A GEOSTATISTICAL EVALUATION OF THE UNCONFINED AQUIFER
UNDERLYING THE ROCKY MOUNTAIN ARSENAL
COMMERCIAL CITY, COLORADO

by

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ABSTRACT

A geostatistical evaluation was performed on the geology of the unconfined aquifer underlying the Rocky Mountain Arsenal (RMA). To identify the upper and lower boundaries of the aquifer, the water table surface and bedrock surface were simulated using the GSLIB Sequential Gaussian Simulation program. By combining these simulations, probability maps of saturated alluvium were produced. Simulations of the alluvial lithology were created by using ISIM3D, a multiple indicator conditional simulation program. The alluvial simulations were combined with the water table and bedrock surface simulations to create probability maps of connected coarse-grained facies. Areas of probable continuous coarse-grained facies within probable saturated alluvium zones can be used to assess likely routes of rapid contaminant migration within the alluvium.

Although beyond the scope of the research project described herein, the configuration of the water table is better determined through groundwater flow modeling. In addition, connected high hydraulic conductivity paths do not fully control contaminant migration. Relative hydraulic conductivity values, degree of discontinuity along flow paths, boundary conditions, and the advection/dispersion equations must be considered when evaluating contaminant migration. To provide an example of the impact of using
groundwater modeling, flow and contaminant transport were simulated using a sample realization of the aquifer. The modeling demonstrated that slow contaminant migration will occur in areas where coarse-grained zones are not continuous.
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Chapter 1

INTRODUCTION

This chapter presents the thesis project background, project objectives, previous work and site description.

Project Background

In 1942, the Rocky Mountain Arsenal (RMA), located in South Adams County, Colorado, was established by the United States Army for the production of chemical and incendiary munitions for World War II. Beginning in 1947, portions of the RMA were used for the research and production of pesticides. Disposal and leakage from both activities resulted in substantial contamination of the unconfined aquifer underlying the RMA. Unconfined aquifers (water-table aquifers) are aquifers (water-bearing geologic units) in which the water table forms the upper boundary, whereas confined aquifers (artesian aquifers) have head greater than a low hydraulic conductivity layer which forms their upper bound. The groundwater system of the RMA is located in the Denver basin, a structural unit which covers approximately 6,700 miles² (Harding Lawson Associates, et al., 1990).

It is imperative to know all contamination routes, especially those reaching offpost. The expense of drilling makes it impossible to know all subsurface information, therefore
other methods of subsurface characterization must be employed. Typically, subsurface maps are generated by hand using visual interpolation or by computers using techniques such as inverse distance or triangulation (Davis, 1986). These methods do not evaluate the connectivity of aquifer heterogeneities which can significantly influence contaminant transport.

Kriging, a geostatistical estimation method, does account for the spatial continuity of the data, but it smoothes the results. To maintain the variability of the natural system heterogeneities, stochastic conditional simulations were implemented. Multiple realizations of the subsurface were generated to assess possible alternative configurations. Their probability of occurrence can be used in groundwater flow and contaminant transport evaluation. Spatial distribution of the uncertainty associated with the interpretation is evaluated and can be used to guide planning of further field data collection.

**Project Objectives**

The object of this research was to create and interpret possible configurations of the unconfined aquifer underlying the RMA. Multiple simulations of the bedrock surface, water table surface, and alluvial lithology were created using stochastic geostatistical methods. These simulations were combined to create probability maps pertaining to the spatial extent of the aquifer and the connectivity of the coarse-grained pathways within the aquifer. Geologic character of the alluvium would be better represented by a process
model, however the complex stratigraphy coupled with lack of sufficient core and geophysical logs precluded such analysis.

The locations of saturated alluvium are of importance because saturated alluvium is a more likely medium for contaminant transport than unsaturated alluvium. Two-dimensional (2-D) probability maps of saturated alluvium locations were created by combining bedrock surface and water table surface simulations.

Within the constraints of hydraulic conditions, the predominant route of contaminant transport will occur along continuous coarse-grained (sand or gravel) bodies within the saturated alluvium. Three-dimensional (3-D) representations of saturated alluvial bodies were created by combining bedrock surface, water table surface, and alluvial lithology simulations. Within these bodies, connected coarse-grained pathways were determined and probability maps of the pathways were calculated.

The interpretation of these probability maps can be used to guide planning for further data collection. If an area has high uncertainty, it is a candidate for additional data collection. An area of high probability for saturation and/or connected coarse-grained pathways, that is not currently monitored for contamination, may be a suitable location for additional water quality sampling. Although the approach has application at the RMA, this procedure is most valuable during early stages of site investigation when the drilling program is being designed. Use of RMA data, where the site is well characterized, illustrates that the procedure can successfully delineate the subsurface.

Although groundwater flow and transport modeling of each realization of the
aquifer is the best way to establish a water table surface and probability of contaminant migration, such extensive modeling was beyond the scope of this project. An example of the advantages of modeling over the connected coarse-grained pathway analysis is provided to illustrate the concept.

**Previous Work**

Before this project, no site-wide regional geostatistical studies of the RMA had been performed. However, some localized geostatistical projects have been conducted. Researchers from Colorado State University used Kriging/Co-Kriging on several aquifer properties in a study of the North Boundary Containment System (Abdel-Rahman, et al., 1994). Conditional simulation based on the Turning Band Method was also implemented. These simulations of hydraulic conductivity were combined with a finite-element flow and contaminant transport model to study the operation and management of the Offpost Groundwater Intercept and Treatment System located north of the RMA (Tamayo-Lara, et al., 1994). To the author's knowledge, no geostatistical studies on geological properties such as alluvial lithology and bedrock surface have been conducted at the RMA prior to this research.

Geostatistical studies similar to this research have been conducted at other sites. Poeter and Townsend (1994) used a 2-D multiple indicator conditional simulation technique to simulate a fluvial, unconfined aquifer at the Hanford Site, Washington. They investigated two interpretations of the aquifer, flat-lying strata and undulating strata. The
undulating strata interpretation is based on the same theory as the transformation of the alluvial lithologic data to a stratigraphic coordinate system used herein. Poeter and Townsend concluded that the undulating strata model better fit their available data. Journel and Gomez-Hernandez (1993) also transformed a clastic sequence to stratigraphic coordinates before creating stochastic sequential indicator simulations.

Ritzi, et al. (1994) conducted a geostatistical study of the Miami buried-valley glaciofluvial aquifer system in southwestern Ohio. Three methods of geostatistical hydrostratigraphic analysis were investigated, stochastic conditional indicator simulation and two deterministic models. Due to the complex geology of the site, the authors found that for contaminant transport simulation, the stochastic model was preferable over the deterministic models because it better represented the heterogeneity of the site.

Johnson and Dreiss (1989) used kriging to interpret hydrostratigraphy. Two interpretations of the Unified Soil Classification System were investigated for indicator assignment. Interpretation (a) separates predominantly fine-grained sediments (ML, CL, OL, MH, CH and OH) from all others, while interpretation (b) distinguishes clean sand and gravel (GW, SW, GP and SP) from all other sediments. It was found that the experimental semivariograms from the two interpretations were not significantly different, so interpretation (a) was used. The research described herein used a lithological separation similar to interpretation (a).
Site Description

The site description of the RMA includes location, history, geology and hydrogeology.

Site Location

The RMA is located approximately nine miles northeast of downtown Denver in southern Adams County, Colorado (Figure 1.1). It occupies 27 miles$^2$ (Harding Lawson Associates, 1992). Figure 1.2 displays a map of the onpost RMA and the locations of South Plants and Basin A.

History of the RMA

The United States Army established the RMA in 1942 for the production and assemblage of chemical and incendiary munitions. From 1947 to 1982, the RMA was also used for the research and production of herbicides and pesticides by private industry (Environmental Science and Engineering, Inc., 1987). These activities resulted in the production or usage of many chemical agents such as levinstein mustard (H), phosgene, napalm, white phosphorous, isopropylmethyl fluorophosphonate (Sarin or GB), chlorine, chlorinated benzenes, and dichlorodiphenyltrichloroethane (DDT) (Harding Lawson Associates, 1992). The liquid waste was disposed of in lined and unlined evaporation basins. The waste was either first held in settling ponds or sent directly to the basins through sewer systems or surface drainage ditches. Solid waste was put in burning and burial pits (Kuznear and Trautmann, 1980). After demilitarization, the munitions were
Figure 1.1: Location of the Rocky Mountain Arsenal (from Harding Lawson Associates, 1992).
Figure 1.2: Map of the onpost region of the Rocky Mountain Arsenal.
deposited in trenches or on the surface (Harding Lawson Associates, 1992). These disposal methods along with accidental leakages and spills resulted in significant environmental contamination.

The effects of the contamination were evident by the 1950s. Early indications of the problems were high waterfowl mortality and extreme crop loss (Harding Lawson Associates, 1992). Diisopropylmethylphosphonate (DIMP) and dicyclopentadiene (DCPD) were detected in offpost surface water in 1974. By 1978, dibromochloropropane (DBCP) was found in offpost groundwater (Environmental Science and Engineering, Inc., 1987). Groundwater remediation efforts in the form of containment systems were initiated in 1978. These systems intercept, pump, treat and inject the groundwater (Harding Lawson Associates, 1992).

Basin A, an unlined evaporation pond consisting of 125 acres located in Section 36, is one of the major sources of groundwater contamination. It was the site of original waste disposal between 1942 and 1956 (Environmental Science and Engineering, Inc., 1987). This site was the origin used in the connected coarse-grained pathway investigation which is discussed later.

**Geology of the RMA**

The unconfined aquifer underlying the RMA resides in two geologic features, the Denver Formation and the alluvium. A geologic history and description of these features follows.
Costa and Bilodeau (1982) describe the general geology of Denver. During the Laramide Orogeny, as the Rocky Mountains rose, there was subsidence east of the Front Range that formed the Denver Basin. Sediments were eroded from the mountains and deposited in the Denver Basin as the Arapahoe, Denver, Dawson and other formations (Costa and Bilodeau, 1982). The Denver formation is the uppermost formation under the RMA, and is commonly referred to as the bedrock. It generally consists of clay shale, siltstone and sandstone. The glacial and interglacial periods of the Quaternary period produced the environments that resulted in the current bedrock and ground surface features (Morrison-Knudsen Engineers, Inc., 1988). In general, the bedrock surface is weathered and follows the ground surface topography. However the bedrock has greater vertical relief and variability than the ground surface (Zebell, 1979). For example, the bedrock surface has many paleochannels and paleovalleys (Costa and Bilodeau, 1982) which are not reflected in the surface topography.

In their 1988 report on the geology of the RMA, Morrison-Knudsen Engineers (MKE) reported that Quaternary unconsolidated surficial material, or alluvium, overlies the bedrock in most areas in the RMA. The alluvium consists primarily of fluvial sediment deposited by the ancestral South Platte River System with a thin layer of eolian sand overlying part of the fluvial deposits. The South Platte eroded into the underlying Denver formation, creating the South Platte Valley and depositing the fluvial portion of the alluvium. The deposition of the alluvium was closely related to the cyclic glacial periods of the Pleistocene time. Meltwater from alpine glaciers carried sediment to the
plains and valleys east of the mountains where it was deposited (Morrison-Knudsen Engineers, Inc., 1988). The alluvium is comprised of gravel, sand, silt and clay.

According to MKE (1988), there are nine recognized alluvial deposits at the RMA. They are (from oldest to youngest) the Verdos Alluvium, Older Slocum Alluvium, Younger Slocum Alluvium, Louviers Alluvium, tributary channel fill (unnamed), Broadway Alluvium, eolian (unnamed), Piney Creek Alluvium, and Post Piney Creek Alluvium. The six oldest deposits were deposited during glacial periods. Erosion occurred in the interglacial periods between each deposition. Thus, some of the deposits were significantly eroded before the next stage of alluvium was deposited (Morrison-Knudsen Engineers, Inc., 1988). Hence, the alluvial stratigraphy is extremely complex.

MKE (1988) also specifies the geologic periods of deposition and erosion. The Verdos Alluvium was deposited in the Kansan glacial period, followed by erosion in the Yarmouth interglacial period. The Older and Younger Slocum Alluviums were deposited in two separate glacial events during the Illinoian glacial time. After the Illinoian period, the Sangamon interglacial period of erosion ensued and was followed by the deposition of the Louviers Alluvium in the first Wisconsin period alpine glacier advance. Erosion then occurred again during the next interglacial period which completely eroded the Denver Formation at the South Platte River, exposing the upper Arapahoe Formation. Later, granular sediments accumulated in the paleochannels due to increase of stream flow. The Broadway Alluvium was then deposited in the Late Wisconsin time from outflow of a glacier. In the Late Wisconsin/Early Holocene period, loess-like sediments
were deposited followed by rapid eolian sand deposition. In the last 5000-7000 years, the Piney Creek Alluvium, a thin fluvial deposit found in tributary channels, and the Post-Piney Creek Alluvium, a flood plain deposit of the South Platte River, were deposited (Morrison-Knudsen Engineers, Inc., 1988).

The majority of alluvial deposits are probably braided stream deposits because, according to Boggs (1987), braided streams are common on glacial outwash plains. Unlike meandering stream deposits which have a very distinctive fining-upwards trend in grain-size, braided stream deposits may have no vertical grain-size trend or they may have a fining-upwards trend (Boggs, 1987). At the RMA, typically the younger deposits are finer-grained than the older deposits (Harding Lawson Associates, 1992). This fining-upwards grain-size trend is probably due more to the variety of deposits that comprise the alluvium, than to a fining-upward trend within individual braided stream deposits.

Anisotropy of the alluvial deposits is of interest when determining spatial continuity of the alluvium. Braided stream deposits are typically sheetlike or wedge-shaped (Boggs, 1987), without significant anisotropy. However, the channel and bar complexes of the braided stream may leave some elongated bodies within the deposit, lending some distinguishable anisotropy to the alluvium. Also, the anisotropy of the paleochannels may influence the determination of spatial continuity.
**Hydrogeology of the RMA**

Both unconfined and confined groundwater aquifers exist at the RMA. This project was concerned with the unconfined aquifer which consists of alluvium, eolian, and weathered (more permeable) subcropping portions of the upper Denver Formation. The alluvium and eolian deposits will hereafter be referred to as the alluvium. The confined aquifers reside in sand layers within the Denver Formation.

The primary groundwater flow paths are to the north and northwest along major paleochannels cut into the bedrock. The paleochannels have high hydraulic conductivity (K) values and serve as conduits for the known contaminant plumes (May, 1982). A groundwater mound under South Plants, from which radial flow occurs, has been known to exist since 1957. This mound is predominately in weathered bedrock of low K and in some places occupies alluvial clay and silt deposits of low K. The alluvium around the mound has a higher K. Recharge from the South Plants into these low K units causes the water table to mound. The recharge occurred from leaking sewer lines, leaking pipes, low area water collection and various South Plants activities. The mound is declining due to a decrease of recharge (Ebasco Services Incorporated, 1989).

Aquifer test analyses indicate K varies significantly throughout the unconfined flow system. Weathered bedrock K ranges from 0.03 to 3 feet/day. K of the fine-grained alluvium varies from 10 to 100 feet/day and the K's of the coarse-grained deposits range from 60 to 3000 feet/day. Specific yield estimates are 0.01 feet³/feet³ to 0.05 feet³/feet³ for the fine-grained deposits and 0.23 feet³/feet³ to 0.25 feet³/feet³ for the coarse-grained
alluvium. Specific yield estimates for the weathered bedrock are unreliable. Horizontal hydraulic gradients vary from 0.0001 to 0.01 feet/feet where alluvium dominates the flow system and 0.007 to 0.02 feet/feet where weathered bedrock dominates. The weathered bedrock estimates have more uncertainty (Ebasco Services Incorporated, 1989).

Recharge and discharge to/from the flow system under the RMA occur from/to surface-water bodies, precipitation, boundary inflow and outflow, groundwater pumping, and interaction with the underlying Denver Formation aquifers (Harding Lawson Associates, et al., 1990). A substantial portion of the recharge comes from inflow from the bedrock and from boundary inflow via a large buried channel southeast of the RMA (May, 1982).

The groundwater system of the RMA is located in the Denver basin, a structural unit which covers approximately 6,700 miles\(^2\) (Harding Lawson Associates, et al., 1990). The boundaries of the Denver basin could be considered to be the hydrologic boundaries of the groundwater flow system. However, for research purposes, a smaller area of 87 miles\(^2\) bounded by the South Platte River, Sand Creek, Second Creek and Highline Canal can be studied. Hydrological processes which affect the groundwater system under the RMA can be modeled within this area. This region was used by Harding Lawson Associates, et al. (1990) for their regional flow model of the RMA. The current project evaluated only the onpost region (27 miles\(^2\)) of the RMA flow system.
Chapter 2

GEOSTATISTICS

This chapter provides a brief introduction to geostatistics. Geostatistical tools aid in understanding and modeling spatial variability of natural phenomena (Deutsch and Journel, 1992). Basic concepts include the regionalized variable, stationarity, the semivariogram, kriging, and stochastic simulation.

Regionalized Variable

Davis (1986) explains that the basic concept underlying geostatistics is the regionalized variable (ReV). Its properties lie between a random variable and a deterministic variable. The ReV is spatially continuous but complex and is often used to represent natural phenomena such as geologic surfaces. A deterministic function could not describe the complexity of the ReV and a random function does not describe the spatial correlation. Known data values or samples are used to define the ReV’s modeled characteristics (Davis, 1986).

Stationarity

Most geostatistical estimation methods assume stationarity of the ReV (Isaaks and Srivastava, 1989). Stationarity implies that for every search neighborhood, the average
of the ReV is the same (Davis, 1986). According to Isaaks and Srivastava (1989), non-stationarity can result if a data set contains separate distinct populations or contains a trend. In the first case, the data set can be split into the subpopulations and each analyzed separately. In this study, some data sets contained a regional trend causing non-stationarity. This trend can be removed in two ways. The first is universal kriging, which can produce undesirable behavior (Isaaks and Srivastava, 1989), because the trend is calculated and removed from data points in each individual search neighborhood (Davis, 1986). Removal of local variations may occur depending on the size of the search neighborhoods. The second trend removal process is trend analysis which calculates and removes one regional trend surface from the entire data set (Davis, 1986). This is a separate, distinct step, creating more control of the trend removal process (Isaaks and Srivastava, 1989). The latter method was chosen for this study.

Most authors agree that field data sets rarely approach stationarity, and it is not of practical significance. But it is still a fact that geostatistical theory based on ReVs is not valid when the data show non-stationarity (Henley, 1981). Ordinary kriging can be used as a non-stationary algorithm because it assumes only stationary covariances and varying means within each search neighborhood (Deutsch and Journel, 1992).

**Semivariograms**

Covariance, a basic measure of geostatistics (Davis, 1986), is used for modeling spatial variability of the data (Deutsch and Journel, 1992). It reflects the correlation of
data values along a specified direction and displays spatial dependence between data samples (Davis, 1986). Semivariograms are often used to display spatial variability. The experimental semivariogram is defined as:

$$\gamma_h = \frac{1}{2n} \sum_{i=1}^{n} [z(x_i) - z(x_i + h)]^2$$

where $h$ is the distance between data points, $z(x)$ and $z(x+h)$ are the data values at two locations, and $n$ is the number of data pairs (Journel and Huijbregts, 1978). As $h$ increases there is less correlation between data points and the gamma value increases. At and above a specific value of $h$ (defined as the range of the semivariogram), the points will no longer be correlated and the gamma value is constant at approximately the variance of the data set. For $h$'s greater than or equal to the range, the gamma value is defined as the sill. A sample experimental semivariogram is displayed in Figure 2.1. The range defines the neighborhood in which data are correlated (Davis, 1986).

Directional semivariograms calculate spatial correlation in different orientations. Anisotropy of a data set can be determined by using directional semivariograms to find the long (maximum) and short (minimum) ranges of the data set.

Occasionally, the semivariogram will not go through the origin. This is called a nugget effect. It occurs when there is variability in the data over distances shorter than the sampling interval (Davis, 1986).

The experimental semivariogram only defines spatial continuity at discrete values of $h$. Therefore, the experimental semivariogram must be fitted with a continuous,
Figure 2.1: Sample experimental semivariogram. The range is the distance at which there is no longer data correlation. The sill is the value at which the gamma values level off. The nugget value occurs when there is variability in the data over distances shorter than the sampling interval.
smoothly varying model which defines spatial variability for all h values (Davis, 1986). This model must also be a positive definite function which will allow the estimation equations to have a single, stable solution. Positive definite models that are commonly used are the spherical, exponential, Gaussian, power, and linear models (Isaaks and Srivastava, 1989). If necessary, multiple models can be linearly combined to create another positive definite model called a nested structure (Isaaks and Srivastava, 1989). When fitting models to directional experimental semivariograms, nested models are often more flexible than single models when trying to obtain a good fit in multiple directions (Poeter and Townsend, 1994).

**Estimation and Simulation**

Kriging is a technique used for estimation of a value at an unsampled location. Kriging uses the semivariogram model to assign weights to known data values that are within a search neighborhood of the point for which a value is to be estimated. The assigned weights vary according to the distance from the point under estimation (Davis, 1986). Estimation of many unknown points will generate a kriged map of the area.

Kriging has a smoothing effect, reducing the variance of the data. Kriging also produces only one map of the area (the best linear unbiased estimate). Multiple realizations that honor the known (conditional) data, honor the spatial continuity described by the semivariograms, and maintain the original data variability, can be created by using a conditional, stochastic simulation technique (Gomez-Hernandez and Srivastava, 1990).
At each location, a cumulative probability distribution function is calculated, and the value assigned to the location is chosen randomly from that function. This method allows for generation of multiple realizations that honor the known values and their spatial statistics. Figure 2.2 displays a comparison of estimation, simulation, and reality.

Another way of generating stochastic simulations is the turning band algorithm. This method is unconditional, shows artifact banding in 3-D, and cannot easily handle anisotropy directions other than the coordinate axes. After completion of the simulation, postprocessing algorithms can be utilized to condition the simulation although this can be slow and cumbersome (Deutsch and Journel, 1992). For these reasons, the sequential indicator conditional simulation method was chosen over the turning band algorithm for this study. A comparison of the two methods is discussed in detail by Ruskauff and Field (1993).

Spatial data clustering can influence data estimation or simulation because clustered data with similar values are given too much weight in the calculation of nearby unknown values. This could potentially be a problem with RMA data because there are many wells clustered in areas of contamination or remediation, such as the boundary containment systems. In some cases, it may be necessary to decluster the data. In this study, the clustering problems were solved with ordinary kriging and octant searches. Ordinary kriging takes into account the clustering of nearby samples and their distance to the estimation point (Isaaks and Srivastava, 1989). Octant searches allow only a predetermined number of data points from each octant surrounding the location to be used
Figure 2.2: Comparison of reality, kriging estimation, and conditional simulation. Kriging tends to smooth the data while conditional simulation retains the original data variability of reality (after Journel and Huijbregts, 1978).
in the calculation of the data value. Both of these methods help to reduce clustering side-effects.
Chapter 3

METHODS

The methods of research consisted of data collection, trend analysis, alluvial data transformation, semivariogram analysis, simulation, connected coarse-grained pathway determination, probability map generation, groundwater flow modeling and contaminant transport modeling.

Data Collection

The data for this project came from a variety of sources. Previously computerized data such as easting coordinates, northing coordinates, ground elevations, and water elevations were obtained from RMA computer databases. The rest of the data were manually gathered from borehole lithological logs.

Data were collected for wells and bores within the onpost area of the RMA. Offpost data were not used. "Wells" were defined as boreholes that were developed into water wells with casing and screens, and "bores" were boreholes that were not developed into water wells. Data were collected from 974 wells and bores. Figure 3.1 shows the data site locations. The breakdown of the 879 well locations and 95 bore locations are displayed in Figure 3.2. The average site spacing was 378 feet. The majority of data were obtained from the borehole logs of the wells used in the Groundwater Monitoring
Data Collected - Wells and Bores

974 Data Points

Figure 3.1: Locations of data collected for both wells and bores.
Well Data Collected - 879 Data Points

Bore Data Collected - 95 Data Points

Figure 3.2: Breakdown of data into wells and bores.
Program (GMP) Network. These boreholes were easily available for analysis. To obtain data for areas without GMP wells, borehole logs of bores and non-GMP wells were obtained from the Research Information Center Technological Library at the RMA.

The borehole logs were written at the drill sites. Some logs were illegible due to poor handwriting or generations of poor copies, but the majority were legible. The characteristics gathered for each stratum were depth of stratum, Unified Soil Classification System (USCS) code (Al-Khafaji, et al., 1992), degree of calcification, description of calcification, degree of cementation, number of blows per 1.5 feet, and, if number of blows were not available, degree of compaction. The degrees of calcification, cementation, and compaction were recorded as low, medium, high, or not given. These lithological characteristics were chosen for collection because they influence hydraulic conductivity. High calcification, high cementation, high number of blows and high compaction all lower hydraulic conductivity. Although it was not known during data collection which of these characteristics were essential for data analysis, they were recorded in case they would be needed.

In some borehole logs, the USCS code for the stratum was not given. In these cases, a USCS code was assigned according to the written description of the stratum. If the stratum was described as weathered Denver Formation claystone, Denver Formation sandstone, or volcaniclastic sediments, the code assigned was DW, DS, or VC, respectively.

In order to find spatial continuity and create geostatistical simulations, the
lithology had to be numerically represented, therefore integers known as indicator values were assigned to the lithologies. The data were divided into two indicator values, 1 and 2, where 1 was coarse-grained alluvium and 2 was fine-grained alluvium. Coarse-grained alluvium was defined as any sand- or gravel-dominated lithologies and fine-grained as any silt- or clay-dominated lithologies.

Bedrock depth and confining layer depth were also recorded for each borehole. In boreholes in which the bedrock was not reached in drilling, the bedrock depth was recorded as "greater than" the deepest recorded stratum. Ninety-four percent of the wells reached bedrock, whereas only 20% of the bores reached bedrock.

The top of the confining layer was assumed to be at or below the bedrock surface. The confining layer could only be deduced when the detail of the lithological description of the bedrock was sufficient. The confining layer was determined to be the depth at which the alluvium, sandstone bedrock, weathered claystone bedrock or weathered siltstone bedrock was in contact with competent bedrock. Competent bedrock could be described as non-weathered claystone. Weathered bedrock was identified by terms such as iron oxide coating on fractures and oxidation. Eighty percent of the borelogs did not have sufficient bedrock lithological detail to deduce the confining layer depth or did not reach competent bedrock in the drilling. In these cases, the confining layer depth was recorded as "greater than" the deepest stratum of alluvium or incompetent bedrock recorded.

The above information from the borehole logs was recorded on handwritten forms
as displayed in Figure 3.3. The data were entered into an INGRES computer database designed specifically for this project. The borehole data are presented in the Appendix (diskette). The database also included computerized data retrieved from the Arsenal databases such as water levels, ground elevations and borehole coordinates. Computer programs were written in ESQLC to interface with the database. These programs pulled requested data from the database and compiled it into the required data format for input into the data analysis software.

**Trend Analyses**

Often when analyzing the data, it was necessary to consider whether a regional trend was affecting the data values. Some data could be separated into a regional trend and local fluctuations. This implied that there were at least two geologic forces acting, one that created the general geologic nature or regional trend of the area and another that caused smaller scale deviations. A trend surface is a surface defined by a linear polynomial function that minimizes the squared deviations of the trend from the data. The function is based on geographic coordinates. The better the fit of the trend to the data, the smaller the variance of the residuals, where the residuals are the original data minus the trend surface (Davis, 1986). The trend residuals were used to find the true spatial continuity of the data without the introduction of severe anisotropy caused by the regional trend.

Trend surfaces of different orders were fit to the original data. A first order trend surface was a flat, dipping plane, while higher order trend surfaces were curved planes.
Borehole Information for Rocky Mountain Arsenal Geostatistical Study

Section Number ____________ Well Number ____________ Date Data Collected ____________

Bedrock Depth (ft) ____________

Confining Layer Depth (ft) ____________

Description of Unconfined Strata in Borehole  
(N,L,M,H = Not Given, Low, Medium, High)

<table>
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<tr>
<th>Bottom of Interval (ft)</th>
<th>Unified Soil Classification</th>
<th>Degree of Calcification (N,L,M,H)</th>
<th>Degree of Cementation (N,L,M,H)</th>
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The higher the order of trend surface, the more unstable the surface was when predicting trend. But, the fit of the trend surface to the data was usually better with higher order trend surfaces. ANOVA (Analysis of Variance) statistics such as Goodness-of-Fit, F-Test, and variance were available to check the significance of the polynomials. Thus, the goal was to determine a trend surface which appropriately removed the regional trend from the original data without introducing unstable conditions to the study and without removing any local variations that were desired for the semivariogram analysis.

There were many ways to compare different degree trend surfaces to determine which would be the appropriate trend to remove. The first was a visual comparison of the trend surface to the original data. Another was the study of the ANOVA statistics. The $r^2$ or $(\text{Goodness-of-Fit})^2$ values showed how close the trend surface approached known points (Davis, 1986). A third test was to visually examine the residual maps for successful trend removal.

A final way to compare the trend surfaces was to compare semivariogram maps of the original data and the residual data sets. This method was of particular interest because the residuals were used for the determination of spatial variability. The idea of trend surface removal was to eliminate the anisotropy created by the regional trend. Semivariogram maps of different residual data sets were compared to determine the strength of anisotropy for each degree trend removed. A sample semivariogram map showing contours of variance is displayed in Figure 3.4. The map can be read by starting at the center of the map and looking outward in all directions. The orientation of a radius
Example Semivariogram Map
Contour Interval = Variance = 3034.7 ft

Figure 3.4: Example of a semivariogram map. White is high correlation between data points and black is low correlation.
on the map is the directional orientation of the corresponding semivariogram. The center is the beginning of the semivariogram and should be a low value (light color) due to high correlation. As the map goes outward, the spatial correlation should decrease into darker colored areas (low correlation). Spatial anisotropy can be seen when a dark color is closer in one direction from the center than a dark color in another direction. One can also compare when the variance (first contour from the center) is reached in different directions from the center. Complete isotropy of the data set is represented by a bulls-eye effect in the map. The outer portions of the semivariogram maps are not significant because they are beyond the range and are often based on a limited number of data pairs.

In this study, regional trends were apparent in two 2-D surface studies: the bedrock surface and the water table surface. A regional trend was not found in the 3-D alluvial lithological data.

The trend residual data set was used for semivariogram calculations to determine spatial continuity. But the question arose of which data set, the original data or the trend residual data, should be used for input into the simulation software. To answer this question, a first degree trend surface was removed from the bedrock surface and the residuals were used to find the spatial continuity of the data. Then, two simulations were run using the same spatial continuity values but different data sets, original bedrock elevation data and trend residual data. The results of this test are displayed in Figure 3.5. The simulation created with the residual data set was significantly smoother than the simulation created with the original data because the original data set had more variability
Figure 3.5: Comparison of original bedrock data simulation with first degree trend residual data simulation.
in elevation than the residual data set. The smooth surface better represented the 
continuity expected in an eroded surface rather than the abrupt highs and lows of the 
original data surface simulation. Therefore, the residual data set was used for input into 
all simulations involving data where a regional trend is evident.

After simulations were run using the residual data, the regional trend was returned 
to the data set. This was necessary for the accurate interpretation of the simulations.

**Alluvial Data Transformation**

Preliminary semivariogram results of the 3-D lithological alluvial data set 
(discussed in Chapter 4) demonstrated that it was necessary to transform the data. 
Transformation of data from original Cartesian coordinates to stratigraphic coordinates is 
discussed in detail by Journel and Gomez-Hernandez (1993) and is illustrated in Figure 
3.6. The gravel, sand, silt, and clay deposits were likely to conform to stratigraphic 
coordinates rather than Cartesian coordinates, consequently transformation of the data 
allowed for more accurate determination of the spatial continuity of the lithologic bodies. 
Semivariograms were calculated for the transformed data and simulations were run using 
the transformed data. After the simulations, the coordinates were restored to the original 
Cartesian system (Journel and Gomez-Hernandez, 1993).

Only the elevation or the z coordinate was changed in the transformation process. 
The x and y coordinates remained unchanged. First, the greatest alluvial thickness and 
accompanying ground elevation were determined. Next, for each borehole, the greatest
Figure 3.6: Theory behind the transformation of the alluvium data. In the top figure, spatial variance calculations do not take geologic stratification into account when comparing horizontal data points. The bottom figure is a transformed data set in which horizontal data points compared do honor the geologic stratification (after Journel and Gomez-Hernandez, 1993).
alluvial thickness was divided by that borehole's alluvial thickness to create a transform factor. The depth of each stratum in that borehole was then multiplied by the factor, so that each borehole had the same alluvial thickness as the maximum alluvial thickness. Each borehole was assigned the same ground elevation as the borehole with the greatest alluvial thickness. Data points were then assigned at three foot vertical intervals. The end result was a regular rectangular grid.

After simulation of the alluvium, the data were returned to their original coordinate system by reversing the transformation process. To calculate the thickness of alluvium for the transformation reversal, ground and bedrock elevation values were needed. These values were available for the original alluvial coordinate transformation, but, in the simulations, there were many points simulated that the exact ground and bedrock elevations were not known. Due to the large amount of ground elevation data available, an inverse-distance generated ground surface map was determined to be suitable to supply ground elevations for the transformation reversal. Bedrock elevations were supplied by the bedrock surface simulations.

**Semivariogram Analysis**

Semivariogram analyses were run on each data set to determine spatial continuity. Semivariograms are explained in Chapter 2. For the water table and bedrock surface data sets, the experimental semivariograms were generated using the trend residual data sets. For the alluvial data set, the experimental semivariograms were run on the
stratigraphically-transformed data set.

Long and short range directions were determined by the generation of multiple experimental semivariograms in the horizontal plane for each of the data sets. All of the data sets displayed anisotropy. A vertical semivariogram was also generated for the 3-D alluvial data set.

Often it is desirable to produce an experimental jackknifed semivariogram to determine the level of confidence in the semivariogram (Wingle and Poeter, 1993). For this study, the jackknifed semivariograms had extremely small error bars due to the large amount of data, indicating confidence in the experimental semivariograms.

Semivariogram models, single and nested, were fit to the experimental semivariograms. These models were used to describe the spatial continuity of the data to the simulation software. The values input to the simulators were: nugget value, model type for each model, sill value for each model, range value for each model, direction of the long range semivariogram and range anisotropy in the short range direction and vertical direction for each model. The simulation software required that the sill values were the same for the long range, short range, and vertical directions, so only the range differed between the directional semivariograms. The anisotropies were calculated by dividing the range values for the orthogonal directions.
Simulations

Two simulation software packages were used in this project. The SGSIM code of GSLIB was used for the 2-D water table and bedrock surface simulations and ISIM3D was used for the 3-D alluvial lithology simulations. Chapter 2 explains geostatistical simulations.

GSLIB, a "Geostatistical Software Library" (Deutsch and Journel, 1992), contains many different simulation modules. The module used in this project was SGSIM, a "Sequential Gaussian Simulation" (Deutsch and Journel, 1992) program. SGSIM creates stochastic, conditional simulations of a continuous variable (Deutsch and Journel, 1992). Stochastic, conditional simulations are multiple realizations which honor the known data. In this study, the continuous variable was elevation.

ISIM3D is an "Ansi-C Three-Dimensional Multiple Indicator Conditional Simulation Program" (Gomez-Hernandez and Srivastava, 1990). ISIM3D creates multiple stochastic conditional simulations as does SGSIM. ISIM3D is different from SGSIM in that it simulates indicators, such as 1 (sand and gravel) and 2 (clay and silt), rather than a continuous variable (Gomez-Hernandez and Srivastava, 1990).

Saturated Alluvium Probability Maps

Saturated alluvium probability maps were created of the RMA onpost region. These were plan-view contour maps displaying the probability of occurrence of saturated alluvium. To calculate a map, multiple water table simulations and bedrock surface
simulations were combined. In each combination, each node of the water table simulation was compared to the corresponding node of the bedrock surface simulation. If the elevation of the water table node was above the elevation of the bedrock surface node, that node was considered to be saturated. The number of times a particular node was saturated for all of the combinations, e.g. 1500, was divided by the total number of combinations, e.g. 2025, to determine the probability that the node was saturated, e.g. 0.74 or 74%. All of the probability nodes were then combined to create a saturated alluvium probability map.

**Connected Coarse-Grained Pathways**

To add a third dimension to the study, the alluvial lithological simulations were combined with water table and bedrock surface simulations to create 3-D saturated alluvial bodies. For each body, one alluvial simulation was combined with one water table simulation and one bedrock simulation. Any coarse- or fine-grained nodes in the alluvial simulation that fell above the water table elevation or below the bedrock elevation were disregarded. All alluvial nodes below the water table and above the bedrock were retained as saturated alluvium. In cases where the water table was below the bedrock surface, there was no saturated alluvium and all simulated alluvial nodes were disregarded for that x,y location. The water table and bedrock surface simulations were chosen based on their respective combined volumes. This is discussed in Chapter 4.

The preferred route of contaminant transport will occur along connected coarse-
grained pathways within the saturated alluvial bodies. With Basin A as an origin, connected coarse-grained pathways between Basin A and the RMA boundaries were determined in each of the saturated alluvial bodies. Each node in the Basin A boundary was used as a starting point. A path was tracked into one adjacent coarse-grained node and continued until a point was reached where the node was surrounded by fine-grained nodes. This path was backtracked to the last juncture and coarse-grained nodes that were not visited were tracked in the same manner. This recursive procedure was followed until all connected paths were found. This had its limitations in that discontinuity just offpost would not be identified by the procedure but would slow down contaminant migration. Future research could expand this work to the natural hydraulic boundaries of the flow system.

Probability maps of the connected coarse-grained pathways were created as 2-D plan-view maps. The individual paths were weighted in the probability calculations according to the Latin Hypercube Sampling weight (Chapter 4) associated with each bedrock surface/water table combination used to create the corresponding saturated alluvial body. To create the probability map, a bird’s-eye view of each 3-D connected coarse-grained pathway was taken. If a grid node was part of a connected pathway, the counter for that node and the counter for the total number of saturated alluvial bodies were incremented according to the corresponding weight. If the weight was 1.0, the node counter and total counter were incremented by 1.0 or if the weight was 0.5, the node counter and total counter were incremented by 0.5. After examining all pathways, the
counter for each node was divided by the total number of saturated alluvial bodies to get the probability that that node was part of a connected coarse-grained pathway.

The connected coarse-grained pathway probability maps show only probable paths for rapid contaminant migration. This is a simplistic view of contaminant transport, ignoring groundwater flow properties such as relative hydraulic conductivity and hydraulic gradient. To truly simulate transport, groundwater flow and contaminant transport modeling must be utilized.

**Groundwater Flow and Contaminant Transport Modeling**

The advantages of groundwater modeling over the connected coarse-grained pathway analysis was demonstrated with the application of the computer codes, MODFLOW and MT3D, to one saturated body.

Before simulating contaminant migration with the transport model, MT3D, the flow system was modeled. MODFLOW, "A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model" (McDonald and Harbaugh, 1988) was utilized for groundwater flow modeling. MODFLOW uses a 2-D or 3-D, finite-difference, block-centered approach. The software was written in modules to allow the user to selectively choose the portions of the hydrologic system to model and the method for solving the linear equations of the flow system (McDonald and Harbaugh, 1988).

Contaminant migration was modeled using MT3D, "a modular three-dimensional transport model" (S.S. Papadopulos & Associates, Inc., 1991). MT3D simulates chemical
reactions, advection, and dispersion of contaminants in 2-D or 3-D systems. The advective-dispersive equation was solved using the modified method of characteristics. Like MODFLOW, MT3D is structured in a modular fashion (S.S. Papadopulos & Associates, Inc., 1991).
Chapter 4

ANALYSIS AND RESULTS

The study results can be divided into five categories: bedrock surface, water table surface, alluvial lithology, simulation combination, and flow and transport analyses.

**Bedrock Surface**

The bedrock surface data consisted of 842 data points with an average data spacing of 410 feet. The locations of these data are displayed in Figure 4.1. The analysis consisted of trend surface determination, semivariogram generation and bedrock surface simulation.

**Bedrock Surface Trend Analysis**

At the RMA, the erosional slope of the bedrock surface dips slightly towards the Platte River in the Northwest (Harding-Lawson Associates, 1992). The bedrock surface elevations differ up to approximately 250 feet within the onpost region of the RMA. The dip of the surface introduced anisotropy and non-stationarity into the semivariogram analysis, therefore it was necessary to remove a trend surface to eliminate the dip of the bedrock without removing the local variations of paleo-channels and paleo-highs.

Three trend surfaces (first, second, and third degree) were fit to the bedrock
Figure 4.1: Locations of bedrock surface data points.
elevation data set. All three trend surfaces displayed the northwest-dipping trend. These surfaces were compared to determine which would be the appropriate trend to remove. A visual comparison of trend surfaces to the bedrock contour map is shown in Figure 4.2. The second and third degree trend surfaces were similar and both fit the apparent concavity of the bedrock surface. The first degree trend surface was a flat plane which did not fit the concavity of the data.

Next, ANOVA statistics were compared. These are listed below in Table 4.1. The F-Test results were fine for all trend surfaces due to the large number of data points. The $r^2$ or (Goodness-of-Fit)$^2$ values varied from 79% to 85% which were all acceptable. The second and third degree trends had almost indistinguishable $r^2$ values of 84% and 85%. The variances of the trend surfaces were also important. The variance decreased significantly from the original data (3,034.7 feet) to the first degree residual variance (630.2 feet). It also decreased significantly from the first to second degree residual data (480.1 feet). However there was not much change from the second to third degree residual data (451.1 feet). All of these statistics indicated that all three of the trend surfaces would be suitable for trend removal. However, the second and third degree trend surfaces were better matches than the first degree surface. Since the second and third degree trend surfaces were similar, it was preferable to use the second degree trend surface because it was a lower degree trend and was more stable (based on less coefficients).
Figure 4.2: Comparison of bedrock surface with first, second, and third degree trend surfaces.
Table 4.1: Analysis of Variance (ANOVA) results from bedrock trend surface analysis.

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<th>Variance (ft)</th>
<th>F-Test</th>
<th>Degree of Freedom</th>
<th>Goodness of Fit (r)</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Degree Trend</td>
<td>630.2</td>
<td>1068.4</td>
<td>3 / 840</td>
<td>0.890</td>
<td>0.792</td>
</tr>
<tr>
<td>2nd Degree Trend</td>
<td>480.1</td>
<td>742.3</td>
<td>6 / 837</td>
<td>0.918</td>
<td>0.842</td>
</tr>
<tr>
<td>3rd Degree Trend</td>
<td>451.1</td>
<td>477.2</td>
<td>10 / 833</td>
<td>0.922</td>
<td>0.851</td>
</tr>
</tbody>
</table>

Examination of the residual (original data minus the trend) maps of the three trend surfaces was also useful. These are shown with the original bedrock map in Figure 4.3. The first degree residuals displayed a trend of a surface dip to the Southeast. The second and third degree residuals appeared very similar with the elevation highs in the middle and corners of the maps. A dipping trend was not visible in the second and third degree residual maps. Again, the second degree trend appeared to be the desired trend to fit to the bedrock because it was more stable than the third degree trend and the corresponding residual map did not display a trend.

Semivariogram maps for the bedrock residuals are displayed in Figure 4.4. In these maps, the contour interval is the variance of the individual data sets. The semivariogram map of the original data clearly shows the northwest trend of the data. The northwest/southeast direction had very low spatial correlation (short range) while the northeast/southwest direction had high spatial correlation (long range) because it was at
Figure 4.3: Comparison of bedrock surface with first, second, and third degree trend residual surfaces.
Figure 4.4: Comparison of bedrock surface semivariogram map with first, second, and third degree residual surface semivariogram maps.
strike to the trend. The semivariogram map of the first degree trend residuals showed that there was still obvious anisotropy to the spatial correlation, again with the long range in the northeast/southwest direction. The anisotropy was not as strong as in the original data, but was still evident. This anisotropy was due to the fact that there was still a trend with the removal of the first degree trend surface although the direction of dip was reversed from the original trend. The second and third residual semivariogram maps showed that the anisotropy had decreased significantly. In the distance of the first contour interval (variance) from the center of the semivariogram map, the second and third degree trend residuals were essentially the same. This final comparison of the three trend surfaces again pointed to the second degree trend surface as the desirable trend surface to use.

After comparison of the trend surfaces, residual surfaces, ANOVA values, and semivariogram maps, the decision was made to remove a second degree trend surface from the bedrock surface data.

**Bedrock Surface Semivariogram Analysis**

Spatial variability of the surface was described by experimental semivariograms generated on the residual data. These semivariograms are displayed in Figure 4.5. Semivariograms were created for both the long (170 degrees clockwise from North) and short (80 degrees) range directions. Doubly nested spherical models were fit to the long range semivariogram. The long range values for the two nested models were 4,300 feet
Figure 4.5: Bedrock surface semivariograms.
and 11,000 feet. Since the doubly nested spherical models did not fit the short range semivariogram well, it was decided to fit the models to the first six gamma values because generally the first gamma values of the semivariogram are the most important for describing the spatial continuity of the data. This fit caused the range to be larger than desired so the search radius value used for the simulations was set to 4,500 feet rather than the model’s range of 6,900 feet. The experimental semivariogram specifics are presented in Table 4.2.

Table 4.2: Bedrock experimental semivariogram specifics.

<table>
<thead>
<tr>
<th>Semivariogram</th>
<th>Lag (ft)</th>
<th>Direction (Degrees from North)</th>
<th>Bandwidth (ft)</th>
<th>Half Angle (Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedrock Long Range</td>
<td>550</td>
<td>170</td>
<td>180</td>
<td>15</td>
</tr>
<tr>
<td>Bedrock Short Range</td>
<td>500</td>
<td>80</td>
<td>200</td>
<td>10</td>
</tr>
</tbody>
</table>

**Bedrock Surface Simulations**

Forty-five simulations of the bedrock surface were run using SGSIM. The regional trend was then added back to the simulations. Four simulations are displayed in Figure 4.6. The grid specifications were 150 nodes in the X direction and 125 nodes in the Y direction with each node equal to 215 x 215 feet².
Figure 4.6: Examples of bedrock surface simulations. Contour interval is 50 feet.
Water Table

Precipitation, evaporation, transpiration, filling and draining of surface water storage facilities, well pumping, and well injection cause the water table to vary as a function of time. Multiple water table data sets were necessary for a comprehensive study of the water table. The most accurate procedure for establishing water table configurations is through conduction of a flow model for each stochastic realization. Such extensive modeling was beyond the scope of this project. An example analysis for one realization is provided later to illustrate the procedure. The water table analysis entailed selection of time periods, regional trend removal, semivariogram analysis, and simulations.

Selection of the Water Table Measuring Periods

Water table measurements from three time periods were desired. For good spatial data coverage, all time periods were required to have a significant number of wells measured. Also, the time periods must occur during different seasons to demonstrate a maximum, intermediate, and minimum water table. The periods were twenty days in span in order to get a maximum amount of data with small probability of significant fluctuations in water levels.

as to which day the well was measured. More accuracy was desired, so only 1990-1991 and 1991-1992 were considered in detail. In these two years, five periods had significantly more data than other times. These five periods were 1/16/91 - 2/4/91 (612 wells), 3/31/91 - 4/19/91 (601 wells), 9/12/91 - 10/1/91 (588 wells), 3/3/92 - 3/22/92 (577 wells), and 5/28/92 - 6/16/92 (575 wells). To reduce the five periods to three, thirty preliminary water table simulations were run on each of the five data sets. Each water table simulation was combined with the same bedrock surface simulation to determine the groundwater volume. The volume was calculated by subtracting the bedrock elevation from the water table elevation for each node of the simulation in which the water table was above the bedrock surface. All volumes for each time period were then averaged. The maximum groundwater volume average occurred in the time period 3/31/91 - 4/19/91 (Spring 1991). The minimum average volume came from the period 9/12/91 - 10/1/91 (Fall 1991). The other three periods had very close volume averages. The intermediate groundwater volume time period was chosen to be 1/16/91 - 2/4/91 (Winter 1991) to keep the analysis in one calendar year. The locations of the wells for these three measuring periods are displayed in Figure 4.7. The average data spacings were 486 feet, 496 feet, and 501 feet for Winter, Spring, and Fall 1991, respectively.

**Water Table Trend Analysis**

As in the bedrock surface analysis, it was apparent from viewing the water table surface map that a regional trend existed in the data. This was due to the slope of the
Figure 4.7: Locations of water table data points for the time periods: Winter 1991, Spring 1991, and Fall 1991.
water table as the water flows from the Southeast towards the South Platte River in the Northwest. Because the water table surfaces were all very similar, one data set (Spring 1991) was utilized in the trend order selection process. The water table surface map and first, second, and third degree trend surfaces are shown in Figure 4.8. Visually, the second and third degree trend surfaces were a better fit to the data than the first degree trend surface. The semivariogram maps of the original data and trend residuals are displayed in Figure 4.9. As with the bedrock semivariogram maps, there was obvious anisotropy due to the trend in the original data and the first degree trend residuals. The second and third degree trend residual semivariogram maps were quite similar and did not display anisotropy due to the trend of the sloping water table. The original data and trend residual surfaces are mapped in Figure 4.10. Ideally the residual surface should show no trend. The first degree residual surface showed a trend dipping to the Southeast. The second and third residual surfaces did not display the original trend or the reverse trend. Both of these residual surfaces were acceptable for semivariogram analysis and surface simulation.

The analysis of variance results are detailed in Table 4.3. All of the statistics were acceptable. As in the bedrock trend ANOVA analysis, the variance decreased with the increasing trend degree. The original data had a variance of 2,620.8 feet. The trend residual variances (276.7 feet, 197.7 feet, 172.6 feet) were significantly smaller. Any of the trend surfaces were statistically acceptable for removal from the water table surface data.
Figure 4.8: Comparison of water table surface with first, second, and third degree trend surfaces.
Figure 4.9: Comparison of water table surface semivariogram map with first, second, and third degree trend residual surface semivariogram maps.
Figure 4.10: Comparison of water table surface with first, second, and third degree trend residual surfaces.
Table 4.3: Analysis of Variance (ANOVA) results from water table trend surface analysis.

<table>
<thead>
<tr>
<th></th>
<th>Variance (ft)</th>
<th>F-Test</th>
<th>Degree of Freedom</th>
<th>Goodness of Fit (r)</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Degree Trend</td>
<td>276.7</td>
<td>1685.6</td>
<td>3 / 597</td>
<td>0.946</td>
<td>0.894</td>
</tr>
<tr>
<td>2nd Degree Trend</td>
<td>197.7</td>
<td>1213.6</td>
<td>6 / 594</td>
<td>0.962</td>
<td>0.925</td>
</tr>
<tr>
<td>3rd Degree Trend</td>
<td>172.6</td>
<td>818.1</td>
<td>10 / 590</td>
<td>0.966</td>
<td>0.933</td>
</tr>
</tbody>
</table>

Overall, the second and third degree trend surfaces fit the data better than the first degree trend surface. Since the second degree trend was more stable than the third degree trend, it was chosen to represent the trend in the water table data. Separate second degree trend surfaces were fit to each of the three sets of water table data.

**Water Table Semivariogram Analysis**

After a second degree trend was removed from the Spring 1991 water elevation data, semivariograms were generated on the data to determine spatial continuity. The long range was found in the 35 degree (clockwise from North) direction and the short range was in the 125 degree direction. A single Gaussian model was fit to the data. The range anisotropy found was 2,600/4,700 or 0.55. The semivariograms are shown in Figure 4.11. The semivariogram specifics are listed in Table 4.4. To justify using the same semivariogram specifics for all three water table data set simulations, the second
Figure 4.11: Water table surface semivariograms for the Spring 1991 period.
degree trend residual maps for each data set were compared in Figure 4.12. Because the residual maps were very similar, it was assumed the spatial continuity for the data sets were the same and, hence, these semivariograms were used for all of the water table surface simulations.

Table 4.4: Water table experimental semivariogram specifics.

<table>
<thead>
<tr>
<th>Semivariogram</th>
<th>Lag (ft)</th>
<th>Direction (Degrees from North)</th>
<th>Bandwidth (ft)</th>
<th>Half Angle (Degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Table Long Range</td>
<td>580</td>
<td>35</td>
<td>250</td>
<td>10</td>
</tr>
<tr>
<td>Water Table Short Range</td>
<td>580</td>
<td>125</td>
<td>250</td>
<td>10</td>
</tr>
</tbody>
</table>

Water Table Simulations

Forty-five stochastic simulations were generated on each water table data set using SGSIM. The grid specifications were the same as for the bedrock simulations. There were 150 nodes in the X direction and 125 nodes in the Y direction with the area of each node equal to 215x215 feet². The regional trend was returned to the data after the simulations were run. Four simulations from each of the three data sets are displayed in Figures 4.13, 4.14, and 4.15. The differences in the water table data sets were in the magnitude of a couple of feet, and were not distinguishable in these contour plots.
Figure 4.13: Examples of water table surface simulations for the Winter 1991 period. The contour interval is 20 feet.
Figure 4.14: Examples of water table surface simulations for the Spring 1991 period. The contour interval is 20 feet.
Figure 4.15: Examples of water table surface simulations for the Fall 1991 period. The contour interval is 20 feet.
Differences between the data sets did become apparent when combined with the bedrock surface simulations to create saturated alluvium probability maps.

Alluvial Lithology

The third analysis completed was the study of the lithology of the alluvium. This included analysis of the original data, data transformation, semivariogram analysis, and geostatistical simulation. Alluvial deposits can be simulated by geologic process modeling. However, the complexity of the multiple braided stream and eolian depositional periods intermixed with erosional periods precludes such an analysis. The lithological data set was in a 3-D coordinate system, unlike the bedrock and water tables analyses which were 2-D.

Original Alluvial Data

The alluvial lithological information was collected from borehole logs and entered into a computer database as discussed in Chapter 3. A computer program was developed to retrieve the lithological information and assign x, y, z coordinates and an indicator value to the lithology. The alluvial data were retrieved at three foot vertical intervals, creating 11,139 data points. The data are presented in Figure 4.16.

Experimental indicator semivariograms generated on the alluvial data calculated the spatial continuity at one threshold between the two indicator values, 1 and 2. The average range was approximately 1,800 to 3,500 feet depending on lag values, where the larger lag values (e.g. 500 feet) yielded the larger ranges. Higher range values were
Figure 4.16: Alluvium data before transformation. Black is coarse-grained alluvium and grey is fine-grained alluvium.
expected due to the continuous nature of braided stream deposits. The low range values occurred because the stratigraphic units do not appear continuous in the Cartesian coordinate system due to the natural variation in alluvial deposition. Transformation of data to a stratigraphic coordinate system was necessary for reasonable spatial continuity calculations.

**Alluvial Data Transformation**

Data transformation from original Cartesian coordinates to stratigraphic coordinates is discussed in Chapter 3. The transformation process increased the number of data points from 11,139 to 35,870 due to the fact that the transformed space had a much larger volume than the original space and the same level of detail was maintained. The end result was a regular rectangular grid. The transformed data are shown in Figure 4.17.

**Alluvial Semivariogram Analysis**

Experimental semivariograms were calculated using the transformed data set. As expected, ranges were much higher than the original data semivariograms with an average of approximately 4,200 to 6,600 feet, depending on lag values. These higher range values demonstrated that the stratigraphic coordinate system had a more realistic representation of the continuity of coarse-grained and fine-grained bodies in a braided stream deposit than the original Cartesian coordinate system. Since the data had been transformed, it was sufficient to search for anisotropy in the horizontal plane (no dip) and perpendicular to the horizontal plane. The transformed alluvial system was found to be anisotropic with
Angle Above Horizon: 15 degrees
Viewing Direction: 10 degrees
Exaggeration: 35
Zoom: 0.65

Figure 4.17: Alluvium data after transformation. Black is coarse-grained alluvium and grey is fine-grained alluvium.
the horizontal long range in the 45 degree (clockwise from North) direction and the horizontal short range in the 135 degree direction. Nested exponential and spherical models were fit to the experimental semivariograms. These models were primarily dictated by the vertical semivariogram because it was calculated using more closely spaced data (Poeter and Townsend, 1994). The range anisotropies for the exponential models were found to be: 102/204 or 0.5 in the 45 degree horizontal direction and 25.40/204 or 0.124 in the vertical direction. For the spherical model, the range anisotropies were: 5,916/10,200 or 0.58 for the 45 degree horizontal direction and 73.66/10,200 or 0.007 for the vertical direction. These experimental semivariograms and their accompanying models are displayed in Figure 4.18. The experimental semivariogram specifics are listed in Table 4.5.

<table>
<thead>
<tr>
<th>Alluvium Semi-variogram</th>
<th>Lag (ft)</th>
<th>Horizontal Direction (clockwise from North)</th>
<th>Horizontal Bandwidth (ft)</th>
<th>Horizontal Half Angle</th>
<th>Vertical Bandwidth (ft)</th>
<th>Vertical Half Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horiz. Long Range</td>
<td>400</td>
<td>135</td>
<td>150</td>
<td>10</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Horiz. Short Range</td>
<td>400</td>
<td>45</td>
<td>150</td>
<td>10</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Vertical</td>
<td>2</td>
<td>0</td>
<td>Not Applicable</td>
<td>Not Applicable</td>
<td>5</td>
<td>10</td>
</tr>
</tbody>
</table>
Long Range Horizontal Alluvium Semivariogram
Direction=45; Exponential: Range=204, Sill=0.156, Nugget=0; Spherical: Range=10200, Sill=0.081

Short Range Horizontal Alluvium Semivariogram
Direction=135; Exponential: Range=102, Sill=0.156, Nugget=0; Spherical: Range=5916, Sill=0.081

Vertical Alluvium Semivariogram
Exponential: Range=25.40, Sill=0.156, Nugget=0; Spherical: Range=73.66, Sill=0.081

Figure 4.18: Indicator semivariograms for the transformed alluvium data.
Alluvial Simulations

Using the spatial continuity described by the alluvium semivariograms, fifty geostatistical simulations of the alluvium were generated using the ISIM3D software. The simulations were run using the transformed data set. The grid size was 150x125x40 with nodes of the size 215x215x3.225 feet$^3$. The simulations were then transformed back to the original Cartesian coordinate system.

Simulation Combinations

Combinations of the multiple water table, bedrock surface and alluvial simulations were used to build probability maps concerning the location of saturated alluvium and where connected coarse-grained pathways lie within the saturated alluvium. The process for creating these probability maps entailed: combining water table and bedrock simulations for saturated alluvium probabilities, statistically sampling the bedrock and water table simulations, and determining the probability of connected coarse-grained pathways within saturated alluvial bodies.

Saturated Alluvium Probability Maps

At the RMA, there are known areas of saturated and unsaturated alluvium. In the areas of unknown saturation, the water table and bedrock simulations were used to find probabilities of the existence of saturated alluvium. Saturated alluvium was defined to be areas of alluvium where the water table was above the bedrock and unsaturated alluvium was where the water table was at or below the bedrock. Zones of saturated
alluvium were very important when considering contaminant transport because contamination at the RMA generally moves only in saturated alluvium and saturated weathered bedrock.

Saturated alluvium probability maps are plan-view contour maps displaying the probability of the occurrence of saturated alluvium. Three maps were created for each of the three water table measuring periods. To calculate a map, all forty-five water table simulations from a time period and all forty-five bedrock surface simulations were combined for a total of 2,025 combinations. Probabilities were determined for all of the 18,750 nodes in the grid for each of the three water table data sets. The three probability contour maps are displayed in Figure 4.19. The regions with high probabilities of saturated alluvium were more extensive for the Spring 1991 period and were less extensive for the Fall 1991 period. This was expected because the Spring 1991 period had a higher water table and was more likely to have saturated alluvium, whereas the Fall 1991 had the lowest water table and was less likely to have saturated alluvium. The intermediate case, Winter 1991, had high probability saturated alluvium regions sized between those of the maximum and minimum maps.

**Latin Hypercube Sampling**

The same water table/bedrock surface simulation combinations that were used for the calculation of saturated alluvium probabilities were combined with alluvial simulations for a 3-D view of the lithology of the alluvium in the saturated zones. This three way
combination of simulations can easily become overwhelmingly computer intensive. If there are 40 alluvium simulations, 45 bedrock simulations and 135 water table simulations (three periods of 45 simulations), then there will be 243,000 3-D combinations to analyze. To bring this situation back to a useable size, it was necessary to limit the number of water table/bedrock surface combinations used for creation of the 3-D saturated alluvial bodies.

The water table/bedrock surface combinations were selected according to their groundwater volumes. The bedrock elevation was subtracted from the water table elevation for every node of each combination and the sum of these values for the whole grid were added to obtain the groundwater volume for that combination. The volumes for all of the water table/bedrock surface combinations for the time period were plotted in three histograms for the three water table time periods. The histogram for the Winter 1991 period is shown in Figure 4.20. All three histograms exhibited normal distributions.

Ideally, the water table/bedrock simulation combinations that exemplified the full range of possible volumes should be chosen for the 3-D saturated alluvium combinations. To choose these volumes, the Latin Hypercube Sampling method was used. This method allowed for a random sampling of a population while maintaining the original distribution (Rohen, 1988). To implement this method, the distribution was divided into 10th (10th, 20th, 30th, ..., 90th) percentiles. The 10th and 90th percentiles were further divided into 5th percentiles, creating twelve divisions of the distribution. One volume was randomly picked from each division, yielding twelve volumes total. The bedrock and water table
Figure 4.20: Histogram of volumes between bedrock and water table simulations. Forty-five bedrock surface simulations and forty-five water table simulations were individually paired and the volumes were calculated for all 2025 combinations. This distribution was used to find simulation combinations representative of the full range of volume possibilities.
simulations that produced those chosen volumes were then determined. When these simulations were used in probability calculations, the four water table/bedrock combinations from the 10th and 90th percentiles were given a weight of 0.5 while the other combinations were given a weight of 1.0. These weighted calculations are explained in Chapter 3. The Latin Hypercube Sampling Method was used on all three histograms from the three water table sampling periods.

Latin Hypercube Sampling of alluvial simulations by percentage of coarse-grained nodes was also investigated. However, it was found that connectivity of coarse-grained nodes was not correlated to percentage of coarse-grained nodes. Therefore, forty alluvium simulations were randomly chosen.

The 36 water table/bedrock combinations combined with the 40 alluvium simulations created 1,440 3-D saturated alluvium combinations. This number was much more manageable than the above mentioned scenario of 243,000 combinations. The distribution of groundwater volumes was maintained, so there was representation of large, small, and intermediate groundwater volumes.

**Connected Coarse-Grained Pathways**

The alluvial simulations were combined with the chosen water table and bedrock surface simulations to create 3-D representations of the saturated alluvium called saturated alluvial bodies. Two examples of saturated alluvial bodies are displayed in Figures 4.21 and 4.22. Figure 4.21 shows a body with a small volume of saturated alluvium, while
Figure 4.21: Saturated alluvial body with small volume of saturated alluvium. This body was created by combining one alluvial simulation, one water table surface simulation and one bedrock surface simulation. Black is coarse-grained alluvium and grey is fine-grained alluvium.
Figure 4.22: Saturated alluvial body with large volume of saturated alluvium. This body was created by combining one alluvial simulation, one water table surface simulation and one bedrock surface simulation. Black is coarse-grained alluvium and grey is fine-grained alluvium.
Figure 4.22 displays a large volume of saturated alluvium. Two east-west cross-sections from one saturated alluvial body are shown in Figure 4.23.

Connected coarse-grained pathways originating from Basin A were determined in each of the saturated alluvial bodies. Figure 4.24 shows three examples of the pathways. Plan-view probability maps of the connected coarse-grained pathways were then created using all of the determined pathways. Figure 4.25 shows the probability maps of Winter 1991, Spring 1991, and Fall 1991 with 10% contour intervals. Low probability maps with 0.5% contour intervals are displayed in Figure 4.26. The maps in Figure 4.25 demonstrate that there was more probability of connectivity in the coarse-grained bodies in the Spring of 1991 than in the Fall or Winter of 1991. This was because there was a greater volume of saturated alluvium in the Spring 1991 period. However, the connectivity shown is very limited. The only probability of significantly continuous coarse-grained pathways is shown in the low probability maps in Figure 4.26. These continuous pathways were only 0.5% probable in the Spring and Winter 1991 periods. The only pathway of concern was the Spring 1991 0.5% probable pathway because it extended northwest from Basin A in the direction of groundwater flow.

The absence of probable connected coarse-grained pathways in saturated alluvium extending from Basin A did not indicate lack of contaminant flow potential. If a pathway had all nodes of coarse-grained alluvium except for one node of fine-grained alluvium, the pathway was not considered continuous by these methods. Contamination could still flow through the route because the small fine-grained deposit would slow but would not
Cross-Section at Row 1

Cross-Section at Row 75

Figure 4.23: Cross-sections of a saturated alluvial body. The rows are numbered from the south. Light gray is fine-grained and dark gray is coarse-grained alluvium.
Figure 4.24: Examples of connected coarse-grained pathways originating at Basin A.
Figure 4.25: Comparison of saturated alluvium connected coarse-grained pathway probability maps for the three measuring periods: Winter 1991, Spring 1991 and Fall 1991. Contour interval is 10%.

- Red = 75-100% Probability of Connected Coarse-Grained Pathways
- Green = 25-75% Probability of Connected Coarse-Grained Pathways
- Blue = 0-25% Probability of Connected Coarse-Grained Pathways
Figure 4.26: Comparison of saturated alluvium connected coarse-grained pathway low probability maps for the three measuring periods: Winter 1991, Spring 1991 and Fall 1991. Contour interval is 0.5% from 0% to 10%.
stop contaminant transport. The only way to truly explore potential contaminant transport through the saturated alluvial bodies is through groundwater flow and transport modeling.

**Groundwater Flow and Contaminant Transport Modeling**

To illustrate that flow and transport modeling are important in addition to the connected coarse-grained pathway analysis, a greatly simplified representation of groundwater flow and contaminant transport was modeled in one of the many saturated alluvial bodies. For computational efficiency, the map view portion of the alluvium modeled was reduced to 13.75 mile$^2$ rather than the full 27 mile$^2$. The modeled region included the northwest and central areas of the onpost RMA. Because this was a simple comparison of modeling to the connected pathway analysis, the model was limited. The boundary conditions applied to the model were not natural hydrologic boundaries and this may present problems in the interpretation of the results. For instance, if a continuous gravel channel within the onpost region becomes discontinuous at the RMA border, contaminant migration would be slower than the model with limited boundaries would indicate. Other model limitations included the lack of groundwater-surface water interaction, pumping, injection, precipitation and other forms of discharge and recharge. The only contaminant source simulated in this example model was Basin A.

The finite-difference grid (Figure 4.27) had 112 columns, 87 rows and 84 layers. Each node was 215x215x3 feet$^3$, where the layer thickness was 3 feet. All nodes in the northwest offpost corner of the model area were defined as inactive. The boundaries of
Figure 4.27: Finite-difference grid used for groundwater flow and transport modeling. The grid has 112 columns, 87 rows, and 84 layers. The nodes are 215x215x3 feet.
the grid were designated as constant-head nodes. The constant-head and starting-head values were obtained from the average of the Winter 1991 water table surface simulations. The groundwater mound under South Plants was simulated with 335 general head boundary nodes.

The unconfined flow system consists of alluvium and underlying weathered bedrock. Because the saturated alluvial bodies included only alluvium, it was appropriate to add weathered bedrock to the base of the saturated alluvial body. There were 190 data points for the base of the unconfined flow system gathered during data collection. The data demonstrated a regional trend dipping to the northwest, so a second degree trend was removed from the data. The confining layer surface was generated using ordinary kriging with the OKB2D package from the GSLIB software library and the trend was returned to the surface. This surface was then added to the base of the saturated alluvial body to create an unconfined aquifer of three lithologies: coarse-grained alluvium, fine-grained alluvium, and weathered bedrock. Figure 4.28 displays the unconfined aquifer used in this modeling demonstration. The hydraulic conductivity values were 500 feet/day for the coarse-grained alluvium, 55 feet/day for the fine-grained alluvium, and 1.5 feet/day for the weathered bedrock.

The flow model, MODFLOW, was run in steady state mode. Problems occurred in areas of very thin saturated zones and unsaturated alluvium. Saturated cells became isolated by dry cells, causing instability. Cells with these problems were designated inactive. The final head map is displayed in Figure 4.29. This head map was very
Figure 4.28: Unconfined flow system used for MODFLOW input. Light gray is coarse-grained alluvium, dark gray is fine-grained alluvium and black is permeable bedrock.
Figure 4.29: MODFLOW ending heads contour map. The white regions within the model grid are unsaturated zones.
similar to the average water table used for the starting head values. The differences were generally less than 1 foot although there were areas of head differences between 1 and 10 feet near the boundaries between the saturated and unsaturated zones, where an individual realization may locate the boundary too close or too far from a particular head measurement. These head differences are displayed in Figure 4.30. The flow model was not calibrated to field head and groundwater flow measurements. To simulate actual concentrations in the field, model calibration would be necessary. Without field observations of flow rates, a satisfactory head match could be obtained for any absolute values of K as long as the relative values of K were correct. However, unrealistic values of K will cause unrealistic results from the contaminant transport model.

The contaminant transport model, MT3D, was simulated for a 50 year period. For illustrative purposes, only one realization was evaluated and only the source at Basin A was considered. Consequently, the impact of using transport modeling was demonstrated but the plume did not match the plume occurring at the RMA because this realization was not the best representation of the RMA and all contaminant sources were not included in the model. The contamination was set as a constant source in Basin A at a concentration of 100. Concentration values after the run were presented as percentages of the original source. The final concentration values and the connected pathway results for that realization are compared in Figure 4.31. This comparison demonstrated that modeling shows potential contaminant migration that is not realized by the connected pathway analysis. However, because this realization was discontinuous to the northwest of Basin
Figure 4.30: Head differences between MODFLOW ending heads (no calibration) and the average water table simulation. Black = simulation values 5 to 10 ft. above ending heads. Medium gray = head differences between -5 and 5 feet. Very light gray = simulation values 5 to 10 ft. below ending heads.
Figure 4.31: Comparison of the MT3D concentration contour map and the connected coarse-grained pathway from the same saturated alluvial body. The concentration map, from the simplistic model of transport from Basin A, shows that the connected pathway analysis does not demonstrate full migration potential.
A and not all sources were considered, the model results did not mimic the contaminant plume from Basin A as observed in the field. This comparison simply illustrated that connected path analysis only defines paths of rapid migration, not all migration paths.

This flow and transport modeling demonstrated the plume extends beyond the end of the connected path. Connected path analysis has limited value, providing only qualitative indication of preferred migration direction. The primary value of the geostatistical simulations is in their use in flow and transport modeling, where definition of heterogeneity is essential to accurate prediction of contaminant migration. By conducting flow and transport modeling on all of the geostatistical realizations, multiple contaminant plumes could be generated and probability maps created.
The conclusions of this research project and recommendations for future work are presented in this chapter.

Conclusions

The research objectives were to create and interpret possible configurations of the unconfined aquifer underlying the RMA. The aquifer realizations were created using geostatistics. Stochastic conditional simulations of the bedrock surface, water table surface and alluvial lithology were generated and combined for interpretation. The variability of the heterogeneous alluvium was appropriately expressed by the stochastic nature of the simulations. Each simulation and each combination of simulations honored the known data and exhibited variability observed in the field. Probability maps of saturated alluvium were created from combinations of water table and bedrock surface simulations and probability maps of connected coarse-grained pathways in saturated alluvium were created from combinations of water table, bedrock surface and alluvial simulations.

The saturated alluvium probability maps demonstrate the probability of saturated alluvium within the onpost region. Typically in RMA documents, zones of unsaturated
alluvium are displayed in a deterministic fashion. The probability maps are a more realistic representation of the current understanding of alluvial conditions, because the locations of saturated and unsaturated alluvium are not known with 100% certainty. The interpretation of these probability maps can be used to guide planning for further data collection. If an area has significant uncertainty, or if an area has a high probability for saturation and is not currently monitored, it would be a suitable location for additional data collection.

Groundwater flow modeling should be used to calibrate hydraulic parameters in each alluvial body and determine the water table surface. Gaussian simulation provides a "short cut" to water table definition that does not honor the flow equations.

The connected coarse-grained probability maps are useful in presenting probable pathways for rapid contaminant migration from the Basin A area. Slow migration will proceed through fine-grained zones, as exhibited by transport modeling.

Groundwater modeling is more appropriate for determining migration paths than analysis of connected coarse-grained pathways because it considers the differential equations of groundwater flow and contaminant transport, boundary conditions, relative hydraulic conductivities and degrees of connectivity. The modeling of each aquifer realization could produce a probability map of contaminant plumes, however such an analysis on the entire extent of the data set was beyond the scope of this project.
Recommendations for Future Research

The current project only incorporated data from within the boundaries of the RMA. To understand the unconfined flow system, the area of study should be expanded to natural hydrologic boundaries such as the South Platte River, Second Creek, the Highline Canal and Sand Creek (Harding Lawson Associates, et al., 1990).

Groundwater flow modeling should be utilized to determine the water table surface. Geostatistical conditional simulations of the water table were created for this project. These simulations do not account for the complex physical system of groundwater flowing through a heterogeneous aquifer. There are a substantial number of water table measurements available for model calibration.

In addition to flow modeling, inverse and contaminant transport modeling can be utilized to simulate the contaminant plumes originating within the RMA. Each aquifer realization is run through an inverse modeling process to determine which realizations are realistic representations of the aquifer and to estimate hydraulic properties (i.e. calibrate the model). The acceptable realizations are run through a transport model and the results are compiled into probability maps of the plumes (Poeter and McKenna, 1994).

For more accuracy within the onpost area of the RMA, additional information could be compiled from non-GMP and new GMP boreholes. Soft information, such as geophysical data, can also be utilized in the geostatistical simulation process. The number of indicator values used in the geostatistical simulations of the alluvial lithology could be increased to include compaction, calcification, and cementation for gravel, sand, silt, and
clay rather than the two current indicator values representing coarse and fine-grained alluvium. Further detail can be simulated in the onpost area by using a finer grid for the geostatistical simulations. With nodes that are smaller in area and volume, more of the clustered data can be used to condition the simulations.


Kuznear, Casimir, and William L. Trautmann. 1980. *History of Pollution Sources and Hazards at Rocky Mountain Arsenal*. Prepared for the Rocky Mountain Arsenal, Commerce City, CO.


APPENDIX

The enclosed diskette contains an INGRES database report of the borehole data collected for this study. The diskette is DOS formatted and the file is named borehole.dat. Chapter 3 describes the geologic information collected for each borehole.