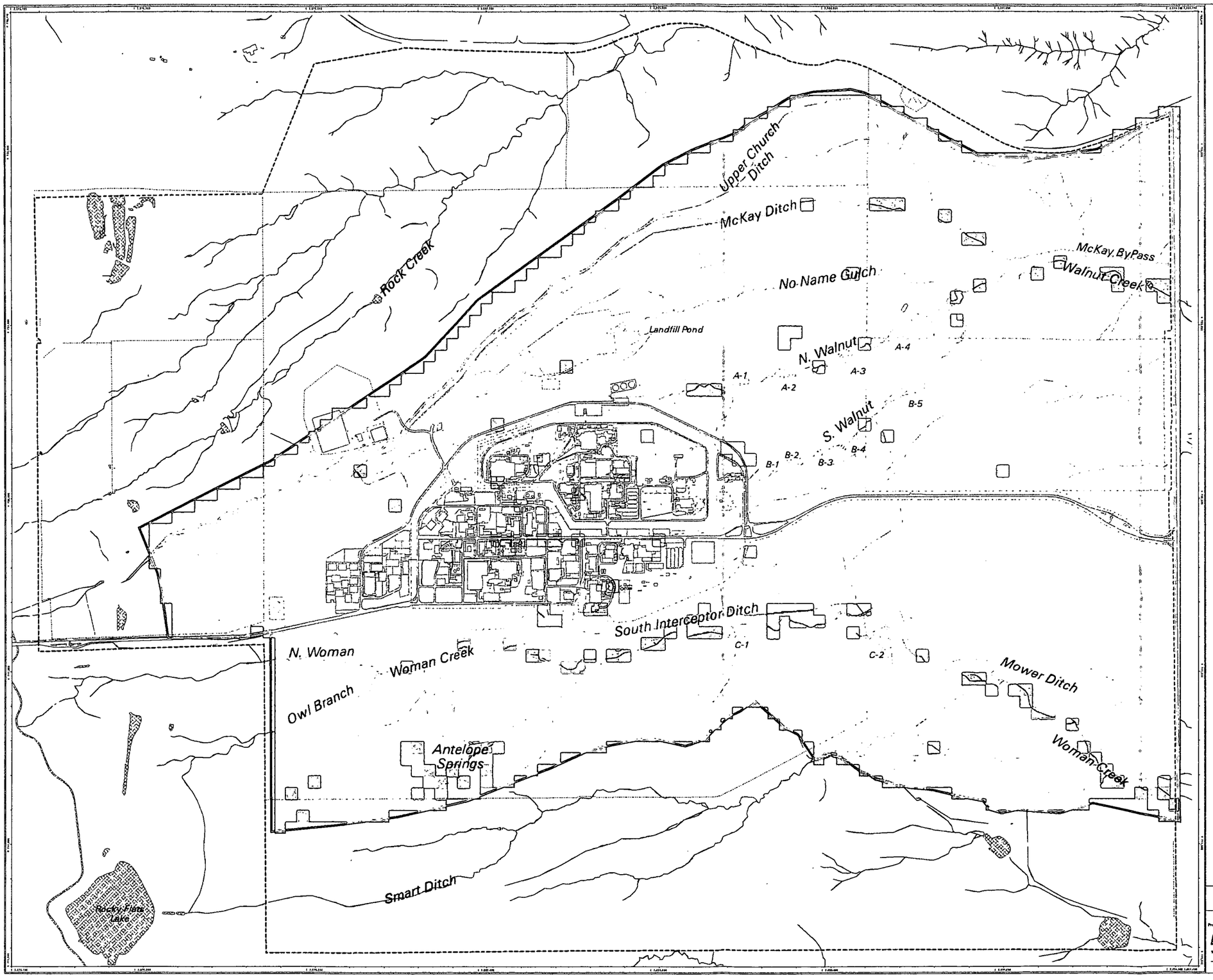


Figure E-10

Site-Wide Water Balance Report

Total Annual Numerical Error (Numerical Model Grid)

EXPLANATION

Numerical Error (m^3/yr)

- -5000 to -1000
- -1000 to -100
- -100 to -10
- -10 to 10
- 10 to 100
- 100 to 1000
- 1000 to 5000
- Outside of Model Boundary

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95

NOTES:

Positive values indicate flows over-predicted; Negative values indicate flows under-predicted.

To convert indicated flow rate to length per time, divide rate by model grid cell area (40,000 square ft).

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

U.S. Department of Energy

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Prepared for: KAISER-HILL

May 13, 2003

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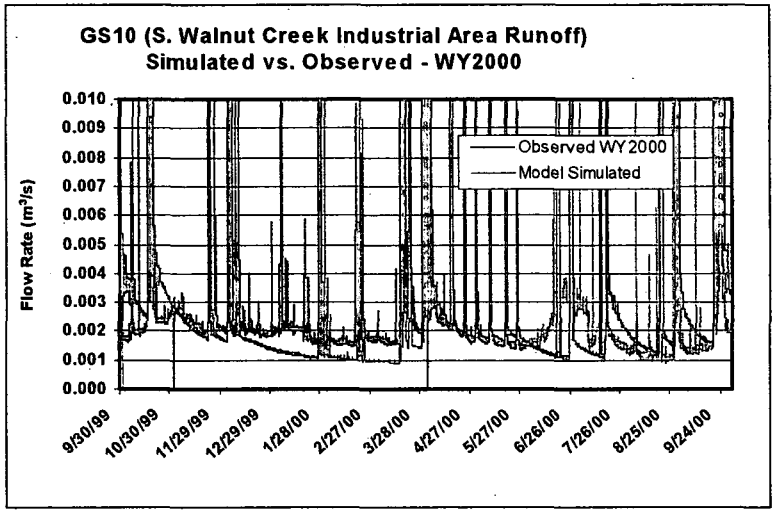
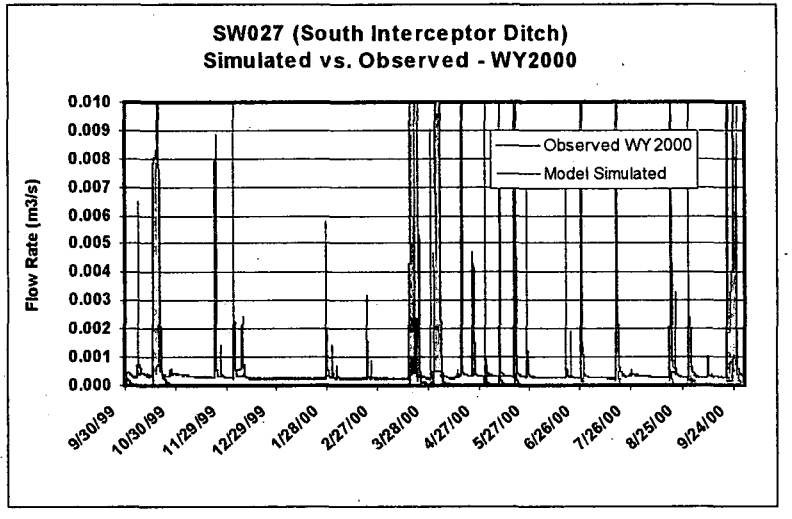
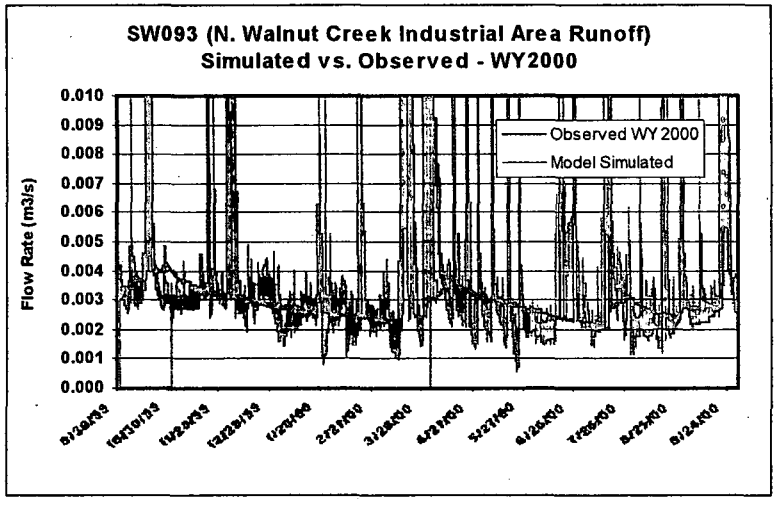
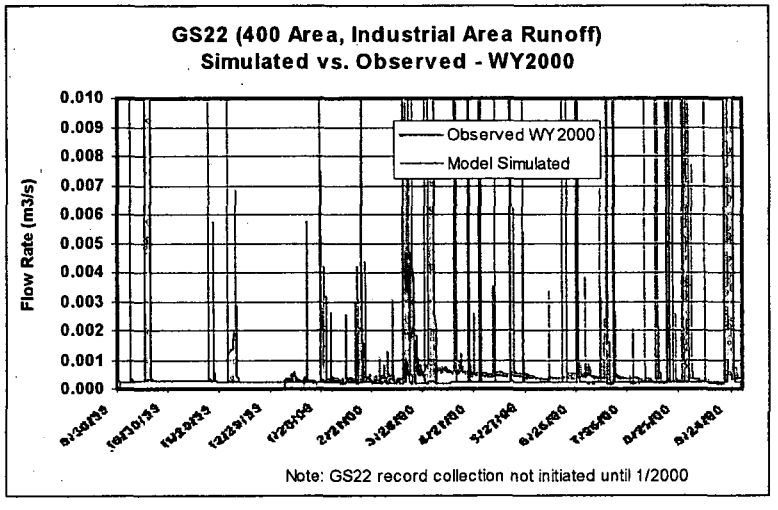
Figure E-11. Simulated and Observed Baseflow at SW093, GS10, GS22, and SW027 (WY2000)



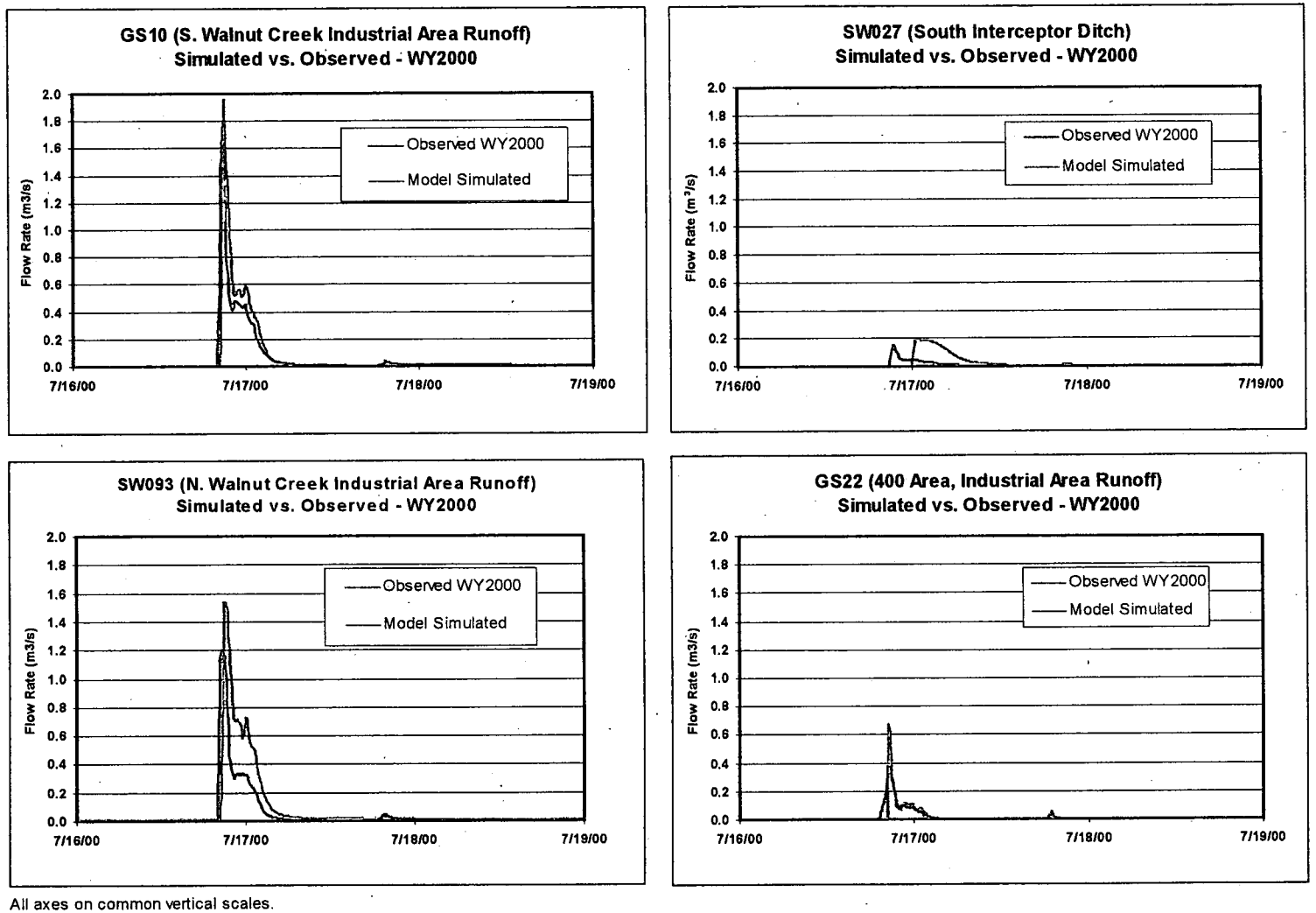






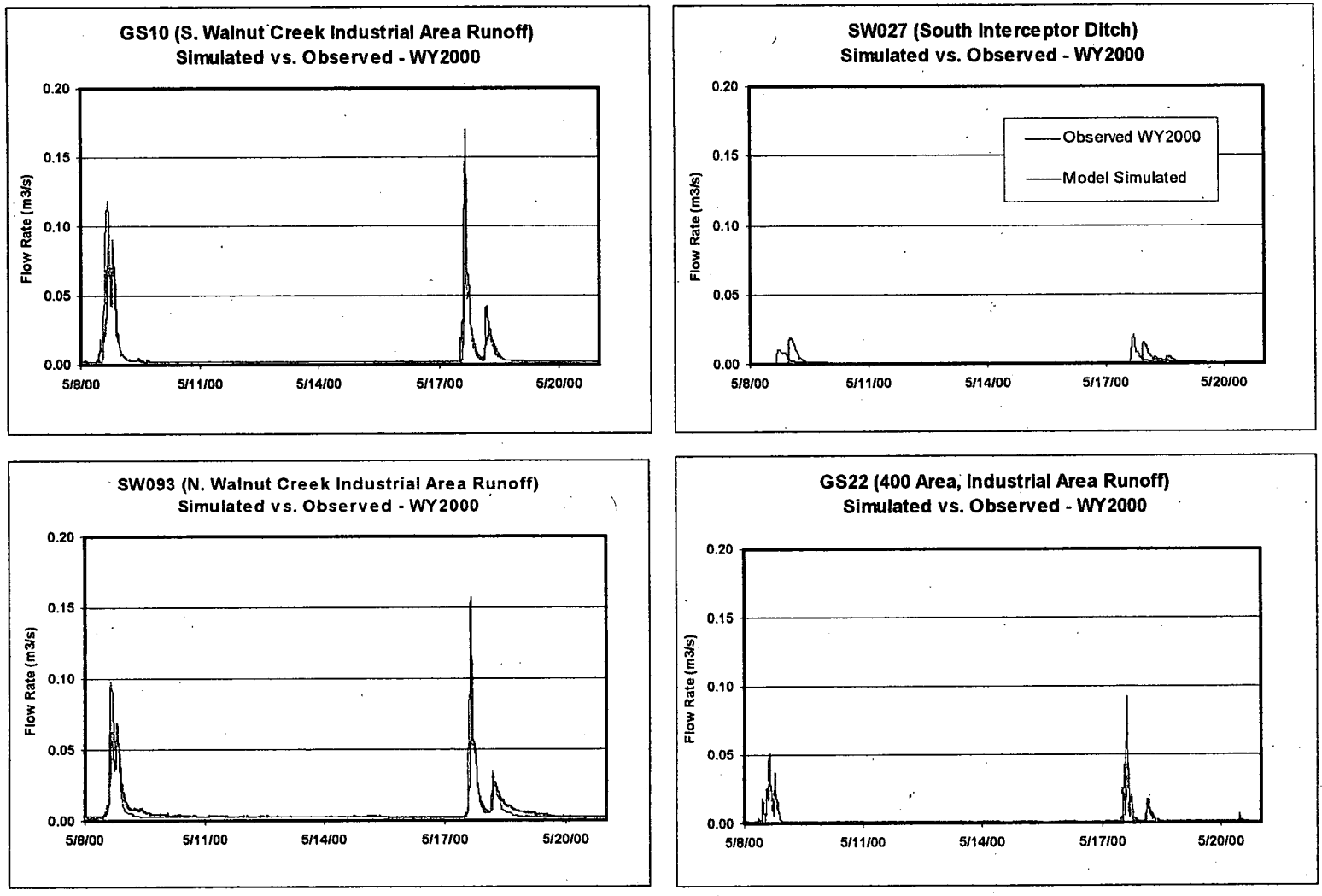
All vertical axes on Common scale.

Figure E-12. Simulated and Observed Large Precipitation Event at SW093, GS10, GS22, and SW027 (WY2000)



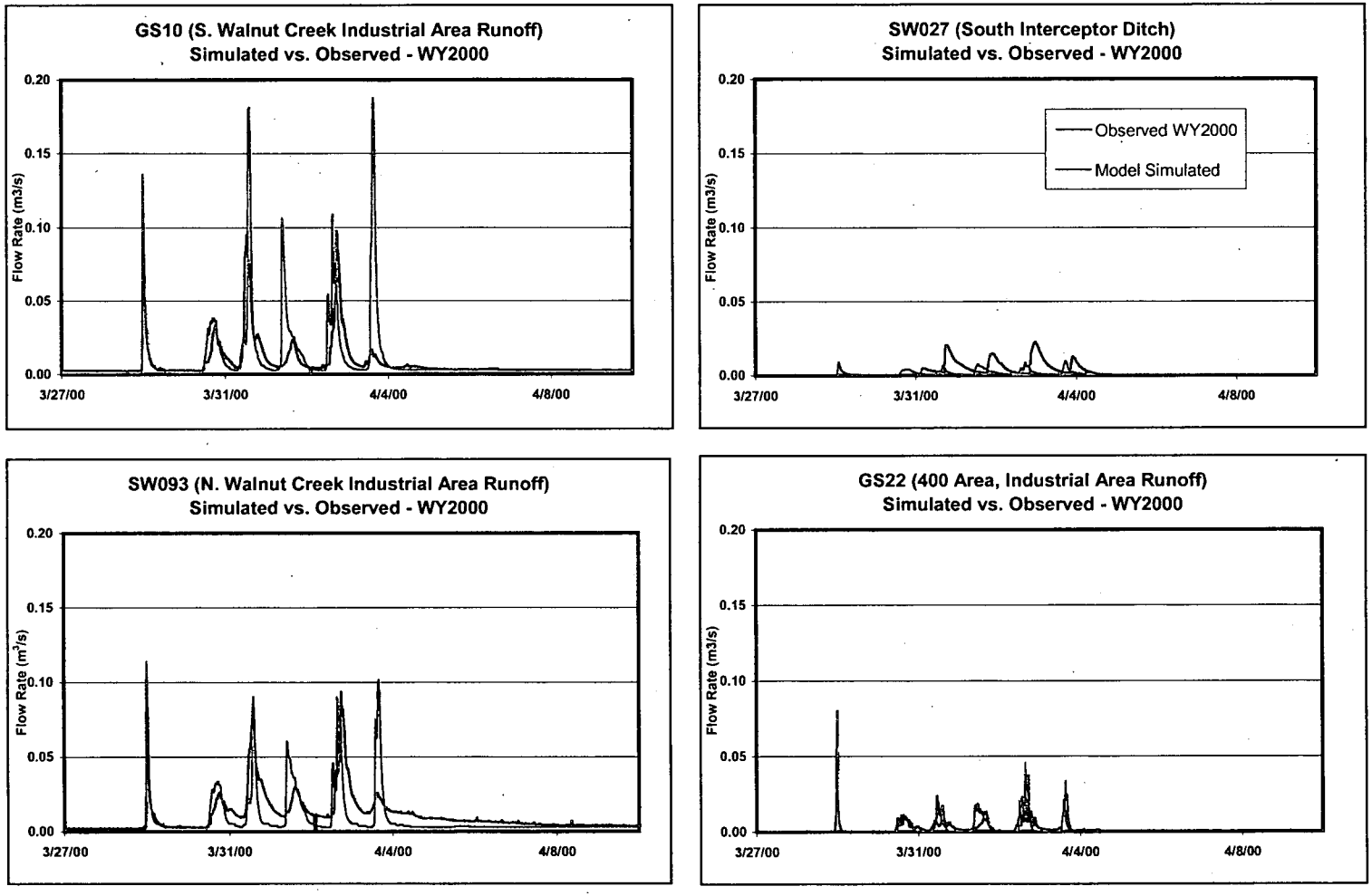
All axes on common vertical scales.

Figure E-13. Simulated and Observed Moderate Precipitation Events at SW093, GS10, GS22, and SW027 (WY2000)



All axes on common vertical scales.

Figure E-14. Simulated and Observed Snowmelt Event at SW093, GS10, GS22, and SW027 (WY2000)



All axes on common vertical scales.

Figure E-15. WY2000 Observed and Simulated Pond Level for Pond C-2

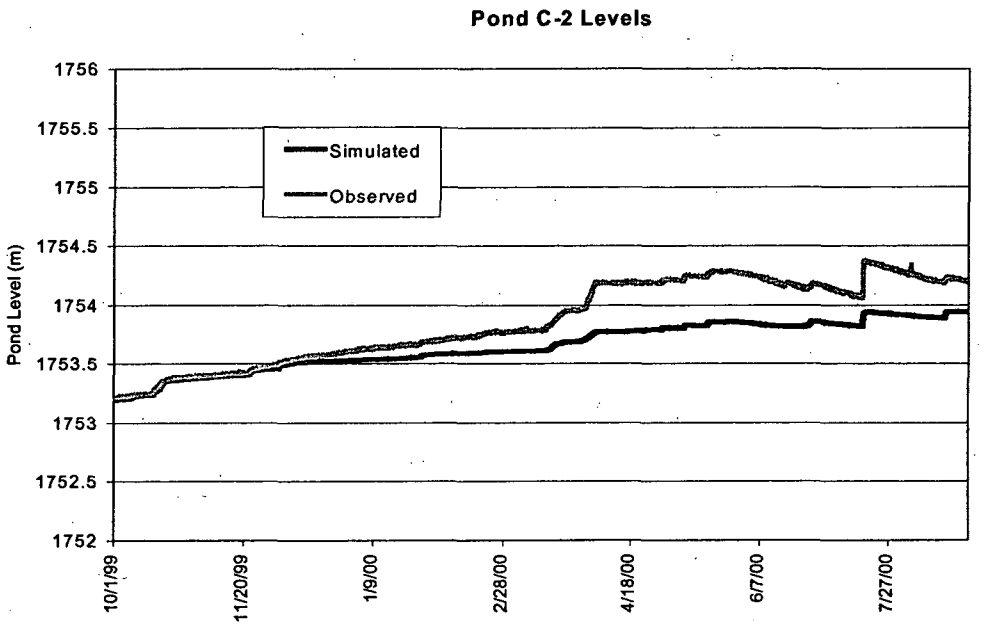


Figure E-16. WY2000 Observed and Simulated Pond Level for Pond B-5

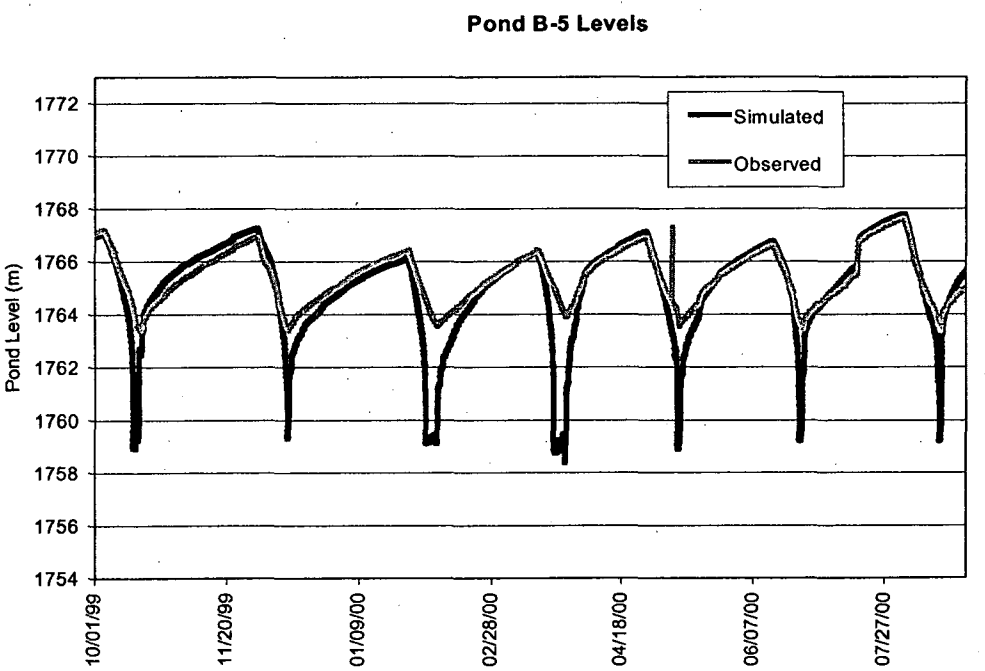
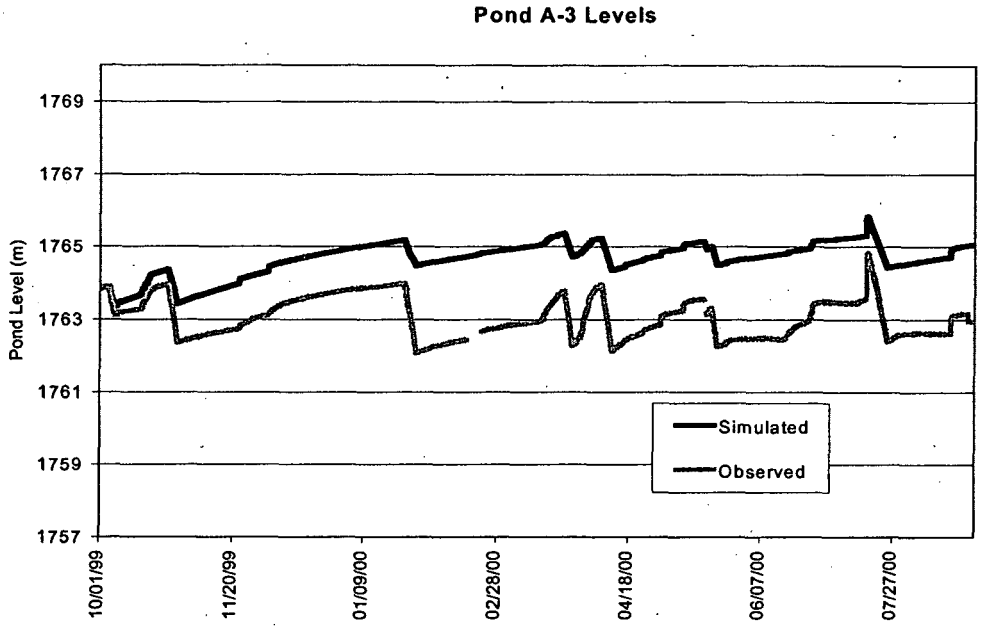


Figure E-17. WY2000 Observed and Simulated Pond Level for Pond A-3



E.1.2.3 Supplementary Discussion of Surface Flow Calibration Uncertainty

There are a number of possible explanations for slight misrepresentation between the observed and simulated Industrial Area surface flows. First, there is uncertainty associated with input values of precipitation, the largest component of the water balance. Observations confirmed that precipitation varies dramatically across the Site. The applied distribution was limited by available data and represented certain assumptions about the system (as discussed in Section 5.1.2.1.1). These factors are likely to have affected the simulated response at each gage on an event-by-event basis.

Differences between observed and simulated results may also be attributed to assumptions made in designing the model. For example, the highly-intricate network of channels within the Industrial Area was simplified (though minimally) for model stability and efficiency. This could have required overland flow to travel further before reaching a channel, thereby giving more time for infiltration. Additionally, there may have been some averaging error associated with designation of impervious surface area cell types

(cells were designated as either impervious or not). For instance, no provisions were made for less infiltrative material such as packed dirt and gravel-covered surfaces.

Further, a 20 percent error was assumed for all observed cumulative volume estimates. This error is based on manufacturer-reported accuracy for the monitoring equipment (ISCO, 1996) and recommendation from the Site hydrologist responsible for estimation of missing data. Estimation was required to fill in data gaps when flume capacities were exceeded, equipment failed or freezing conditions produced questionable results.

In summary, these gages monitor the vast majority of water exiting the Industrial Area, and an excellent representation for a wide variety of flow conditions lend high confidence to model predictions.

E.2 VALIDATION

As discussed in the main report in Section 6, the model was validated (additional check of performance) against periods of record other than WY2000. Specifically, the model was applied to WY2001 and the large precipitation event (series of events) of 1995. The following sections detail the input, setup and results of these simulations.

E.2.1 Climate

For both the 2001 and 1995 validation models, metrology data were gathered for preparation of PET, precipitation and temperature input. For 1995, large gaps in the meteorological data set forced the simulation period to be limited to January 1 through June 1, 1995.

For WY2001, high quality, distributed precipitation data were available. Therefore, input series and spatial distributions for WY2001 were prepared like WY2000 (see Section 6 of the Main Report). For 1995, fewer precipitation gages were available, and data sets exhibited significant gaps, errors and inconsistencies. Consequently, precipitation data for 1995 were applied from a single heated rain gage (the Site Metrology (Met) Tower). This lack of spatial resolution for precipitation is expected to introduce some error in to the 1995 simulation.

Both WY2001 and the May, 1995 event represented very different precipitation conditions for the model, as compared to WY2000. The average precipitation for the Site is roughly 14.8 inches/year (376 mm) (from 35 years of record), with a standard deviation of ~4 inches/year (102 mm). WY2000 was on the dry side with 13.8 inches (351 mm) of precipitation (Site Met Tower Record). WY2001 was on the wetter side, with 15.6 inches (396 mm) of precipitation measured at the Site Met Tower. The Spring of 1995 was extremely wet, with 13.1 inches (333 mm) of precipitation recorded at the Met Tower between January 1, and June 1, 1995 (12.1 inches (307 mm) fell in April, and May, 1995). The 1995 event of May 17 corresponded to roughly a 15-year precipitation event at the Site (EG&G, 1992a).

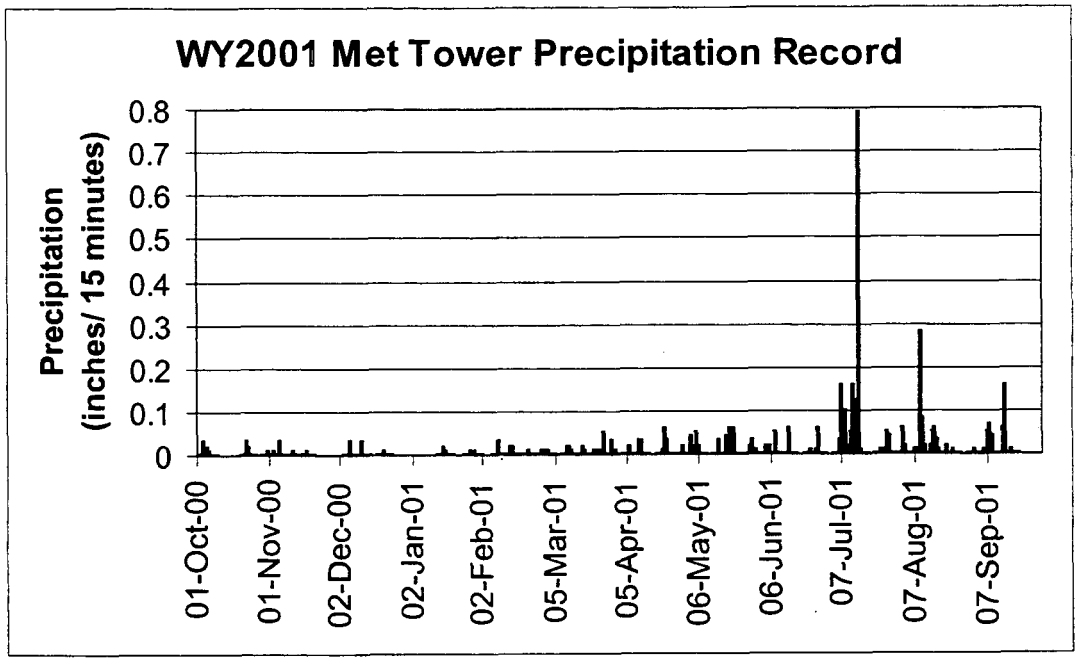
Though the precipitation records for both validation models showed relatively high total amounts, the precipitation intensities were very different. In WY2001, there were several intense events, with a maximum intensity of 0.8 inches (20 mm) in 15 minutes recorded in July 2001 at the Met Tower. The maximum intensity recorded in 1995 was 0.21 inches (5 mm) in 15 minutes, with most readings during April and May below 0.05 inches in 15 minutes. 15-minute precipitation records for WY2001 and 1995 (January through May) are presented below in Figure E-18. For comparison, both periods of record are presented on the same scale.

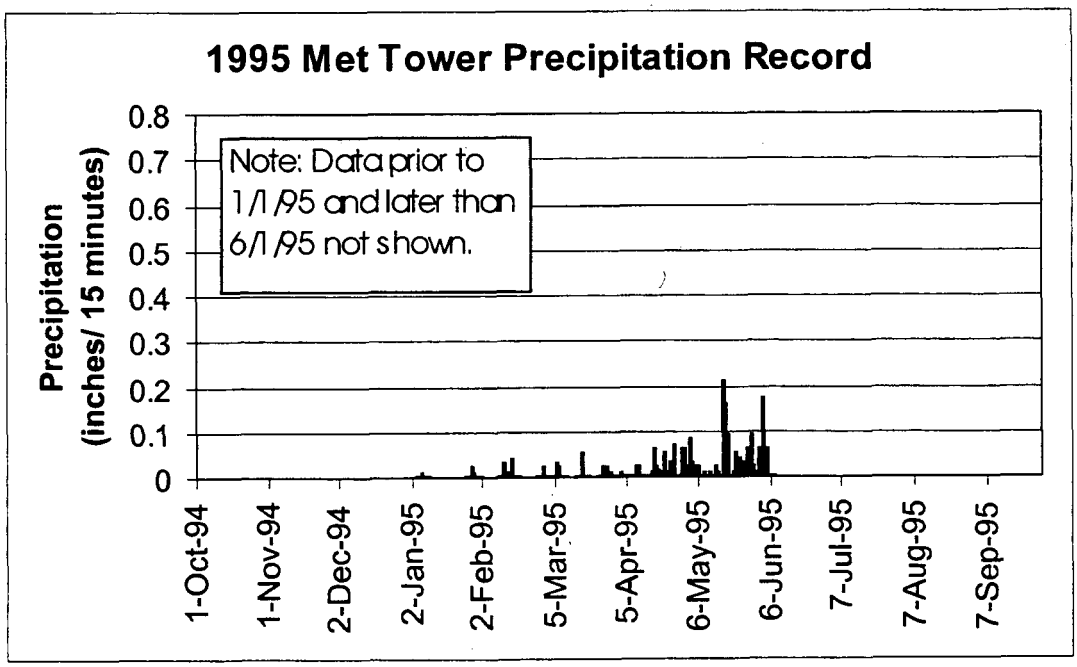
E.2.2 Initial Conditions

In the surface system, initial pond levels were set according to Site records for October, 2000 and January, 1995. Likewise, surface-water inflow boundary conditions were set according to observed record.

Initial conditions for the subsurface were also set. For WY2001, the initial conditions were simply set to match the simulation results at the end of WY2000 by "hotstarting". Hotstarting is defined as initiating a model run by applying the simulated conditions of aprevious model run as the initial conditions of the current run. Setting initial conditions for the 1995 simulation was more challenging than simply hotstarting, as was done for WY2001.

Figure E-18. Met Tower Precipitation Record for WY2001 and 1995 (January through May)





To begin, because of the short 1995 simulation period (as limited by available climatic information), a hotstart was necessary for the unsaturated zone. (If the model is not hotstarted, initial groundwater heads may be set; however, the unsaturated zone is automatically set at field capacity. This setting corresponds to very wet conditions and may erroneously influence the system response for the April/May event.) To create a hotstart, the WY1995 model was run applying WY2000 climate between October, 1999 and January, 2000. The WY1995 model was hotstarted from this run in January, 2000.

The inherent assumption in this approach is that groundwater and unsaturated zone conditions in January, 1995 were similar to those of January, 2000. Though there is likely some error associated with this, it is a reasonable assumption. As discussed in Chapter 3 and Appendix B (Conceptual Model), groundwater levels are fairly consistent from year to year, barring large events such as that of the Spring, 1995. The unsaturated zone moisture conditions may be more dependant on recent precipitation record; however, the hotstart condition should be reasonable and should largely adjust to 1995 precipitation record in the three months before April.

It should also be noted that the inflow data set for the 1995 model was not complete. First, there was no record of surface flow for McKay Ditch (which flowed to GS03 in 1995). McKay Ditch was observed to carry significant amounts of water during the May event (Hoffman, 2002). Second, Smart Ditch was observed to overflow its diversion structure south of the model boundary and flow to GS01 (Hoffman, 2001). Without a good basis for estimation of these inflows, they were left out of the 1995 simulation, recognizing the likely result of underestimation of flow at GS03 and GS01.

E.2.2.1 Model Modifications

Both the WY2001 and the 1995 validation simulations required structural modification of the WY2000 model. WY2001 modifications were minor, while 1995 modifications were significant. The modifications made to prepare each model are listed below in Table E-1.

Table E-1. Validation Model Modifications to WY2000 Model

Model	Modification from WY2000 Model
WY2001 Validation Model	• Apply WY2001 pond transfer records and discharges as boundary conditions
	• Reroute 881 Hillside french drain to the SID (system changed at end of WY2000)
1995 Validation Model	• Apply 1995 pond transfer records and discharges as boundary conditions*
	• Reroute Woman Creek to connect to Mower Ditch
	• Remove East Trenches, Mound and Solar Ponds Plume treatment systems
	• Reroute McKay Ditch to flow to GS03 (remove bypass pipeline)
	• Add overflow restrictions to A-1 and B-1 bypass pipelines.
	• Add control structure to route flow through Central Avenue Ditch Optional Routing channel
	• Reroute Pond C-2 discharge to off-Site pipeline

* Pond transfer and discharge records were applied; however, errors, estimates and omissions were identified.

E.2.3 Model Performance

The validation models were assessed based on available observed data. For WY2001, observed data sets similar to those for WY2000 were available. This includes 15-minute flow record and surface water gages and quarterly groundwater level measurement at wells across the Site.

For the 1995 validation model, comparison data were much more limited. 15-minute surface flow record was available for GS10, SW093 and SW027; however, the records included significant periods of estimated data for peak flows. These peak flows greatly exceeded measurement capacities of the flumes, and estimates in the record were expected to have large uncertainties. For the fenceline surface gages, GS01, GS02 and

GS03, only mean daily flow rates were recorded. These values also include estimates for the high flow periods. (Note: surface gage GS02 is considered in the 1995 validation simulation because at that time, much of the water from Woman Creek was through Mower Ditch, leading to GS02. The routing was changed in April 1997 to direct all flows to GS01. No water flowed at GS02 during WY2000 or WY2001.)

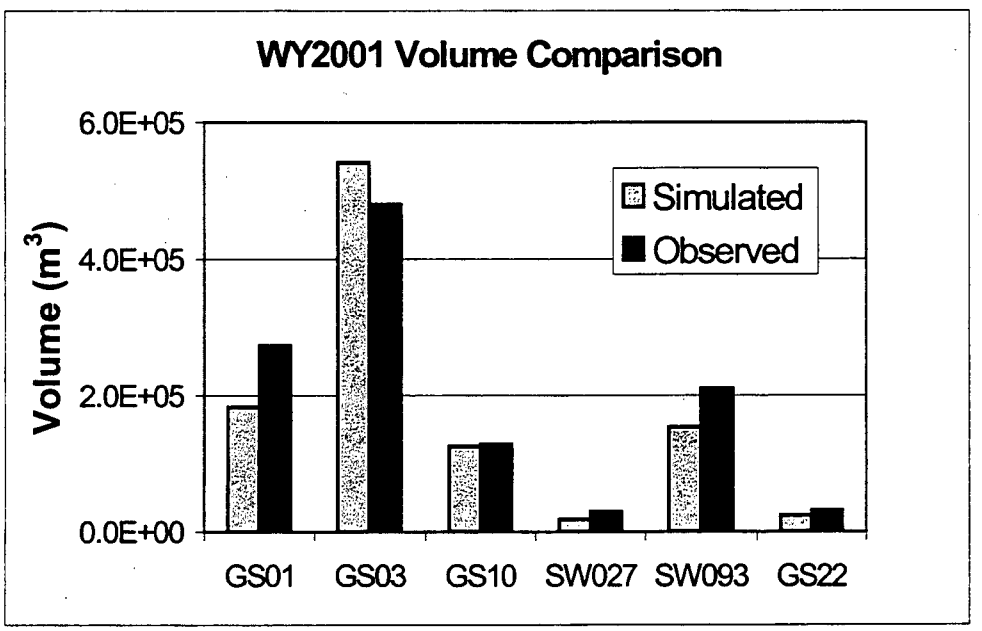
E.2.3.1 WY2001 Simulation Performance

In general, the WY2001 model performed well when compared with available data. Channel flow and groundwater levels are discussed below.

E.2.3.1.1 Channel Flow

Channel flow was assessed relative to the observed record for volume and flow rate at GS01, GS03, GS10, GS22, SW027 and SW093. Volume comparisons for WY2001 are summarized below in Figure E-19.

Figure E-19. Comparison of Observed and Simulated Surface Flow Volumes for WY2001



Annual matches are good, with a greatly improved annual match volume at GS03, despite a slightly worse match at SW093 relative to WY2000.

The hydrographs generated by the WY2001 validation model were also compared to observed records at 15-minute intervals. Individual events matches were good as observed for WY2000. The annual hydrograph for GS01, GS03, GS10, GS22, SW027 and SW093 are presented spatially in Figure E-20.

In general, these matches are as good or better than those observed for WY2000. These results provide additional confidence in the prediction capability of the model.

E:2.3.1.2 Groundwater

Simulation results for groundwater were compared to observation date for four quarters of record:

- January, 2001;
- April, 2001;
- July, 2001; and
- October, 2001.

These comparisons are presented in Figure E-21. Differences in observed and simulated heads are only presented for cells where groundwater measurements were available. Positive values indicated over-simulation of groundwater levels, and negative values indicated under-simulation of groundwater levels.

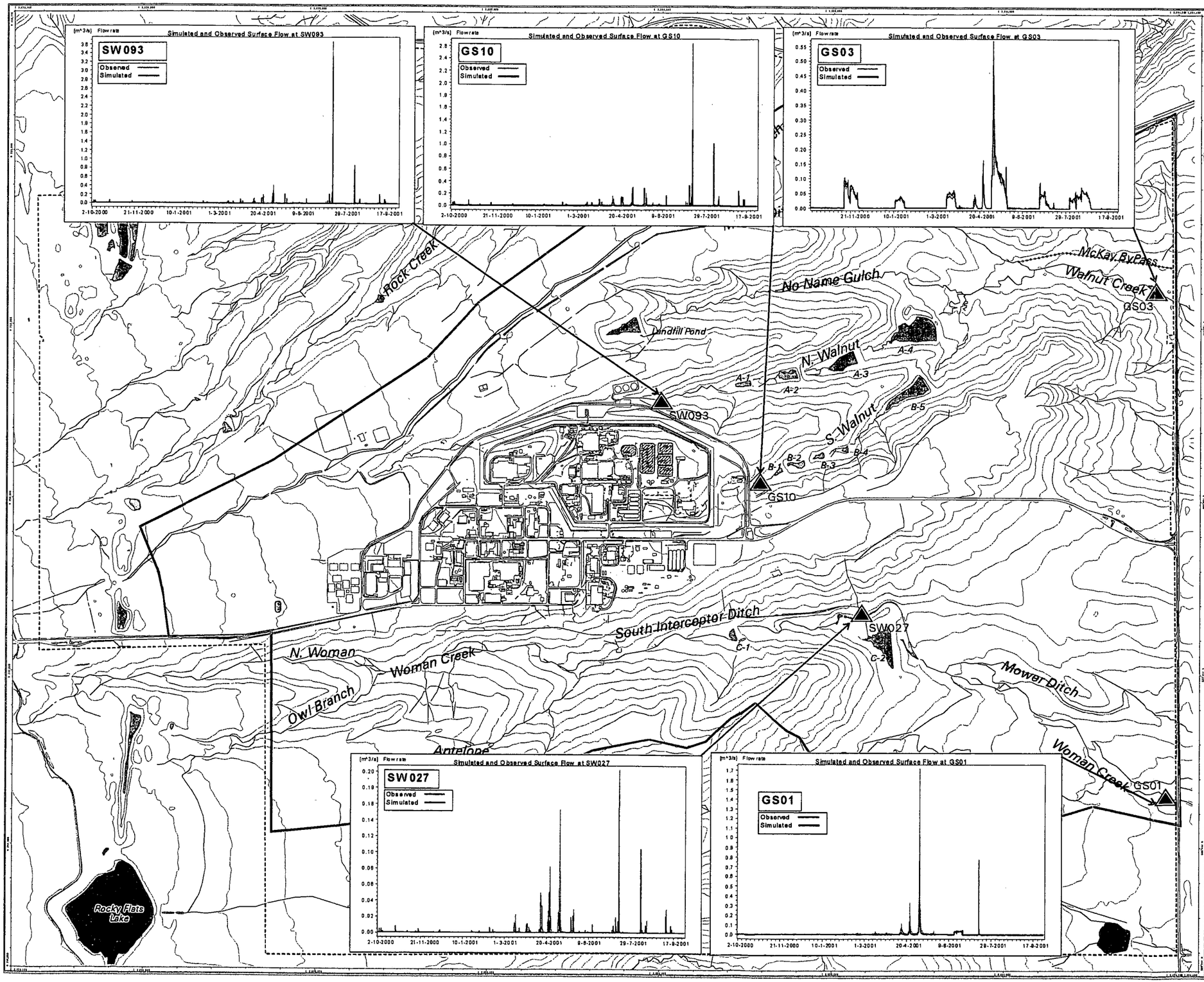


Figure E-20

Site-Wide Water Balance Report

Observed and Simulated Hydrographs for 2001 Validation Model

EXPLANATION

- Gaging Station

Standard Map Features

- Buildings and other structures
- Paved roads fill
- Solar Evaporation Ponds (SEPs)
- Lakes and ponds
- Streams, ditches, or other drainage features
- Topographic Contour (20-Foot)
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95 Topographic contours were derived from digital elevation model (DEM) data by Morrison Knudson (MK) using ESRI Arc TIN and LATTICE to process the DEM data to create 5-foot contours. The DEM data was captured by the Remote Sensing Lab, Las Vegas, NV, 1994 Aerial Flyover at ~ 10 meter resolution. DEM post-processing performed by MK, Winter 1997.

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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Rocky Flats Environmental Technology Site

GIS Dept. 303-966-7707

Prepared by: DynCorp — THE ART OF TECHNOLOGY

Prepared for: KAISER-HILL COMPANY

May 14, 2003

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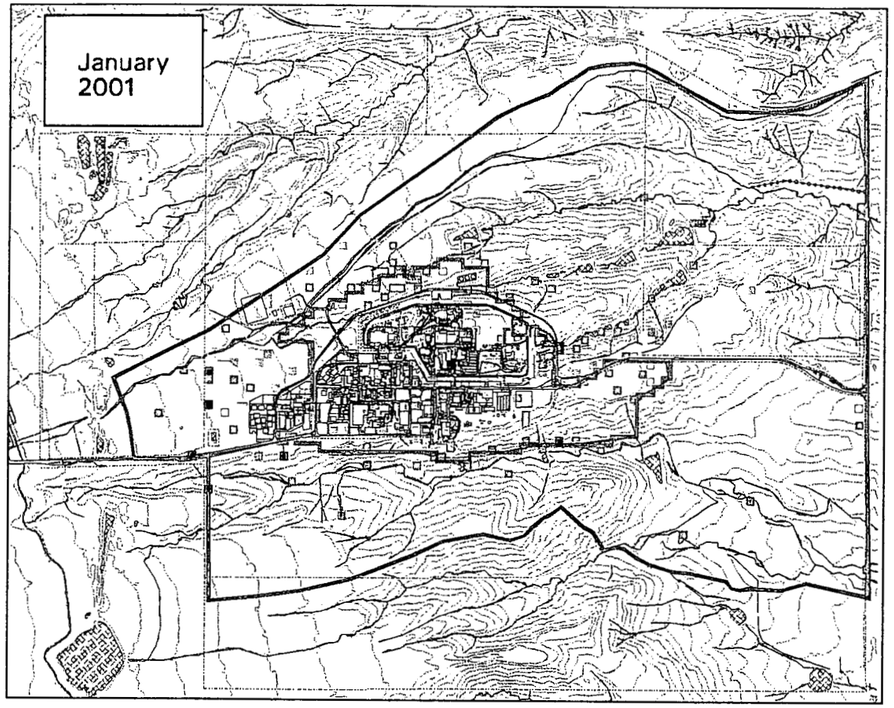

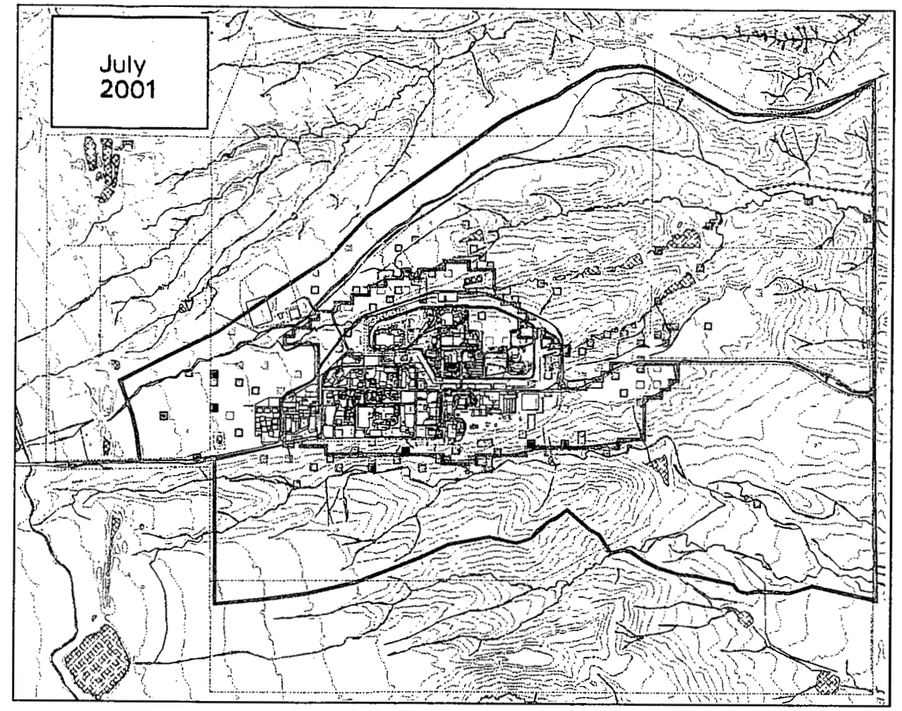

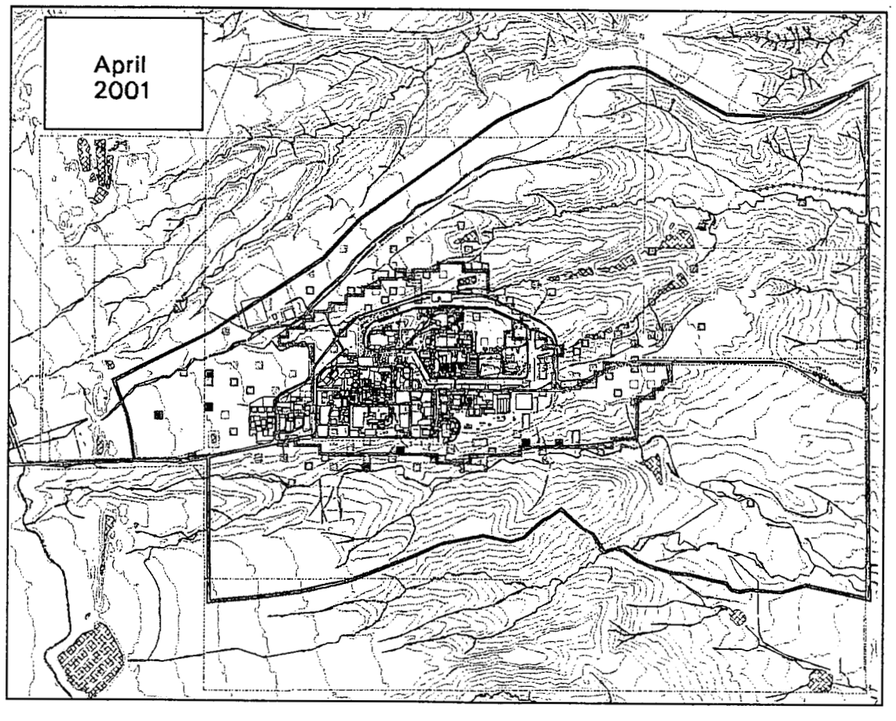

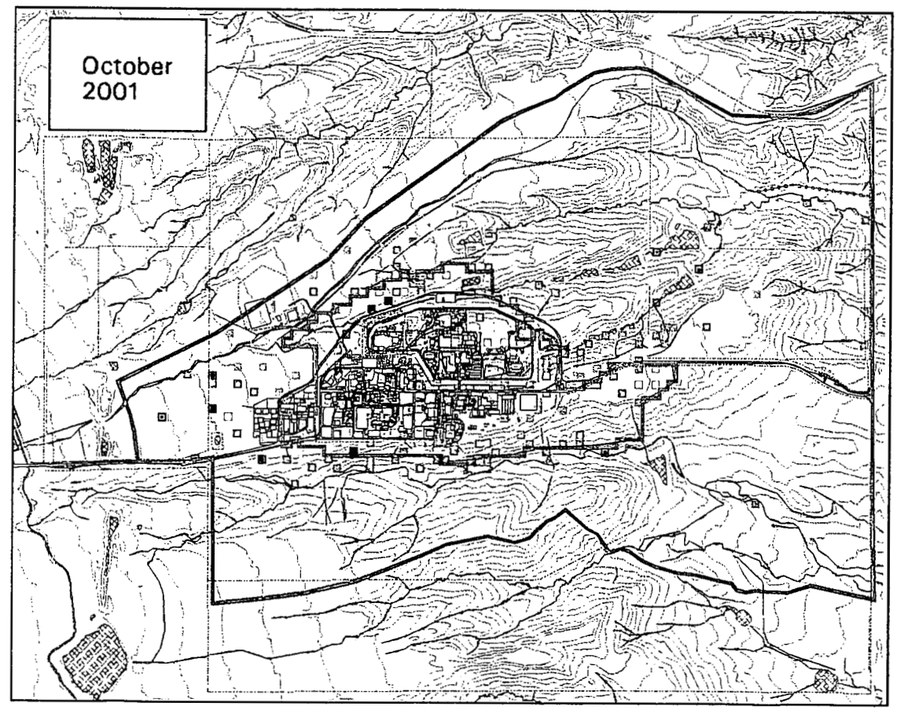

Figure E-21

Site-Wide Water Balance Report

Groundwater Head Residuals

(WY 2001)

EXPLANATION

Groundwater Head Residuals (m)

- Less than -5
- -5 to -2
- -2 to -1
- -1 to 1
- 1 to 2
- 2 to 5
- Greater than 5

Other Features

- Model IA Catchment Boundary

Standard Map Features

- Buildings and other structures
- Lakes and ponds
- Streams, ditches, or other drainage features
- Fences and other barriers
- Topographic Contour (20-Foot)
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/25 topographic contours were derived from digital elevation model (DEM) data by Morrison Knudson (MK) using ESRI Arc TIN and LAI ICE to process the DEM data to create 5-foot contours. The DEM data was captured by the Remote Sensing Lab, Las Vegas, NV, 1994 Aerial Flyover at ~ 10 meter resolution. DEM post-processing performed by MK, Winter 1997.

NOTES:

Positive groundwater residuals denote simulated heads greater than observed.

Negative groundwater residuals denote simulated heads less than observed.

200 0 400 800m

500 0 1000 2000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

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Prepared by: KAISER-HILL COMPANY

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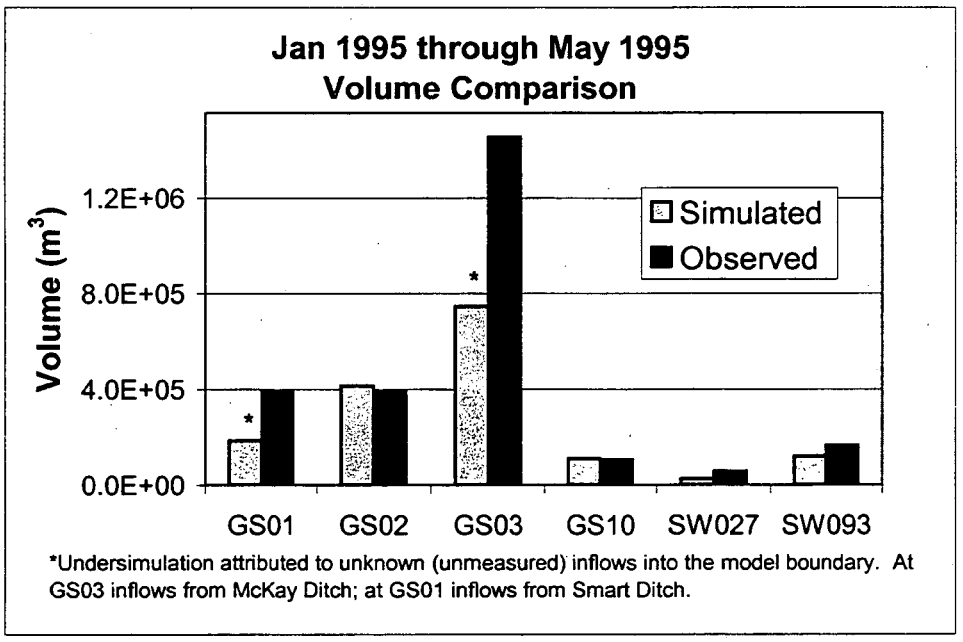
E.2.3.2 1995 Simulation Performance

In general, the 1995 simulation performed well when compared with available data. Channel flow and groundwater levels are discussed below.

E.2.3.2.1 Channel Flow

Channel flow was assessed relative to the observed record for volume and flow rate at GS01, GS02, GS03, GS10, SW027 and SW093. Volume comparisons for January through May, 1995 are summarized below on Figure E-22. (Note: surface gage GS02 is considered in the 1995 validation simulation because at that time, much of the water from Woman Creek was directed through Mower Ditch, leading to GS02. The routing was changed in April 1997 to direct all flows to GS01. No water flowed at GS02 during WY2000 or WY2001.)

Figure E-22. Comparison of Observed and Simulated Surface Flow Volumes for January, through May, 1995



(Note: surface gage GS02 is considered in the 1995 validation simulation because at that time, much of the water from Woman Creek was directed through Mower Ditch, leading to GS02. The routing was changed in April, 1997 to direct all flows to GS01. No water flowed at GS02 during WY2000 or WY2001.)

This figure shows reasonable matches for all gages except GS01 and GS03. The simulated underestimation of volume at GS01 and GS03 was expected based on necessary exclusion of the unknown inflows destined for these gages.

Dynamic matches for the same six gages are presented spatially in Figure E-23. In this figure, mean daily flow rates from the observed record are compared to 15-minute simulation output for the fenceline gages, GS01, GS02 and GS03. For the Industrial Area subdrainages of GS10, SW027 and SW093, both observed and simulated data are presented at 15-minute intervals.

Despite underestimation at gages GS01 and GS03, due to unknown inflows, the results compared well. The good match at the only fenceline gage not missing inflow data (GS02) offered confidence in the Buffer Zone estimates. The Industrial Area surface flow estimates also matched well.

E.2.3.2.2 Groundwater

Due to the limited simulation period (as limited by the available climate data), quarterly groundwater measurements could not be compared to the simulated results. Quarterly data were available for April 1, and July 1, 1995. Because the high precipitation period occurred between April and May, and the simulation ended June 1, the response could not be compared. Comparisons for January 1, and April 1, 1995 showed good matches in near-stream areas.

A comparison of simulated and observed activated seeps was performed. The record of activated seeps was developed by interviews with Site personnel who observed the 1995 event (Murdock, 2002). The following seep locations were observed in 1995 and simulated by the model:

- Landfill area seep;
- Owl Branch seep (East of Owl Branch and South of Woman Creek);

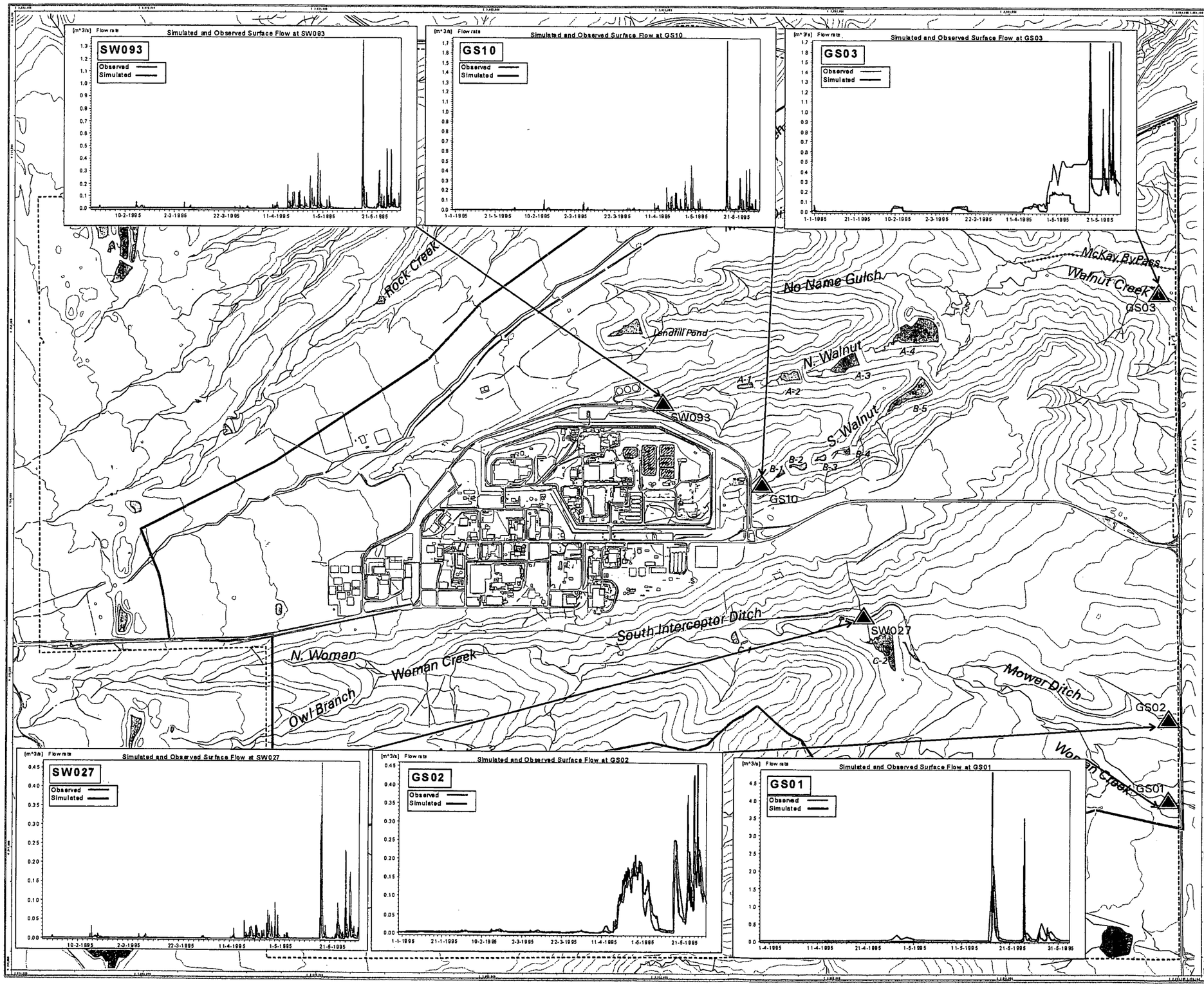


Figure E-23

Site-Wide Water Balance Report

Observed and Simulated Hydrographs for WY1995 Validation Model

EXPLANATION

- Gaging Station

Standard Map Features

- Buildings and other structures
- Paved roads fill
- Solar Evaporation Ponds (SEPs)
- Lakes and ponds
- Streams, ditches, or other drainage features
- Topographic Contour (20-Foot)
- Rocky Flats boundary
- Paved roads
- Underground Pipeline
- SWWB Model Boundary

DATA SOURCE BASE FEATURES:

Buildings, fences, hydrography, roads and other structures from 1994 aerial fly-over data captured by EG&G RSL, Las Vegas. Digitized from the orthophotographs. 1/95 Topographic contours were derived from digital elevation model (DEM) data by Morrison Knudson (MK) using ESRI Arc TIN and LATTICE to process the DEM data to create 5-foot contours. The DEM data was captured by the Remote Sensing Lab, Las Vegas, NV, 1994 Aerial Flyover at ~ 10 meter resolution. DEM post-processing performed by MK, Winter 1997.

NOTES:

1. GS01, GS02, GS03 observed data only available as mean daily flow rates.
2. All gage capacities exceeded during peak flows except SW027.

50 0 100 200m

250 0 500 1000ft

State Plane Coordinate Projection
Colorado Central Zone
Datum: NAD27

U.S. Department of Energy
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GIS Dept. 303-966-7707

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Prepared for: KAISER-HILL

May 14, 2002

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- Antelope Springs;
- Seeps south of Pond C-1;
- Seeps south of Pond B-5; and
- Widespread saturation along low-lying areas on the eastern portion of the Buffer Zone.

Among these seeps, only Antelope Springs is typically active. The model did not simulate seep flow along the north side of the SID (some local seep areas were observed to flow). Saturated hydraulic conductivities were increased in this area to reduce simulated baseflow contributions to the SID (extending down to Woman Creek), however, the local scale nature of flow associated with these seeps could not be incorporated into the SWWB grid. These seeps only flow during a short period of the year and produce insignificant flows compared to the total water balance within the SW027 catchment.

E.3 SENSITIVITY ANALYSIS

E.3.1 Introduction

A sensitivity analysis was conducted for the calibrated RFETS SWWB model. The purpose of traditional sensitivity analysis is to identify the model parameters which most affect hydrologic system response. Identifying the key parameters was used to confirm the focus of the calibration, derive useful information on how the integrated processes affect each another and provide the parameters which were essential to the uncertainty of model predictions. The sensitivity analysis should be seen in the context of the specific use of the SWWB model in simulating hydrological response to configuration scenarios for Site closure. Given the type of scenarios potentially simulated by the model particular emphasis has been put on the modification of the Industrial Area from its present conditions. The hypothetical modeling scenarios simulated conditions closer to the "natural" hydrological characteristics of the surrounding Buffer Zone. Consequently

the sensitivities are evaluated based on the defined primary "decision" points of the stream network, the ponds and the subsurface regime.

Uncertainty assessment was guided by the findings of the sensitivity analysis. The uncertainty assessment quantified the uncertainty in the model outputs from uncertain model parameters. The parameters identified as the most sensitive during the sensitivity analysis were used in the uncertainty assessment along with input data.

The model sensitivity simulations were conducted by introducing a perturbation of the model parameters/inputs. Some parameters may be correlated (covariance); for the purpose of identifying the most significant parameters it is assumed they can be treated independently. This was a post-calibration exercise, intended only to assess sensitivity and to facilitate the uncertainty analysis (as opposed to furthering calibration). A single model parameter was adjusted in each of the eight sensitivity model runs.

E.3.2 Key Model Outputs

The primary purpose of the RFETS SWWB model was to calibrate input parameters using current conditions so that the model could then be used to assess hydrologic impacts of the hypothetical Site reconfiguration scenarios. In the hypothetical Land Configuration Scenario simulated, most changes to the Site were made in the Industrial Area, the Present Landfill and the Original Landfill areas. These changes primarily affected only the local and downstream hydrology. As a result, several key areas were identified where more important management decisions will be made, or where system hydrology will change most. Several types of model output within each of these areas were assessed. These are described below.

E.3.2.1 Surface Water Discharges

Surface water discharge locations are shown on Figure 2-1. The discharges at GS01 and GS03 represent the total runoff from the Site. The GS03 discharge is dominated by controlled pond releases, which are specified as a fixed boundary time series in the model. The GS01 sub-basin mainly comprises the southern part of Buffer Zone.

Secondly, the GS10, SW093 and SW027 gages receive runoff from the Industrial Area and are also represent key points of evaluation. The streamflows were simulated in time steps on the order of seconds; but in water balance context, accumulated yearly, seasonally and monthly runoff was more appropriate. The discharges at each of the five gaging stations were processed to provide monthly and yearly runoff volumes. The simulated change in runoff (m^3) was calculated by subtracting simulated runoff in the reference run.

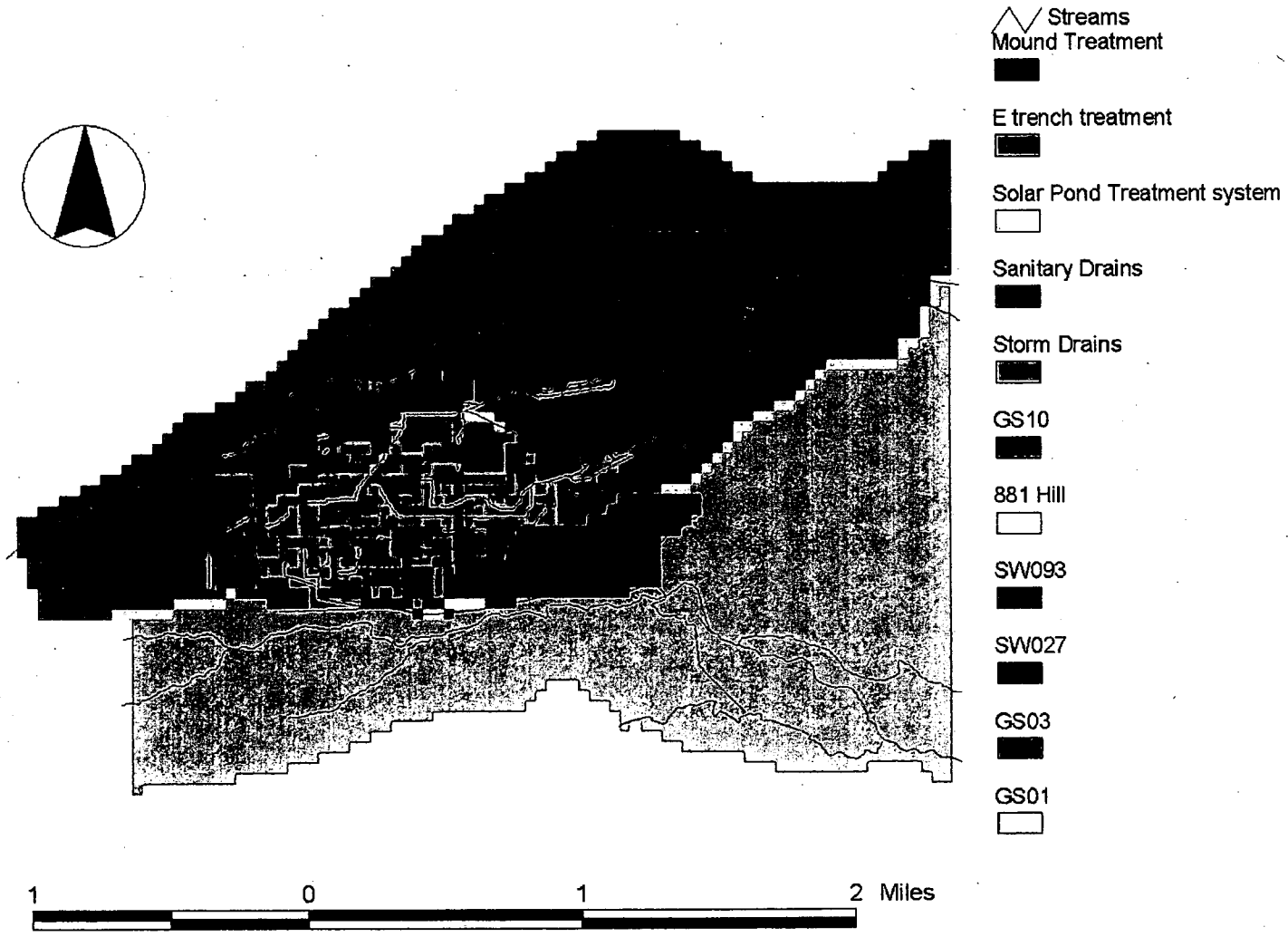
E.3.2.2 Water Balance

Figure E-24 shows several sub-catchments considered for water balance sensitivities. The model simulates a number of water balance variables. Key variables were selected for evaluating sensitivity, including: (1) rainfall; (2) ET losses; (3) subsurface storage change; (4) subsurface flow across boundaries; (5) drain flow; (6) overland flow; and (7) baseflow to the stream network. The sub-areas considered in the water balance outputs are the entire RFETS, GS01, GS03, GS10, SW093, SW027, Mound Plume Remediation System, Solar Ponds Plume Remediation system, Industrial Area storm drain cells, Industrial Area sanitary drain cells, East Trenches Plume Remediation system and 881-Hillside French Drain.

E.3.2.3 Pond Levels

The parameter sensitivity is quantified with respect to water levels in the Site ponds. The A-3, A-4, B-3, B-5 and C-2 ponds were considered. Water depths were compared at the end of each month in the simulation period, October, 1999 through October, 2000. The change in water levels was calculated relative to the maximum pond water depth.

Figure E-24. Areas for water balance outputs



E.3.2.4 Groundwater Levels

Groundwater levels were used in assessing parameter sensitivity. A number of focus areas and representative Site areas were selected for evaluation of the groundwater response to parameter changes (See Figure E-25). The groundwater flow and groundwater levels of the northern Industrial Area (IA North) and the southern Industrial Area (IA South) were strongly controlled by the subsurface drain and pipe systems and behaved differently than the remaining model area. Mesa East and Mesa North represent the higher elevations of the Site with very flat surfaces and bedrock. Hillside areas (881-Hillside French Drain and Solar Ponds System) were selected in order to quantify effects on the sloping terrain connecting the upper mesas to the near-stream zones. Finally, GS01 and GS03 near-stream zones situated at the far downstream end of the Woman Creek and Walnut Creek were selected. These were chosen to indicate the groundwater response where the stream water levels had a pronounced effect on the groundwater dynamics. The two areas were also influenced by the neighboring groundwater levels at the downstream groundwater boundary.

E.3.3 Selection of Model Parameters

Only the eight most sensitive system parameters were included in the sensitivity analysis. These were determined through model calibration and the conceptual understanding of Site hydrology. Specific parameters considered for sensitivity analysis are summarized in Table E-2 below. The change to each parameter specified in the model was based on the range observed in available data, where possible. For some parameters, like the Crop Coefficient (Kc), available data were limited, and values were estimated from available literature.

Figure E-25. Areas for groundwater level output

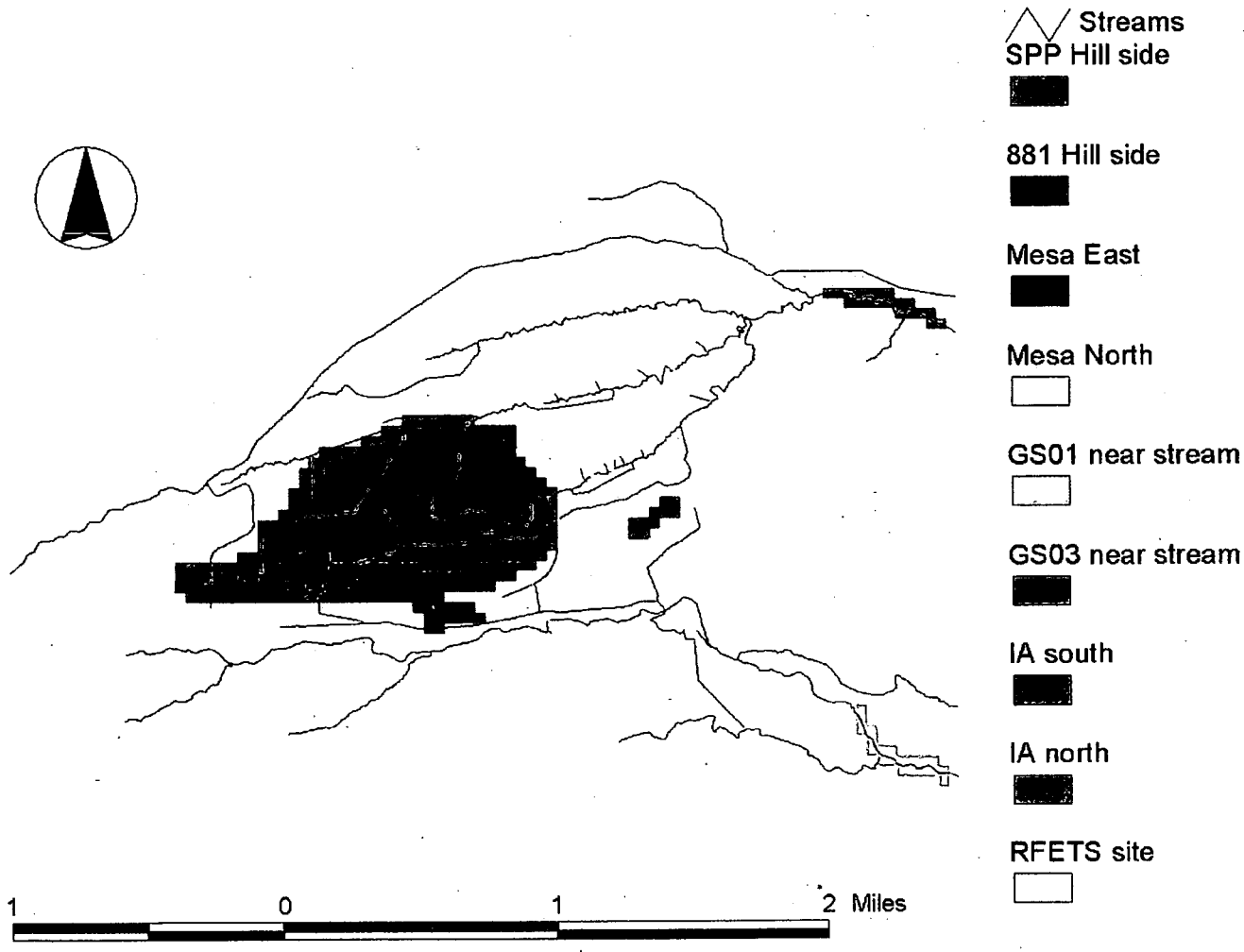


Table E-2. List of Sensitivity Model Runs

Sensitivity Run	Model Component	Model Parameter	Proposed Change
1	Saturated Zone	K_{xx}, K_{yy}, K_{zz}, Hydraulic Conductivity	Multiply by factor 10 globally in all layers
2	Unsaturated Zone	K_{sat}, Saturated Hydraulic Conductivity	Multiplied by factor 5 for all soils
3	Unsaturated Zone	UZ Retention Curve	Use retention curve of one soil all over the model area (#Qrf58)
4	Unsaturated Zone	N exponent of hydraulic conductivity curve	N increased by 50 percent for all soils
5	ET	LAI, Leaf Area Index	LAI decrease by 50 percent for all veg. types
6	ET	RDF, Root Depth Function	RDF decrease by 50 percent for all veg. types
7	ET	Kc, Crop Coefficient	Kc decrease by 50 percent for all veg. types
8	Streamflow (MIKE 11)	L, Leakance Coefficient	Multiply by factor 10 for all stream branches including retention ponds

E.3.4 Model Performance

A summary of the results of the sensitivity analysis is presented in Table E-3. Results are presented in terms of high (H), moderate (M) and low (L) sensitivity by area of interest for each parameter.

Table E-3. Summary of Model Parameter Sensitivity

Model Processes	SZ*	UZ*			ET*			OC*
Model Parameters	K_h	K_{sat}	Ret.[1]	N[2]	LAI	RDF	Kc	L
FOCUS AREAS								
Streamflow:								
GS01	H	L	L	L	L	L	M	M
GS03	M	L	L	L	L	L	M	M
GS10	M	L	L	L	L	L	M	M
SW093	H	L	L	L	L	L	M	H
SW027	H	H	M	M	L	L	H	H
Water balance:								
Total site	H	L	L	L	L	L	M	M
GS01	M	L	L	L	L	L	M	M
GS03	H	L	L	L	L	L	H	H
GS10	M	L	L	L	L	L	M	H
SW093	H	M	L	L	L	L	M	M
SW027	H	M	M	M	M	L	M	H
Mound System	H	M	M	M	M	L	M	H
Solar Ponds System	M	M	M	M	M	M	M	L
IA storm drain cells	H	M	L	M	M	L	L	M
IA sanitary drain cells	H	M	L	L	L	L	L	H
IA footing drain cells	H	L	L	L	L	L	M	H
East Trenches System	H	H	M	H	M	M	M	L
881-Hillside French Drain	M	M	M	L	M	L	M	H
Groundwater level:								
Industrial Area (north)	M	L	L	L	L	L	L	L
Industrial Area (south)	H	L	L	L	L	L	L	L
Mesa East	L	L	L	L	L	L	L	L
Mesa North	H	M	L	L	L	L	M	L
881-Hillside French Drain	H	L	L	M	L	L	M	L
Hillside SPP	M	L	L	L	L	L	L	L
GS01 (near-stream)	M	L	M	M	L	L	M	L

GS03 (near-stream)	M	L	M	H	L	L	H	H
Pond water depth:								
A-3	H	M	M	M	M	L	H	H
A-4	H	L	L	L	L	L	L	L
B-3	H	L	L	L	L	L	L	L
B-5	H	H	H	M	L	M	M	L
C-2	M	M	M	M	L	L	M	H

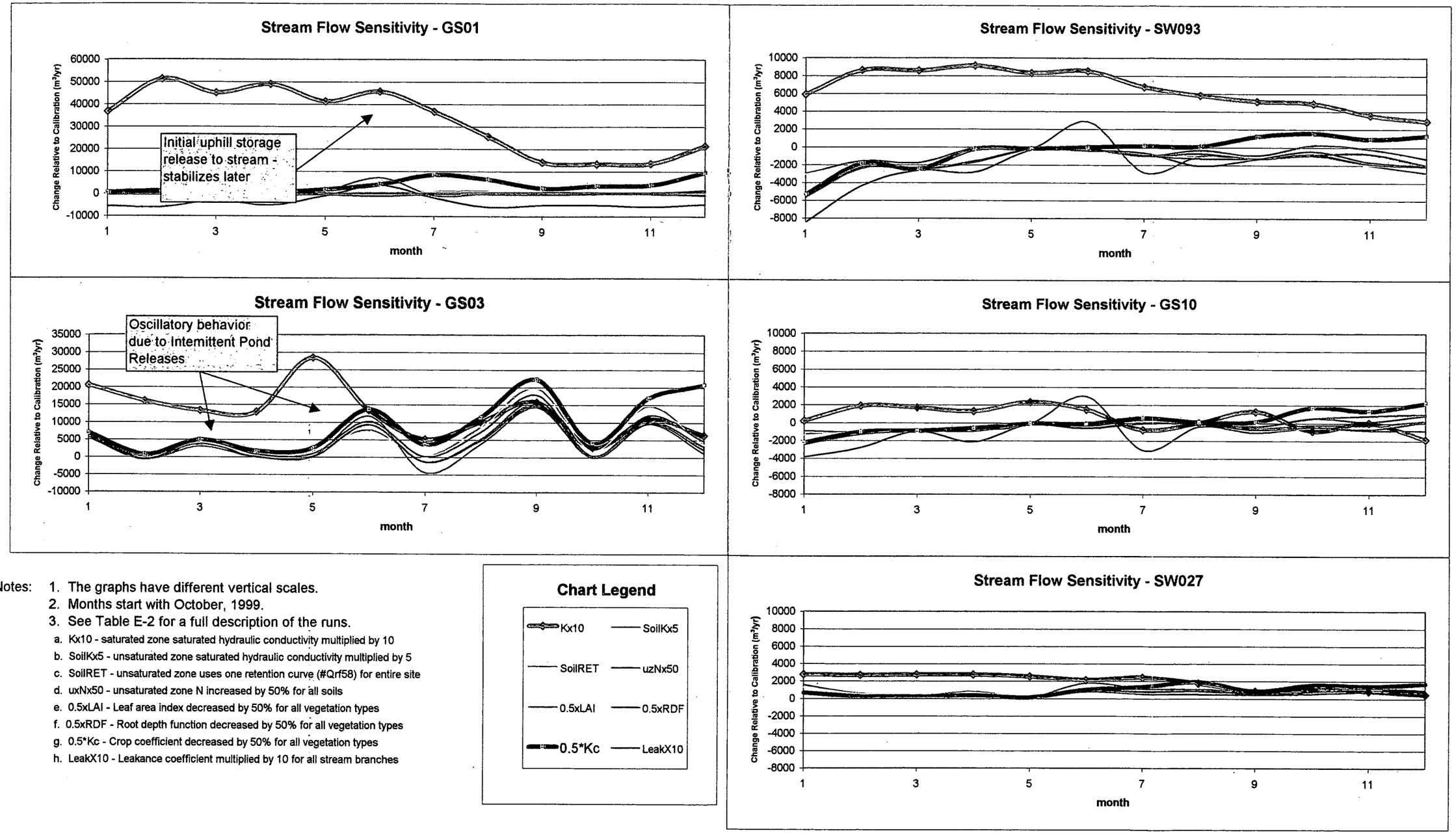
H : High sensitivity, M: medium sensitivity, L: Low sensitivity
*SZ – Saturated Zone, UZ – Unsaturated Zone, ET – Evapotranspiration, OC – Overland/Channel flow (L refers to channel leakance)
[1]soil moisture retention function
[2]n refers to the exponent in the hydrualic conductivity equation.

Results from the three most sensitive model parameters are discussed below, but all results are shown graphically on Figure E-26 through Figure E-29. These include: (1) saturated hydraulic conductivity; (2) LAI; and (3) unsaturated zone hydraulic conductivity. The last parameter, LAI, in many cases affects system hydrology less than the Kc. However, the 50 percent reduction in Kc was considered much more empirical (less physically meaningful) than the same reduction in LAI. Because both LAI and Kc affected the system hydrology in a similar fashion, the LAI was selected as one of the key sensitivity parameters that was used in the uncertainty analysis.

E.3.4.1 Saturated Hydraulic Conductivity – Saturated Zone

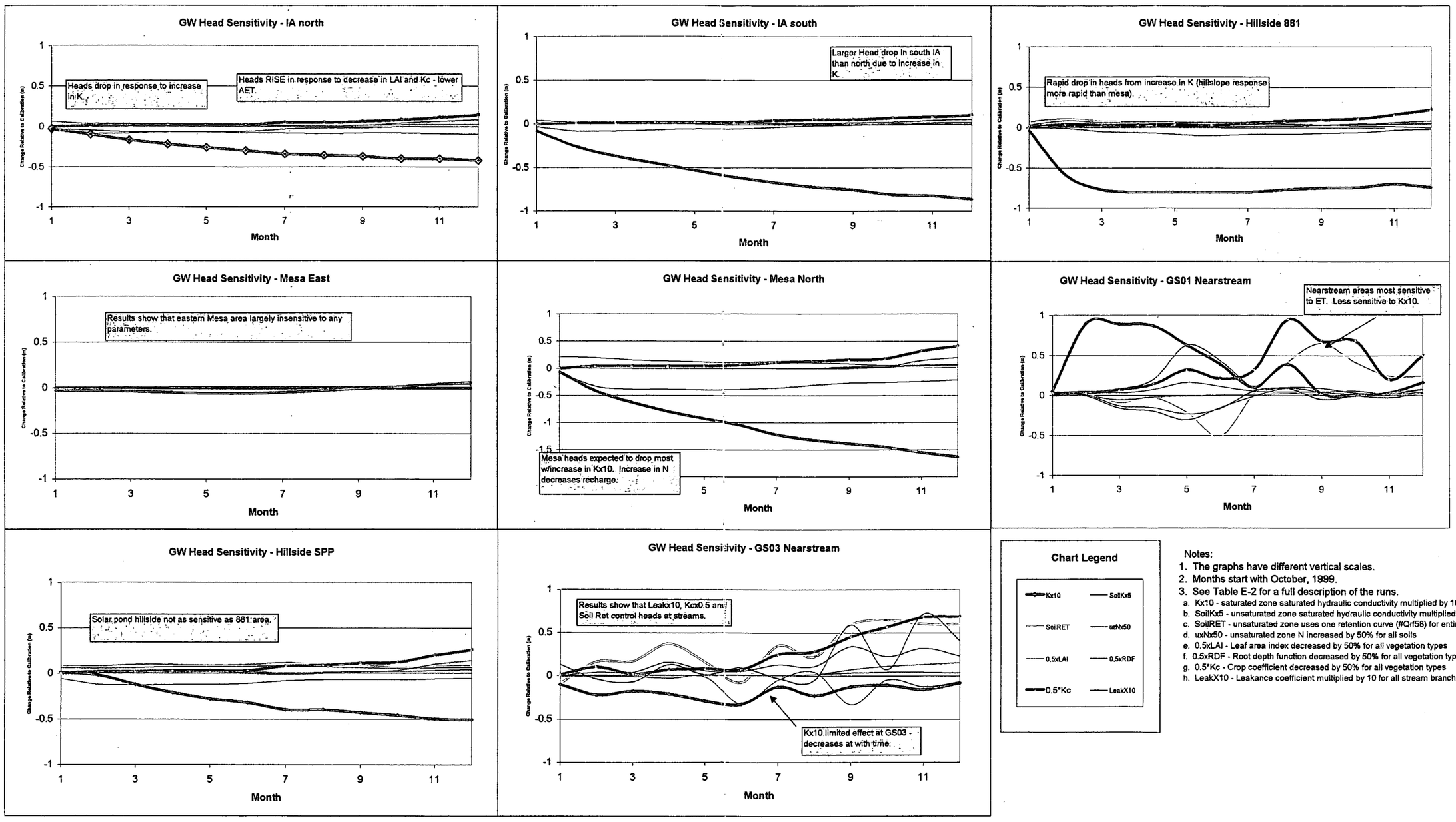
To maintain the anisotropy ratio applied in the reference model all, vertical (K_{zz}) and horizontal saturated hydraulic conductivities (K_{xx}, K_{yy}) were increased by a factor of 10 throughout the entire model area. Values were increased for both Model Layers 1 and 2.

Figure E-26. Sensitivity Analysis Results - Stream Flow



Notes:
1. The graphs have different vertical scales.
2. Months start with October, 1999.
3. See Table E-2 for a full description of the runs.
   a. Kx10 - saturated zone saturated hydraulic conductivity multiplied by 10
   b. SoilKx5 - unsaturated zone saturated hydraulic conductivity multiplied by 5
   c. SoilRET - unsaturated zone uses one retention curve (#Qrf58) for entire site
   d. uxNx50 - unsaturated zone N increased by 50% for all soils
   e. 0.5xLAI - Leaf area index decreased by 50% for all vegetation types
   f. 0.5xRDF - Root depth function decreased by 50% for all vegetation types
   g. 0.5*Kc - Crop coefficient decreased by 50% for all vegetation types
   h. LeakX10 - Leakance coefficient multiplied by 10 for all stream branches

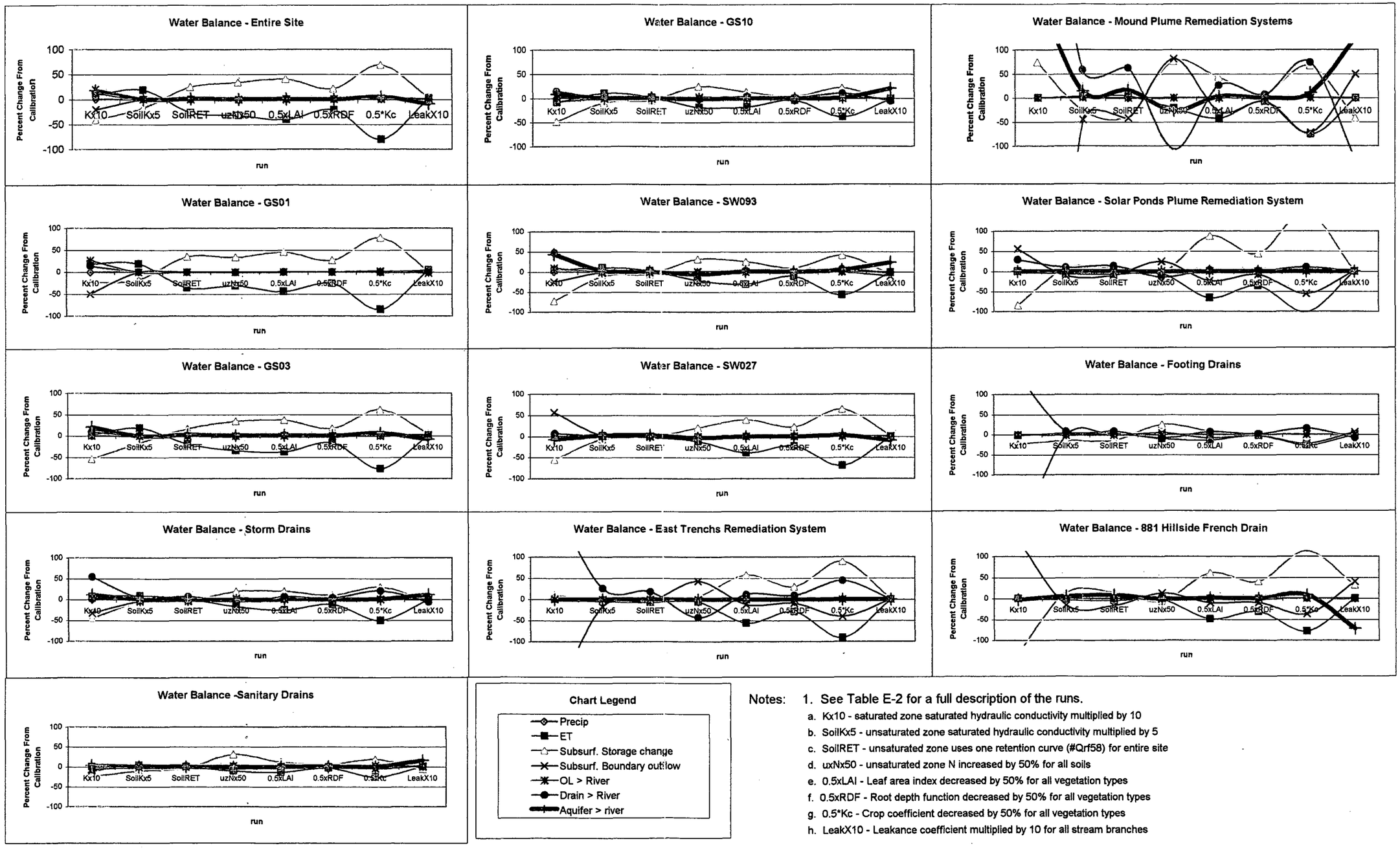
Figure E-27. Sensitivity Analysis - Groundwater Levels



Notes:

1. The graphs have different vertical scales.
2. Months start with October, 1999.
3. See Table E-2 for a full description of the runs.
   a. Kx10 - saturated zone saturated hydraulic conductivity multiplied by 10
   b. SoilKx5 - unsaturated zone saturated hydraulic conductivity multiplied by 5
   c. SoilRET - unsaturated zone uses one retention curve (#Qrf58) for entire site
   d. uxNx50 - unsaturated zone N increased by 50% for all soils
   e. 0.5xLAI - Leaf area index decreased by 50% for all vegetation types
   f. 0.5xRDF - Root depth function decreased by 50% for all vegetation types
   g. 0.5*Kc - Crop coefficient decreased by 50% for all vegetation types
   h. LeakX10 - Leakance coefficient multiplied by 10 for all stream branches

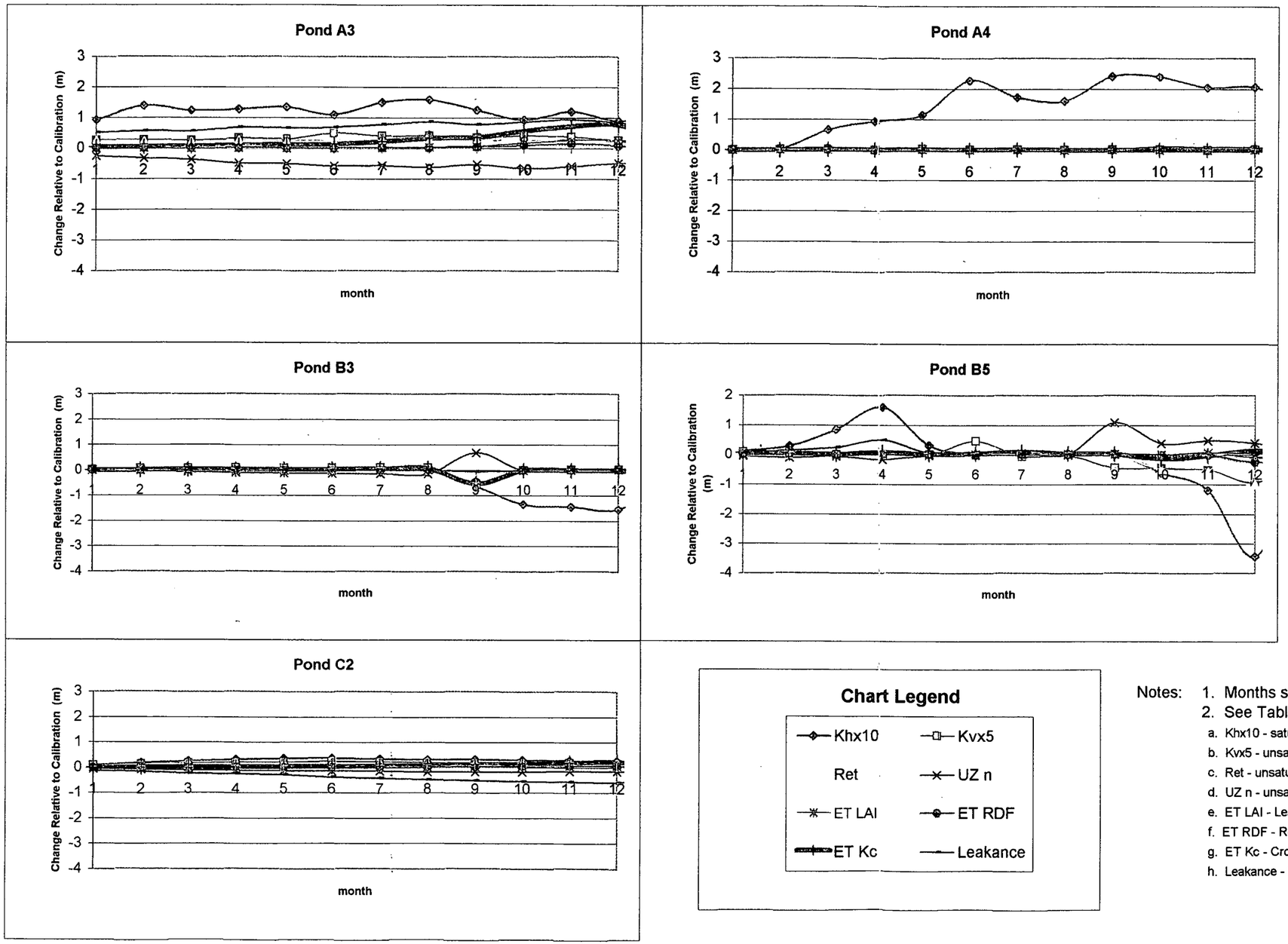
Figure E-28. Sensitivity Analysis - Water Balance



Notes: 1. See Table E-2 for a full description of the runs.

a. Kx10 - saturated zone saturated hydraulic conductivity multiplied by 10
b. SoilKx5 - unsaturated zone saturated hydraulic conductivity multiplied by 5
c. SoilRET - unsaturated zone uses one retention curve (#Qrf58) for entire site
d. uxNx50 - unsaturated zone N increased by 50% for all soils
e. 0.5xLAI - Leaf area index decreased by 50% for all vegetation types
f. 0.5xRDF - Root depth function decreased by 50% for all vegetation types
g. 0.5*Kc - Crop coefficient decreased by 50% for all vegetation types
h. LeakX10 - Leakance coefficient multiplied by 10 for all stream branches

Figure E-29. Sensitivity Analysis - Pond Levels



Notes:
1. Months start with October, 1999.
2. See Table E-2 for a full description of the runs.
   a. Khx10 - saturated zone saturated hydraulic conductivity multiplied by 10
   b. Kvx5 - unsaturated zone saturated hydraulic conductivity multiplied by 5
   c. Ret - unsaturated zone uses one retention curve (#Qrf58) for entire site
   d. UZ n - unsaturated zone N increased by 50% for all soils
   e. ET LAI - Leaf area index decreased by 50% for all vegetation types
   f. ET RDF - Root depth function decreased by 50% for all vegetation types
   g. ET Kc - Crop coefficient decreased by 50% for all vegetation types
   h. Leakance - Leakance coefficient multiplied by 10 for all stream branches

E.3.4.1.1 Saturated Hydraulic Conductivity: Surface Water Discharges

The annual surface water discharges increased by 77 percent at GS01 compared to the calibration simulation. The relative increase in discharge was larger in the first months of the simulation than the last due to the gradual discharge of water stored in the hydrostratigraphic unit. The response at SW027 was similar to that of GS01, but discharge of groundwater storage was greater. GS03 pond releases accounted for the majority of the discharge. The increased hydraulic conductivity increased baseflow contributions to the Pond A-4 to GS03 reach, which increased annual runoff by 25 percent. GS10 was affected less by the saturated zone properties, as seen by the annual change in runoff of only 4 percent. GS10 runoff was dominated by storm water runoff from paved areas within the Industrial Area. A more significant and consistent response was, however, seen at SW093. This was also strongly affected by Industrial Area surface and drain runoff. The monthly runoff volumes at SW093 increased by 16-59 percent, with and average increase of 32 percent. The redistribution of water and changes in discharge mechanisms are indicated in the water balance outputs (Figure E-28).

The Mound Treatment System is situated on a hillside and drains the local groundwater. The release of groundwater in the upstream part of the hydrostratigraphic unit led to increased groundwater inflow to this area, which increased drain flows and baseflow to the stream.

E.3.4.1.2 Saturated Hydraulic Conductivity: Pond Water Levels

Higher drain and baseflow from the saturated zone to the stream network led to higher inflow to the stream network and the ponds. Consequently pond water levels increased as indicated by temporal variations for the B-series ponds. The highest increases in pond water levels are seen in Pond A-3 (1.22 m or 4 ft) and Pond A-4 (1.44 m or ~5 ft). In Pond C-2, the water level was increased throughout the first half year of the simulation (0.36 m or ~1 ft). For the last half year of the simulation period, the water level decreases by 0.08 m (3 in). The water levels of Ponds B-3 and B-5 increases slightly over the first months of the simulation followed by a decrease until June, 2000 (as

expected from the time lag of groundwater discharges). For the July-September, 2000 period a significant drop in water level was observed in both ponds; and the pond water depth was reduced by 50 percent.

E.3.4.1.3 Saturated Hydraulic Conductivity: Water Balance

The general response of the model and the respective sub-basins was a decrease in subsurface storage in response to increased hydraulic conductivity. The decrease in storage was manifested by increased discharge to the stream network. For the entire model area, discharge from overland flow, drain flow and baseflow increased by 20 mm (0.8 in), 12 mm (0.5 in) and 18 mm (0.7 in), respectively. The total AET also increased as more water became available for transpiration in the near-stream zones. The increase in discharge and the corresponding storage decrease of GS01 were close to that of the entire Site. Station GS10 exhibited an atypical response as the storage change increased in drainage runoff but decreased in overland flow. As the water levels of the sub-basin declined, the sub-surface storage capacity increased and a larger volume infiltrated; surficial runoff was reduced. At the surface water gage SW093, the sub-surface storage decreased by 75 mm (3 in) and at the same time the total inflow across sub-basin boundaries increased by 25 mm (1 in). The primary discharge processes were drain runoff and baseflow to the stream. At the surface water gage SW027, the reduction in groundwater storage approximately equaled the increase in sub-surface flow out of the sub-basin. The drain flow and exchange between river and aquifer were insignificant for this sub-basin.

E.3.4.1.4 Saturated Hydraulic Conductivity: Groundwater levels

The mean groundwater levels of the selected zones decreased in response to the increased hydraulic conductivities. For IA North and IA South, the mean groundwater levels decreased through the entire simulation period. The water levels dropped 0.42 m (1.4 ft) and 0.86 m (2.8 ft) by September, 2000.

The two selected mesa areas responded differently to the increased conductivities. Mesa North is situated at the northern no-flow boundary of the model. Mesa East is situated at the upper flat part of a mesa in the central part of the model area. The water level decreased by 1.6 m (5.2 ft) at Mesa North. Mesa East was less sensitive to the changed aquifer properties and a groundwater level drop of 0.02 m (< 0.1 ft) was recorded by the end of the simulation. The 881-Hillside French Drain system and Solar Ponds Plume remediation system showed head drops in the order of 0.5-0.7 m (1.6 – 2.3 ft) during one year. Groundwater levels decreased by 0.37 and –0.18 meters (1.2 – 0.6 ft) for the GS01 and GS03 near-stream zones, respectively.

E.3.4.2 Unsaturated Zone Hydraulic Conductivity

The unsaturated hydraulic conductivity function applied in MIKE SHE is calculated as :

$$K(\Theta) = Ks\left(\frac{\Theta - \Theta_r}{\Theta_s - \Theta_r}\right)^n$$

where, Θ is soil moisture, and the subscripts, r and s, refer to residual and saturated conditions, and n is a Brooks and Corey-type exponent. Increasing the saturated hydraulic conductivity (*Ks*) releases initial water stored in the unsaturated zone columns. This storage increases recharge, which increases groundwater levels over the model area. One result of the increase in groundwater levels is that baseflow contributions to streams, and drains was observed.

E.3.4.2.1 Unsaturated Hydraulic Conductivity: Surface Water Discharges

Increasing saturated hydraulic conductivity of the unsaturated zone soils led to higher groundwater recharge rates and increased surface water discharges. At GS01 and GS03 the annual runoff volumes were increased by approximately 10 percent. For the Industrial Area gages SW093 and GS10, the surface water flow decreased. The runoff areas for these gages are partially comprised by surface water runoff. A larger proportion of water at the surface infiltrates. As a consequence, the largest reduction in runoff was seen in months with significant precipitation. SW027 discharge was more sensitive to the

imposed change. The annual discharge volume increased by 59 percent. The relative increase in flow was approximately two times higher during the first months of the simulation than by the end of it. In September, 2000 the increase in flow was 794 m^3 (28,000 cf) corresponding to a 36 percent increase.

E.3.4.2.2 *Unsaturated Hydraulic Conductivity: Pond Water Levels*

Increasing unsaturated hydraulic conductivity affected pond levels in A-3, B-5 and C-2 most. Levels in Ponds A-4 and B-3 were affected least. Levels increased in Ponds A-3 and C-2, but decreased in Pond B-5. The decrease in Pond B-5 probably resulted from the increased recharge, which decreased runoff that would have entered Pond B-5.

E.3.4.2.3 Unsaturated Hydraulic Conductivity: Water Balance

Water balance plots, shown on Figure E-28, indicate only moderate changes due to increased soil conductivity. For example, only AET increased for stream areas, while discharge to streams increased from the Solar Ponds Treatment system, the East Trenches and Mound Plume systems. AET probably increased in stream areas because groundwater levels increased from increased recharge. This was also probably the case for increased stream discharge from treatment systems. Increasing the soil conductivity decreased soil storage because water drained out more easily from the soil columns.

E.3.4.2.4 Unsaturated Hydraulic Conductivity: Groundwater Levels

Groundwater levels increased in most cases except in the near-stream GS03 area as shown on Figure E-27. Groundwater levels increased more in mesa areas and the Industrial Area. Changes to levels were small compared to effects of changing the saturated hydraulic conductivity values.

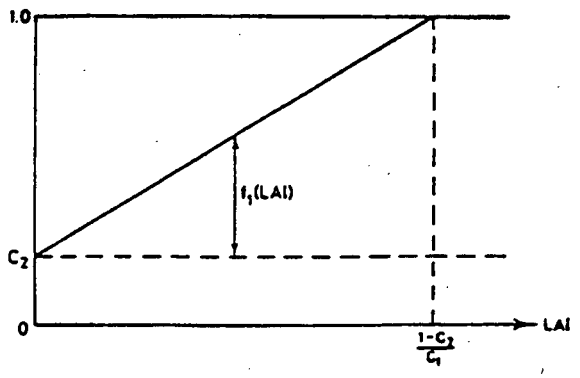
E.3.4.3 Evapotranspiration - Leaf Area Index

The ET component of MIKE SHE simulates the actual rate of ET as:

$$E_{act} = K_c \; E_p \; f_1(LAI) \, f_2(\theta) \, RDF \text{, where}$$

$$f_1(LAI) = C_2 + C_1 LAI$$

Figure E-30. Relationship of ET Parameters



Time series of LAI values are provided as input for the simulation through the vegetation database. Basic soil evaporation (C_2) takes place when there is no transpiration from plants. When the LAI reaches a certain threshold during the growth season (determined by the empirical constants C_1 and C_2) the f_1 function takes the value of 1.0 and the actual ET rate is no more limited by the density of the vegetation cover.

E.3.4.3.1 Leaf Area Index : Surface Water Discharges

Surface water discharges increased consistently throughout the model. The increase in surface water flow ranged from 1 to 6 percent of calibration values. As a result, LAI effects on surface water discharges were minimal.

E.3.4.3.2 Leaf Area Index: Pond Water Levels

Pond A-3 water depths increased by 5 percent, while Pond A4 was unaffected by changing LAI. The discharges from Ponds A-3 to A-4 did not change and the runoff

generated to Pond A-4 was not affected by reduced AET in the sub-basin. Pond B-3 levels were not affected with the exception of June, 2000, where water level dropped. This was not a result of the parameter change and both Ponds B-3 and B-5 are relatively insensitive to the reduction in LAI as the change in water depth was 1 percent for both ponds. In Pond C-2 the water level increased through out the simulation period and reaches a level 0.05 meters (0.2 ft) above the base case simulation. A minor impact was seen for the ponds in general, and the with respect to the terminal ponds no significant reduction in storage capacity was seen.

E.3.4.3.3 Leaf Area Index: Water Balance

Reducing LAI caused annual AET to drop as shown on Figure E-28. For the total model area, GS01 and GS03 losses were reduced by 38-45 mm (1.5 to 1.8 in), approximately 20 percent less than the base case simulation. Sub-surface storage increased by approximately the same volume; the runoff from the sub-basins showed only a minor increase. Annual AET losses were also reduced in the Industrial Area sub-basins, but only by about 18-30 mm (0.7 – 1.2 in). Again the additional volume adds to sub-surface storage, while the increase in surface water runoff is less than 10 percent.

E.3.4.3.4 Leaf Area Index: Groundwater Levels

Decreasing LAI increased water contents (storage) and flow in the unsaturated zone. Groundwater levels also gradually increased over the simulation period in response to increased recharge through the unsaturated zone. In IA North and IA South, mean groundwater water levels increased by 0.08 m (0.3 ft) and 0.05 m (0.2 ft) by September, 2000 (less than 0.02 m (0.8 in) as an average for the year). Groundwater levels did not change at Mesa East, while groundwater levels in Mesa North increased by the end of the simulation period. Water levels in the Solar Ponds Remediation system and 881-Hillside French Drain system areas rose by 0.14 m (0.5 ft) and 0.08 m (0.3 ft) by the end of the one-year simulation period. In the near-stream zones of GS01 and GS03 the mean groundwater table increased by 0.07 m (0.2 ft) and 0.15 m (0.5 ft) higher.

Site-Wide Water Balance Model Report

Appendix F

Hypothetical Scenarios

May 2002

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F APPENDIX: HYPOTHETICAL SCENARIOS

F.1 MODEL MODIFICATION DETAILS

F.1.1 Surface System Modifications- Additional Details

F.1.1.1 Pond Transfer/ Discharge Algorithm

In the calibration and validation models, pond transfers and discharges were pre-designated in the model to match the observed record. This was done to facilitate comparison of results to observed discharge losses and pond levels. For the hypothetical Site scenarios, it was necessary to prepare an algorithm in the model to determine discharge schedules based on simulated pond levels and inflows.

This automation was accomplished in MIKE 11 using logically-operated control structures. Control structure specifications were developed to match the following assumptions, based on current pond operation protocols; namely:

- All ponds transferred/discharged at a maximum rate of 1 ft (0.3 m) of draw down per day;
- All pond transfers/discharges discontinued at 10 percent pond volume; and
- Discharge/transfer destinations and percent volumes required to trigger the discharge/transfer were based on current operating procedures. This information is summarized below, in Table F-1.

Maximum discharge rates were based on pump specifications and as-built engineering drawings for outlet structures. (This information is presented in Table F-2.)

As part of the testing process for the pond automation, the automated setup was run for the calibration year (WY2000). Results compared well to observed manual pond operations, both in number of discharges recorded and in discharge volumes. Table F-3 summarizes the volume comparison.

Table F-1. Discharge Protocol Summary

Pond*	% Volume to Initiate	Destination
Pond A-1	50	Pond A-2
Pond A-2	50	Pond A-3
Pond A-3	40	Pond A-4
Pond A-4	40	Walnut Creek
Pond B-1	50	Pond B-2
Pond B-2	50	Pond A-2
Pond B-3	50	Pond B-4
Pond B-5	50	Walnut Creek
Pond C-2	50	Woman Creek
Landfill Pond	60	Pond A-3

*Ponds C-1 and B-4 are flow through systems, so no transfers/ discharges were programmed.

Table F-2. Maximum Discharge Rates

Pond	Transfer Type	Max Rate* (m^3/s)
Pond A-1	Pumped	0.063
Pond A-2	Pumped	0.063
Pond A-3	Outlet Works	0.855
Pond A-4	Outlet Works	0.983
Pond B-1	Pumped	0.063
Pond B-2	Pumped	0.063
Pond B-3	Pumped	0.063
Pond B-5	Outlet Works	1.09
Pond C-2	Outlet Works	0.963
Landfill Pond	Pumped	0.063

*The model allows passive overflow to spillways, in the event that inflows exceed maximum discharge rates and pond capacities are met.

The preceding list of assumptions was applied in the model, neglecting discharge delays associated with sample turn-around times and regulatory decisions.

Table F-3. Observed Discharge Record Summary

Transfer/ Discharge*	Observed Annual Volume (m^3)	Automated Setup Predicted Annual Volume (m^3)	Percent Difference
Pond B-5 to Walnut Creek	410,200	427,400	-4
Pond A-3 to Pond A-4	114,000	116,200	-2
Pond A-4 to Walnut Creek	102,300	67,700	51**
Pond B-3 to Pond B-4	267,400	226,400	18

*All other discharge/ transfer pathways showed zero volume for WY2000 in both the observed data and in the algorithm simulation.

**This difference is easily explained by the delayed timing of a single discharge. At the end of the year with the pond algorithm, Pond A-4 has 34,100 m^3 less water in storage. Accounting for this leaves less than a 1 percent difference.

Control Structures for the Pond Algorithm in the Model

Two basic types of control structures were developed to simulate the protocols for pond operations: (1) discharge of storage; and (2) discharge of inflow. These control structures were applied in combinations in accordance with the requirements for each pond. The following discussion describes the purpose and development of each type of structure.

Structure Type I: Discharge of Storage

This description applies to all structures with an identification label of "Storage" (in the MIKE 11 model) and is included in the structure combination for every pond.

The "discharge of storage" structure type serves to:

- Initiate a discharge at the appropriate pond level;
- Discharge at a rate corresponding to 1 ft (0.3 m) of draw down per day for the given pond; and

- End the discharge when the pond level reaches a value corresponding to 10 percent capacity.

The priorities were set up as follows:

Priority 1: If the level of the pond reaches the discharge trigger level, then discharge is initiated at a set rate corresponding to 1 ft (0.3 m) of draw down per day (flow rate determined as a function of pond depth).

Priority 2: If the level of the pond is greater than 10 percent capacity AND the discharge is occurring, then discharge is continued at a set rate corresponding to 1 ft (0.3 m) of draw down per day (discharge rate as a function of pond depth). This allows the completion of the discharge. The "AND" part of the logic statement prevents discharge from occurring when the pond is filling after the completion of a previous discharge.

Priority 3: For any conditions other than those of Priority 1 and 2, there will be no discharge of water. This sets up the "ELSE" case in the logic statement that prevents discharge when the pond is filling between discharges.

Structure Type II: Discharge Increase for Inflow

This description applies to all structures with an ID of "Inflow" and is included in the structure combination for ponds with channelized inflow. This includes all ponds except the Landfill Pond, Pond A-1 and Pond B-1.

The "discharge-increase-for-inflow" structure type serves to:

- Increase the discharge rate to account for inflow. (Note: this does not conflict with the 1 ft of draw down per day maximum discharge, because it is discharging water entering the pond in addition to the volume stored.); and

- Set the maximum flow rate by limiting the amount of additional inflow that can be discharged with the "storage" discharge.

The priorities were set up as follows:

Priority 1: If there is a discharge occurring, then this structure will discharge at a rate equal to the inflow rate up to the point where the inflow plus the storage discharge meets the maximum flow rate for the pond.

Priority 2: For any conditions other than those of Priority 1, there will be no discharge of water through this structure. This sets up the "else" case in the logic statement that prevents discharge of inflow if there is no discharge occurring.

F.1.1.2 Final Configuration Channel Network Modifications

Modifications to the MIKE 11 Surface System to create the final configuration scenario are detailed in the Table F-4. This table lists the specific branches removed and added to the surface water network to create the final configuration scenario.

F.1.2 Generation of Wet and Dry Climates

The following text supplements the discussion in Section 7, describing the generation of hypothetical wet and dry years of climate data for input into the model.

F.1.2.1 Annual Precipitation Mean and Standard Deviation

The following discussion presents the approach applied to determine the mean and standard deviation of annual Site precipitation:

Site records provide only 35 years of annual precipitation measurements. To generate a distribution based on a larger sample population, records from surrounding areas were considered. Precipitation records from Golden, CO, Denver (Stapleton), CO, Boulder, CO and Fort Collins, CO were compared to the available Site record. For the available period of Site record, the Fort Collins data showed the best match to average precipitation and standard deviation. Specifically, for the similar periods of record, the Fort Collins data differ in average precipitation by only 5 percent, and differ in standard deviation by only 1 percent. Based on this, the 100-year record available for Fort Collins was applied to determine the mean and standard deviation of annual Site precipitation (See Section 7 for findings).

Table F-4. Branches Removed and Added from the Surface Water Channel Network to Create the Hypothetical Land Configuration Scenario

Branches Removed (including associated connections, boundary conditions, MIKE SHE links, points, Channel M settings and wave approximation settings)

	Branch Name	Reason for Removal	Notes
1	SW022 Main	Regrading	Based on Scheck (2002)
2	Branch 16	Regrading	Based on Scheck (2002)
3	Branch 12	Regrading	Based on Scheck (2002)
4	SW060 Main	Regrading	Based on Scheck (2002)
5	GS22 east	Regrading	Based on Scheck (2002)
6	GS22 west	Regrading	Based on Scheck (2002)
7	GS22 main	Regrading	Based on Scheck (2002)
8	Branch 18	Regrading	Based on Scheck (2002) he confirmed that roads associated with these ditches would be removed.
9	Branch 17	Regrading	Based on conversation with ER Personnel (Scheck, 2002) where he confirmed that road associated with these ditches would be removed. Only removed from 0 to 304 m chainage.
10	SW093 main	Regrading	Based on Scheck (2002)
11	GS10 main	Regrading	Based on Scheck (2002). Partial Removal (to edge of Industrial Area boundary and new channel specifications
12	West section of SID	Old landfill regrading	Based on Scheck (2002)
13	Landfill Pond	Landfill Cover	Based on Scheck (2002)
14	Landfill Evaporation	Landfill Cover	Based on Scheck (2002)

Table F-4 (continued)

Branches Added (including associated connections, boundary conditions, MIKE SHE links, points, Channel M settings and wave approximation settings)

	Branch Name	Reason for Adding	Notes
1	Industrial Area (IA) North Walnut	Scheck (2002)	Based on Scheck (2002)
2	IA South Walnut	Scheck (2002)	Based on Scheck (2002)
3	Pond B-1 Discharge connection for algorithm	For Pond Algorithm	To allow for placement of control structures to automate ponds and route discharge to discharge point
4	Pond B-2 Discharge connection for algorithm	For Pond Algorithm	To allow for placement of control structures to automate ponds and route discharge to discharge point
5	Pond B-3 Discharge connection for algorithm	For Pond Algorithm	To allow for placement of control structures to automate ponds and route discharge to discharge point
6	Pond B-5 Discharge connection for algorithm	For Pond Algorithm	To allow for placement of control structures to automate ponds and route discharge to discharge point
7	Pond A-1 Discharge connection for algorithm	For Pond Algorithm	To allow for placement of control structures to automate ponds and route discharge to discharge point
8	Pond A-2 Discharge connection for algorithm	For Pond Algorithm	To allow for placement of control structures to automate ponds and route discharge to discharge point
9	Pond A-3 Discharge connection for algorithm	For Pond Algorithm	To allow for placement of control structures to automate ponds and route discharge to discharge point
10	Pond A-4 Discharge connection for algorithm	For Pond Algorithm	To allow for placement of control structures to automate ponds and route discharge to discharge point
11	Pond C-2 Discharge connection for algorithm	For Pond Algorithm	To allow for placement of control structures to automate ponds and route discharge to discharge point
12	Landfill Pond Discharge for algorithm connection	For Pond Algorithm	To allow for placement of control structures to automate ponds and route discharge to discharge point (Not in the hypothetical Land Configuration Scenario as pond has been removed)

F.1.2.2 Synthesized Precipitation Intensities

The approach to synthesizing precipitation record by applying a multiplier had the potential to generate unrealistically high intensities for the wet climate, so generated intensities were assessed prior to application in the model. Generated intensities (15-minute interval) were compared to observed intensities (15-minute interval) recorded between January, 1995 and October, 2001.

The synthesized wet year precipitation record has one 15-minute intensity value that exceeded the maximum intensity recorded since 1995. This value (0.92 in (23 mm)/15 minutes) is 17 percent higher than the highest recorded value (0.79 in (20 mm) /15 minutes, recorded in WY2001). The next highest synthesized intensity is only 0.38 in (9.7 mm) /15 minutes, and is well within the observed range. Because only one synthesized value exceeded observed intensities, the wet year record was considered to be reasonable.

F.2 DETAILED RESULTS FOR UNCERTAINTY ANALYSIS

F.2.1 Uncertainty Analysis Details

F.2.2 Approach

The sensitivity analysis identified the model parameters, which had the greatest effect on key outputs including surface water discharges, pond water levels, groundwater levels and the water balance. Three parameters were selected for the uncertainty assessment including the horizontal hydraulic conductivity of the UHSU (K_h), the saturated hydraulic conductivity of the soils (K_s) and the leaf area index (LAI) controlling plant transpiration. The three parameters were changed globally for the entire Site. The uncertainty analysis was performed exclusively on the hypothetical Land Configuration Scenario. The parameter changes were determined from the distribution of available field data (aquifer test data) and literature. The mean value of each parameters was determined from available data and compared to the calibration setting. The parameter value ranges for the

uncertainty runs were set as the difference between the observed data mean value and the calibrated model value.

A simple Monte-Carlo type uncertainty analysis (Melching, 1995) was performed as planned in the Work Plan (Kaiser-Hill, 2000a). This approach typically involved many simulations where input parameters (singly and in combination) were randomly varied based on probability distributions to determine reliability in model predictions. The relatively long simulation times (15 hours) prevented a full sampling of all input. Therefore, a simple triangular sampling approach was used to specify low, calibration, and high values for each of the three model parameters. Table F-5 summarizes specific parameter adjustments made to the saturated and unsaturated zone hydraulic conductivities and LAI. The calibration value was multiplied by the low and high factors shown to determine the low and high parameter values to be tested. All hydraulic conductivity values within the unconsolidated material (Model Layers 1 and 2) were multiplied by the factors shown. Adjustments were not made to the weathered bedrock layers (Model Layers 3 and 4). The time series of LAI for each vegetation type was multiplied by the low and high factors indicated.

A total of 27 runs were simulated to evaluate each possible combination of the three uncertainty parameters with three values each (low, calibration and high). For each of the parameter combinations the model was run for a two-year period. The first year was run to generate initial conditions. All results used in the uncertainty assessment were based on the second year run. This approach was adopted to eliminate initial condition effects on parameter changes.

F.2.3 Results

The results of the uncertainty runs confirmed that the parameters identified in the sensitivity runs had a significant impact on key model outputs. The responses seen from each of the uncertainty runs comply with the expected response of the hydrological system based on the conceptual model. In general, parameter changes affected the primary variables of specific processes; and due to the coupled nature of the integrated

Table F-5. Uncertainty Analysis - Parameter Adjustments

	Low Factor Multiplier	Calibration Value (m/s or none)	High Factor Multiplier
Aquifer conductivity (m/s):			
Rocky Flats Alluvium – Qrf	0.33	$1x10^{6}$ to $6x10^{-6}$	2.9
Colluvium/Landslide – Qc	0.25	$3.7x10^{-7}$ to $6.3x10^{-7}$	4.0
Valley-Fill Alluvium – Qal	0.1	$1.5x10^{-5}$ to $2.5x10^{-5}$	10.0
Artificial Fill – Af	0.17	$3.3x10^{-7}$ to $3.5x10^{-7}$	5.9
Soil conductivity (m/s) :			
Alluvium, Qrf#58	0.01 to 0.02	$1.0x10^{-4}$ to $2.0x10^{-4}$	47.6 to 95.2
Alluvium, Qal#3	20.5	5.0x10-5	2.0
Colluvium, Qc_{east}	0.13	7.0x10-5	75
Colluvium, Qc_{west}	0.09 to 0.14	$0.5x10^{-5}$ to $1.0x10^{-5}$	5.4 to 10.7
Leaf area index (-) :			
All vegetation types	0.5	Varies in time	1.5

model, the effect propagates to the remaining hydrological components affecting the entire water balance.

Surface water discharges and pond releases were the primary focus. The total annual accumulated discharges and associated uncertainty ranges simulated by the uncertainty runs are summarized in Table F-6. The results imply that the surface water discharges, which are the key outputs from the model, varied significantly with the change in these sensitive parameters. The hypothetical Land Configuration Scenario predicted streamflow leaving the Site at GS01 was approximately 100,000 m^3/yr ($3.5x10^6$ cf/yr). Given the parameter uncertainty, there is 90 percent certainty that the discharge will be in the 80,000-120,000 m^3/yr range.

Table F-6. Uncertainty Analysis – Stream and Pond Discharges

All m^3/yr

Q station	Calibrated model	Mean of uncertainty runs	Standard deviation of uncertainty runs	Q_{min} 90 percent confidence interval	Q_{max} 90 percent confidence interval
GS01	99900	135000	60600	80700	119000
GS03	54800	69100	36700	42600	67100
SW093	54800	61800	18000	49100	60500
GS10	9490	11800	3450	8400	10600
SW027	0	1890	1780	0	564
A4	35800	34000	27100	27000	44400
B5	0	0	0	0	0
C2	0	0	0	0	0

(2.8×10^6 – 4.2×10^6 cf/yr). At GS03, the model predicted the annual surface water runoff volume at 55,000 m^3 (1.9×10^6 cf/yr)with an uncertainty of approximately ± 12,000 m^3/yr at 90 percent confidence interval.

Terminal pond water level variations were limited by the operation protocol that kept water levels within relatively narrow bounds. Uncertainty analysis results are summarized in Table F-7. The mean Pond A-4 water level, which may be used to assess pond water storage, was predicted at 1,751 m (5744 ft) with a 90 percent confidence interval range of ± 0.09 m. For Ponds C-2 and B-5 uncertainty ranges of ±0.14 m and ± 0.21 m were estimated (no discharges occur during the simulation period for Ponds C-2 and B-5).

Table F-7. Uncertainty Analysis - Pond Water Levels

(All m elevation)

Pond	Land Configuration Scenario Results	Mean	Maximum	Minimum	Standard deviation	90 percent confidence	95 percent confidence
C-2	1752.1	1752.5	1753.6	1752.1	0.5	0.1	0.2
A-4	1750.9	1750.9	1751.4	1750.4	0.3	0.1	0.1
B-5	1764.1	1764.5	1765.7	1763.6	0.7	0.2	0.3

Uncertainty in mean annual groundwater levels for the hypothetical Land Configuration Scenario is approximately 0.05 m for the regraded Industrial Area, based on 90 percent confidence intervals. Results are summarized in Table F-8. For the near-stream zones (defined as Woman Creek Vegetation/ Habitat and Walnut Creek Vegetation/ Habitat Areas), similar uncertainty ranges (0.05-0.06 m) were found. A higher uncertainty was associated with the landfill groundwater levels, 0.24 m (0.8 ft) for the Original Landfill and 0.16 m (0.5 ft) for the Present Landfill.

The water balance outputs from the model comprise a range of individual terms describing flow within the entire hydrologic system and internally between model components. Discharge as ET showed the greatest degree of uncertainty. The net rainfall, calculated as precipitation minus total ET, varied between approximately 10 and 60 mm/year (0.4 to 2.4 in/yr). The effect on flows through the Site, however, was limited. Additional water in the system was balanced by higher subsurface storage due to lower ET rates. Baseflow to the streams was not affected significantly.

Table F-8. Uncertainty Analysis - Groundwater Levels
(All m elevation)

Area	Hypothetical Land Configuration Scenario Results	Mean	Maximum	Minimum	Standard deviation	90 percent confidence	95 percent confidence
Old Landfill	1821.2	1821.7	1822.8	1820.9	0.6	0.20	0.2
Present Landfill	1813.7	1814.3	1814.8	1813.7	0.4	0.10	0.2
Industrial Area (regraded)	1825.8	1825.6	1825.9	1825.4	0.1	0.05	0.1
Woman Veg./ Habitat	1759.2	1759.3	1759.7	1759.1	0.1	0.05	0.1
Walnut Creek Veg./ Habitat	1762.9	1763.0	1763.4	1762.7	0.2	0.06	0.1
903 Pad	1812.0	1811.8	1812.3	1811.4	0.2	0.07	0.1

The uncertainties should be viewed in the context of the Site/model complexity, the limited available field data to set appropriate test ranges and required reliability of model predictions as a Site management tool. The outputs at individual points comprised the aggregated response of the upstream system. A reduction of prediction uncertainty ranges is probably not feasible unless additional field data are obtained to improve the model locally and focus model parameter input uncertainty ranges.

LIST OF ACRONYMS AND BASIC NOMENCLATURE

°C	Centigrade
°F	Fahrenheit
AET	Actual Evapotranspiration
Af	Artificial Fill
AME	Actinide Migration Evaluation
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
B & W	Black and White
BZ	Buffer Zone
CDPHE	Colorado Department of Public Health and Environment
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act
cf	Cubic feet
cfs	Cubic feet per second
C_{int}	Interception Term in Evapotranspitation Calculations
CO	Colorado
DHI	Danish Hydraulic Institute
DOE	United States Department of Energy
DRIP	Drainage Repair and Improvement Plan
dt	time step interval
DWB	Denver Water Board
dx	distance interval
EG&G	EG&G, Inc. formerly Edgerton, Germeshausen and Grier, Inc.
EPA	Environmental Protection Agency

EPL	Erosion Protection Layer
ET	Evapotranspiration
ft	Foot or Feet
ft^2	Foot or Feet squared
FY	Fiscal Year
GIS	Geographic Information Systems
GS	Gaging Station
GW	Groundwater
H	Water Level
HEC	Hydrologic Engineering Center
HSPF	Hydrologic Simulation Program Fortran (EPA model)
IA	Industrial Area
IC	Interim Cover
in	Inch(es)
IR	Infrared
Kaiser-Hill	Kaiser-Hill Company, LLC
K_c	Crop Coefficient
K_h	Horizontal Hydraulic Conductivity
km	Kilometer(s)
K_s	Soil Hydraulic Conductivity
K_{sat}	Saturated Hydraulic Conductivity
K_v	Vertical Hydraulic Conductivity
L	Leakance
LAI	Leaf Area Index
LHSU	Lower Hydrostratigraphic Unit

m	Meter(s)
M	Manning's constant = 1/n
MIKE 11	Surface water modeling code
MIKE SHE	Integrated hydrologic modeling code
m/s	Meter(s) per second
m/yr	Meter(s) per year
m^2	Meter(s) squared
m^3	Cubic meters
m^3/s	Meter(s) cubed per second
mm	Millimeter(s)
MODFLOW	U.S.G.S. Groundwater Modeling Code
MSL	Mean Sea Level
n	Manning's constant = 1/M
N/A	Not Applicable
NREL	National Renewable Energy Laboratory
OC	Overland/ Channelization
PET	Potential Evapotranspiration
POC	Point of Compliance
POE	Point of Evaluation
Q	Flow rate
Qal	Valley Fill Alluvium
Qc	Colluvium
Qp	Piney Creek Deposits
Qrf	Rocky Flats Alluvium
Qt	Terrace Deposits

RDF	Root Depth Function
RFCA	Rocky Flats Cleanup Agreement
RFETS	Rocky Flats Environmental Technology Site
RMRS	Rocky Mountain Remediation Services
SCS	Soil Conservation Service
SID	South Interceptor Ditch
SNTHERM	Snowmelt modeling computer code
S_p	Confined Storage Coefficient
SPP	Solar Ponds Plume
SRM	Soil Rooting Medium
SRRL	Solar Radiation Research Laboratory
SW	Surface water
SWE	Snow Water Equation
SWD	Soil and Water Database
SWMM	EPA Hydrologic Modeling Code
SWWB	Site-Wide Water Balance
S_y	Unconfined Storage Coefficient
SZ	Saturated Zone
UHSU	Upper Hydrostratigraphic Unit
USDA	United States Department of Agriculture
USGS	United States Geological Survey
UZ	Unsaturated Zone
VSA	Variable Source Area
VL	Venting Layer
WEPP	Water Erosion Prediction Project

WWTP	Wastewater Treatment Plant
WY	Water Year
XPS	X-ray Photoelectron Spectroscopy
yr	Year
θ	Water Content
θ_{fc}	Field Capacity Water Content
θ_w	Wilting Point Water Content
θ_s	Saturation Water Content
Ψ	Capillary Pressure

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