EVALUATION OF THE IMPACT OF CHEMICAL CONTAMINANTS UPON THE DALY CITY DRINKING WATER WELLS THROUGH MODELING

ABSTRACT

EVALUATION OF THE IMPACT OF CHEMICAL CONTAMINANTS UPON THE DALY CITY DRINKING WATER WELLS THROUGH MODELING

The research described in this study provides the evaluation of potential contaminant impact to the Daly City drinking water wells through the determination of the capture zones for each drinking water well by groundwater modeling based upon geologic, hydrogeologic, and well data, and the identification of contaminated site locations that lie within the Daly City groundwater tributary area over a five and ten year time interval. The geology and hydrogeology must be evaluated to understand the media which contaminants and groundwater movement occurs, and to provide data for the modeling program. The modeling of the ten municipal wells, in addition to two irrigation wells that may alter groundwater flow, determined the capture zones of each. Then, the location of contaminated sites was evaluated to determine whether they lie within the Daly City Groundwater Tributary Area. The results of this preliminary investigation demonstrated that there is a potential for chemical contaminants to impact to these municipal drinking water wells over a five year time interval.

EVALUATION OF THE
IMPACT OF CHEMICAL CONTAMINANTS
UPON
THE DALY CITY DRINKING WATER WELLS
THROUGH MODELING

This Thesis is Written By
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The thesis written under the guidance of the Faculty Advisory Committee, and approved by all its members, has been accepted in partial fulfillment of the requirements for the degree of:

Master of Science in

Environmental Management

at the

University of San Francisco

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ACKNOWLEDGEMENTS

I would like to thank the following people for their assistance with this project: Brian Zamora, Director, San Mateo County Environmental Health, without whom his encouragement and resources this research would not have been possible; Steven Reynolds, UC Davis Extension, for his support in the use of the WHPA Program; Gus Yates, Loren Metzger, and Steven Phillips of the U.S. Geologic Survey, for their help in collecting geologic and hydrogeologic data; Sunny Kuegle, Cheryl Gustafson, and Steven Inen, of the U.S. Environmental Protection Agency, for their help in obtaining the WHPA Program and information on Wellhead Protection programs; Michael Abramson and Paul Faco, Daly City Water and Wastewater Resources, for their well data and support of this study; and Irene Boczek, faculty member, University of San Francisco, for her encouragement and support.

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CHAPTER ONE

INTRODUCTION

Background

Over 100 million Americans depend on groundwater for their drinking water supply. Thirty-four of the 100 largest cities in the United States depend wholly or partly on the groundwater. Some of these cities that rely solely on groundwater include Memphis, Miami, San Antonio, Dayton, Honolulu, and Long Island (US EPA 1987). The National Water Well Association estimated that over 50% of drinking water in the nation comes from groundwater. Thus, protection of these valuable resources is of primary concern.

Unfortunately, the use of chemicals in industry and agriculture has been found to threaten these valuable groundwater resources. Chemicals released onto the ground often permeate through the soil and migration downward into the groundwater. Leaking underground storage tanks containing petroleum fuel or other chemicals have also been found to contaminate groundwater. Some of these chemicals, known to be hazardous or toxic, have been related to increases in cancer or have caused significant health problems.

From coast to coast, drinking water wells located near these industrial areas have been threatened by improper handling and storage of hazardous chemicals. In many cases, drinking water wells were closed due to health threats by chemical contamination and alternative drinking water supplies had to be obtained from other sources. These alternatives are expensive and often inconvenient. In the short term, bottled water or imported water in large water tanker trucks were needed to supply the community with potable water. In the long term, the construction of pipelines from surface water reservoirs, rivers or lakes was necessary. Ultimately, the increase demand on water must be met with limited supplies.

Due to these problems with contaminated groundwater supplies, the U.S. Environmental Protection Agency (US EPA) under the Safe Drinking Water Act of 1974 and its subsequent amendments, established the Wellhead Protection Program to address the protection of public groundwater supplies from contamination. This program is based upon the concept that the development and application of land-use controls in the areas surrounding drinking water wells can protect groundwater supplies.

A Wellhead Protection Program is an effective method for a community to develop a protection and management strategy for these limited groundwater resources. This program includes several steps: defining the boundaries of an area to be protected; identifying potential sources of groundwater contamination; and, developing regulatory and non-regulatory controls to manage these wellhead protection areas.

In 1987, the US EPA published guidance documents for local or state agencies to develop their own programs. In California, individual local and state agencies as well as water companies were encouraged to develop their own Wellhead Protection Programs. The first step was to assemble of a team of local representatives to gather support and understanding of the program. This team would build consensus amongst the community to aid in the approval process to make the program a success. Without this support and input from the community, it would be difficult to implement the program smoothly.

The second step was to define the land area to be protected. US EPA guidance documents provided a step by step method for determining this area (Blandford and Huyakorn 1991). A computer generated program was provided to incorporate the geology, hydrogeology, well characteristics, soil characteristics, topography, and other influences of groundwater movement (see Appendix A for definition of terms). The computer program would aid in the development of a model to provide a relatively realistic view of the protection area.

The third step was to identify and locate of potential sources of contaminants in the defined area. This involves a review of current land use and the determination of the general type of potential contaminants associated with these land use practices. General categories of land use included agricultural, commercial, industrial, and residential uses. For example, agricultural areas are related to pesticide spills, excessive pesticide applications, and fertilizer leachates. Industrial areas are related to spills from chemicals used in manufacturing, treatment or storage, such as electroplating operations which have spills from corrosive etching solutions and heavy metals. Service stations are related to petroleum fuel leaks from underground storage tanks. Even residential areas are related to spills or leaks from household chemical products, septic systems, and swimming pool chemicals. A survey of the area is then performed to determine the potential for groundwater contamination.

The fourth step was to develop and implement a plan to manage the protected area. This plan may include both regulatory and/or non-regulatory controls. Regulatory controls include the requirement of documentation of transport, storage, and disposal of industrial chemicals and hazardous wastes, and monitoring plans for underground storage tank systems. Non-regulatory controls include the implementation of zoning ordinances which designate the protected area for residential or commercial uses, and provide restrictions for industrial uses in areas which are nearby drinking water wells.

The last step was to incorporate these protection efforts into the future planning of the community. County and city planning departments use the results of a wellhead protection program to better plan their future development and provide for future protection of the groundwater resources for years to come.

This thesis addresses the two technical steps of such a wellhead protection program and provided an evaluation of these steps for the Daly City drinking water wells. These two steps included a time dependent determination of the groundwater area to be protected and the identification of chemical contaminated sites in the area near the Daly City drinking water wells. The evaluation of these two steps determined the potential impact of these identified contaminated sites upon the Daly City groundwater resources over a five and ten year time interval.

Statement of the Research Problem

The research problem is to evaluate the potential contaminant impact to the Daly City drinking water wells over a five and ten year interval through the determination of the capture zones for each drinking water well by groundwater modeling based upon geologic, hydrogeologic and well data; and the identification of the contaminated site locations that lie within the capture zones. The specific study area is the Daly City Groundwater Basin which is the main potable water bearing zone that lies under Lake Merced in the southeastern portion of San Francisco County to San Bruno in the northern portion of San Mateo County, California (Figure 1 and 2). The entire basin consists of two drainage basins, the Lake Merced Drainage Basin and the Colma Creek Drainage Basin (Figure 3). This study will focus upon the Lake Merced Drainage Basin

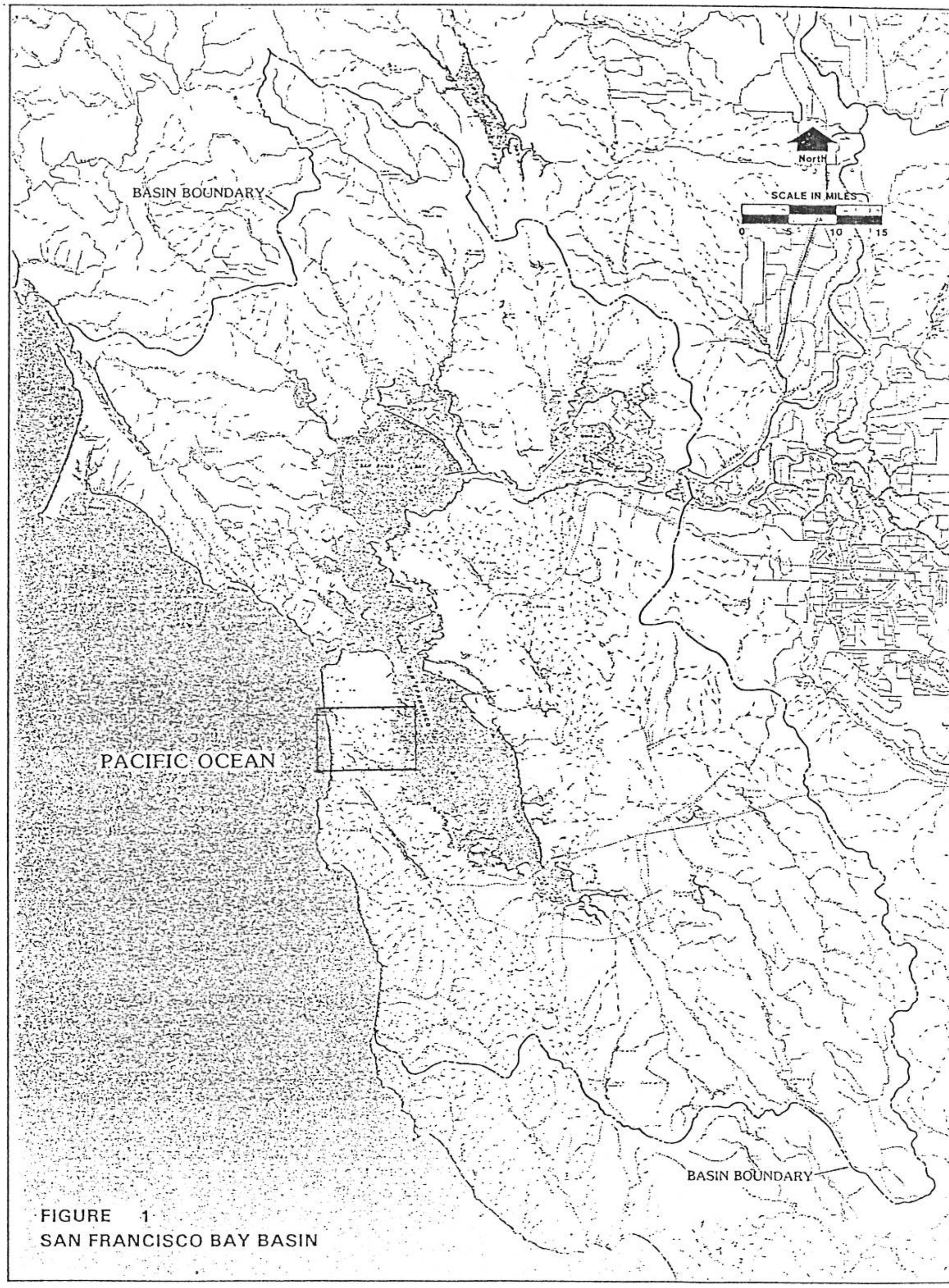
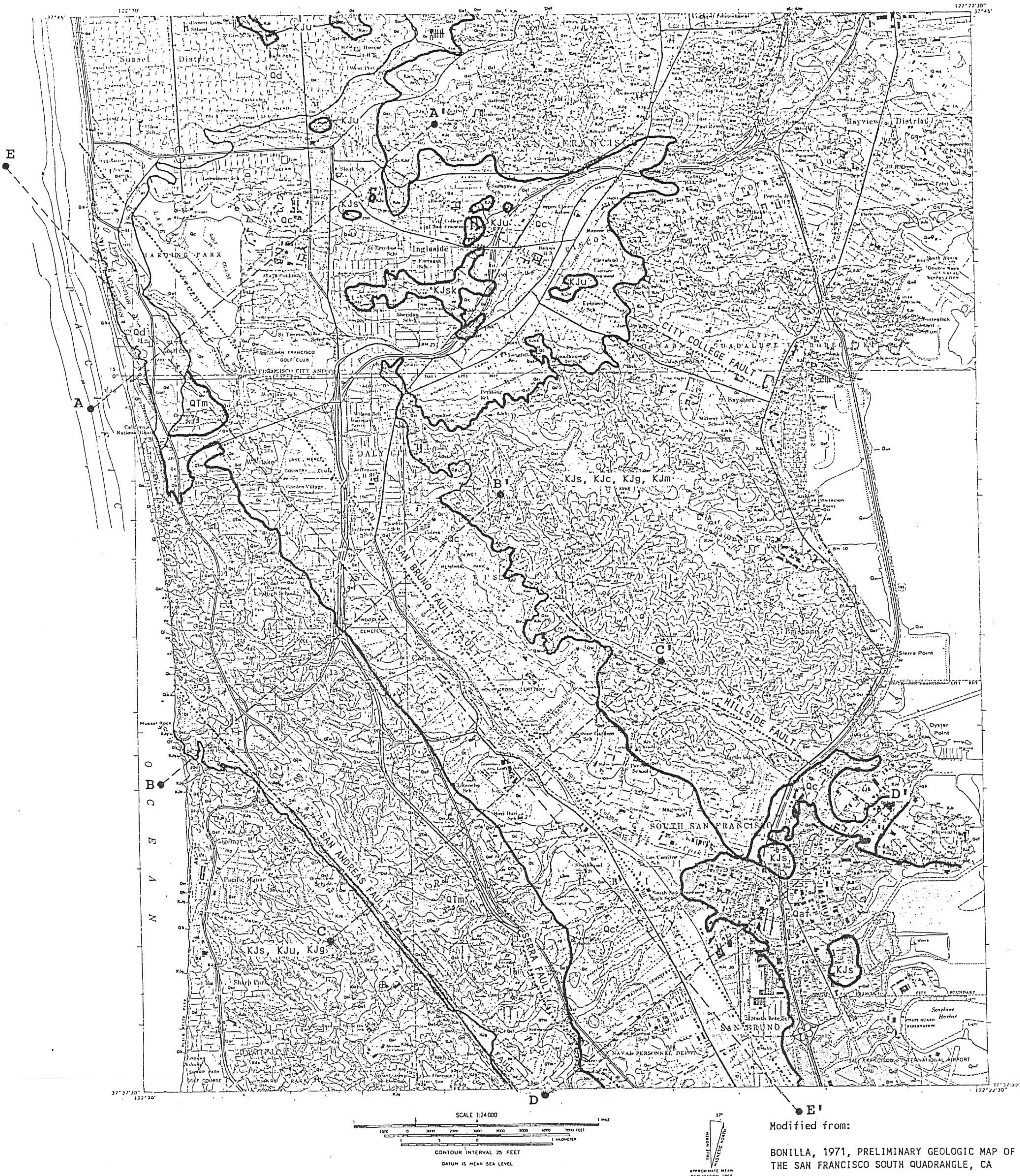


FIGURE 1
SAN FRANCISCO BAY BASIN

1986



Modified from:

BONILLA, 1971, PRELIMINARY GEOLOGIC MAP OF THE SAN FRANCISCO SOUTH QUADRANGLE, CA

LEGEND

Qaf	ARTIFICIAL FILL
Qd	DUNE SANDS
Qc	COLMA FORMATION
Qtm	MERCED FORMATION
KJs, KJsk, KJc, KJg, KJm, KJj	FRANCISCAN FORMATION

FIGURE 2

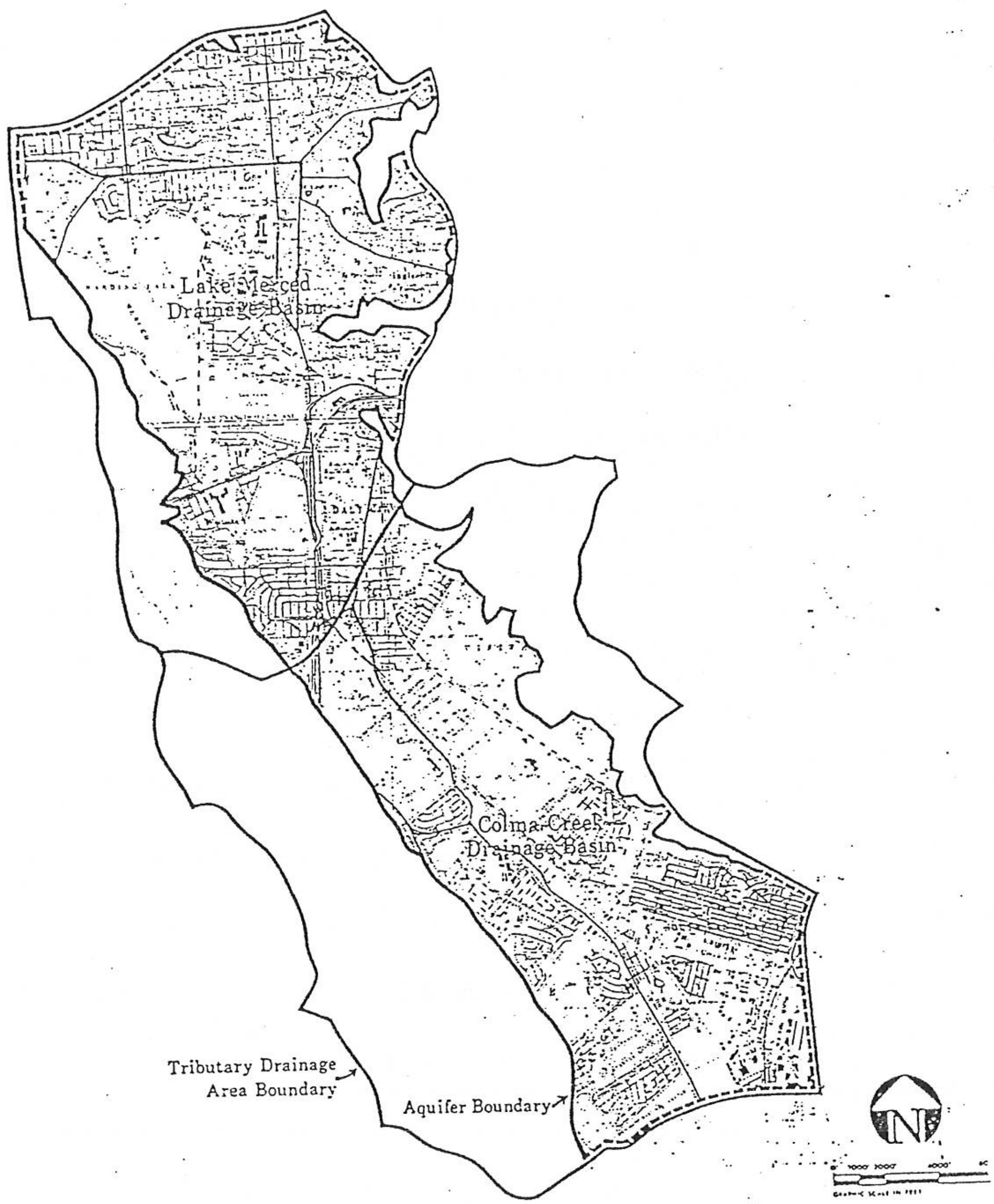


Figure 3. Lake Merced and Colma Creek Drainage Basins (Kirker, el al 1972)

where the Daly City drinking water wells are located. The specific study area within the Lake Merced Drainage Basin is the Daly City Groundwater Tributary Area.

The Subproblems

The first subproblem determined the capture zone based upon the regional geology, hydrogeology, and well data within the Daly City Groundwater Basin. The compilation of geological maps, boring logs, and cross-sections of the basin subsurface provided information to help select the appropriate wellhead protection model. Specific hydrogeologic and well construction data was evaluated and selected for entry into the appropriate wellhead protection model to determine the protection area.

The second subproblem determined the location of sources of contamination within the study area. Known contamination resulting from industrial manufacturing plants, automotive repair shops, and underground storage tank facilities with soil and/or groundwater impact was identified. Confirmation of soil and groundwater contamination by analytical results was made by review of San Mateo County's Remedial Oversight Program (CROP) files. The San Francisco Bay Regional Water Quality Control Board's (SFBRWQCB) toxic sites and the California Environmental Protection Agency

(Cal/EPA) Department of Toxic Substance Control (DTSC) sites were also included in the file review.

The third subproblem evaluated the potential impact of the identified contaminated sites that lie within the capture zone of the ten Daly City drinking water wells over a five and ten year study period. This was performed with the US EPA's computerized modeling program known as the Wellhead Protection Area (WHPA) Program. This Program projected the estimated surface and subsurface area surrounding each water well which supplied the Daly City drinking water wells. The capture zones were delineated and the contaminated sites located within that area were evaluated. All of those contaminated sites within the capture zone was then evaluated for the degree of potential impact upon the Daly City drinking water wells.

The Hypothesis

This research hypothesized that the known chemical contaminated sites that lie within the capture zone of the Daly City drinking water wells in the Daly City Groundwater Tributary Area may impact the drinking water wells within the next five or ten years. The three subproblems proved the following sub-hypotheses:

1. The capture zone was determined based upon the geologic and

hydrogeologic of the study area and well data from the 12 wells in the study area.

2. Soil and/or groundwater contamination sites were found within the study area known as the Daly City Groundwater Tributary Area.

3. The evaluation of data and computer modeling determined that some contaminated sites that lie within the capture zone and have the potential to impact the Daly City drinking water wells.

Methodology

The investigative methodology included research in technical journals, technical reports, and government publications to obtain necessary data to address all areas of concern. The research also included a review of related literature which addressed any research or reports or similar studies performed for drinking water wells throughout the United States. A brief evaluation of each research report was performed as it related to the research problem. This was reported in Chapter Two.

The research data collected for the first subproblem, included the geologic and hydrogeologic data of the Daly City Groundwater Basin and the US EPA literature which addressed the WHPA Program and determination of the capture zone. US Geologic Survey reports, local investigative reports on Daly City geology and hydrogeology, and the well data from wells within Daly City were the sources used. Once the geologic, hydrogeologic, and well data was collected, then the capture zones were determined using this data. The WHPA Program had several different modules depending on the hydrogeologic conditions. The most appropriate one was selected and used to generate a map of the capture zone which was considered to need protection.

The second subproblem required collection of existing sources of contamination which may lie within the capture zone. This data was available through Cal/EPA files, the SFBRWQCB files, and the County of San Mateo CROP files. These files included all known or confirmed releases to soil and groundwater within the study area.

The third subproblem provided evaluation of the location of contaminated sites within the Daly City Groundwater Drainage Basin. Only those sites found within the Daly City Groundwater Tributary Area were considered potential sources of drinking water contamination and were evaluated in relation to the capture zones. These results were evaluated and fine tuned to provide meaningful data. The data and analysis was reported in Chapter Four and a comprehensive evaluation of the all subproblems was reported in Chapter Five.

Limitations

This report provides a general overview of hydrogeology and groundwater contamination within the Daly City Groundwater Basin. It is not a comprehensive analysis of each contaminated area nor is it a detailed evaluation of the sources of the contamination. The following issues limit the study to very specific areas to be used to solve this research problem.

1. The selected US EPA model is only one of many models that can be used for type of study. The one chosen will be based upon ease of use, applicability of the hydrogeology, and available data.
2. The data needed to perform the analysis were generally reported in ranges or estimated averages. Where data is unavailable, the best estimation and a range was be used based upon known similar conditions which may provide results over-estimating the size of the capture zone.
3. Sources of contamination other than reported chemical contamination were not addressed. For example, septic systems and bacterial contamination were not significant problems in the study area and thus was not addressed.
6. Groundwater recharge from rainwater, irrigation, and leaky water and sewage pipes, was not considered significant for the purposes of this study. The WHPA models do not incorporate these factors and thus the results

may over-estimate the size of the capture zone.

7. Groundwater flow is not the only mechanism that accounts for movement of contaminants. Other factors, such as molecular dispersion, dilution, advection, and adsorption will tend to slow its movement. Since these retardation factors are not taken into account in the model, the results provide a conservative "worst-case" scenario.

8. Only known and reported leaking underground fuel tanks, reported toxic releases and state and federal superfund sites were included in the study. Other unreported releases from sources of contamination were not considered and may under-estimate the actual number of contaminated sites.

Assumptions

1. Drinking water wells were installed a certain depth but the pumping rate and saturated thickness may change according to management decisions and natural fluctuations in the groundwater table. For the purposes of the modeling program, the wells are assumed to be fully penetrating and fully screened. Since they are not, the saturated thickness will be considered the aquifer thickness. Average aquifer thicknesses for certain well clusters were shown for ease of interpretation. The most current pump rates and

saturated thicknesses were used.

2. Sites found in the Cal EPA files, SFRWQCB files, or San Mateo CROP sites files with known contamination will be chosen based on confirmed soil and/or groundwater impact by laboratory analyses.

3. Current status of the contaminated sites will not be specific. If the site has a file with a confirmed soil or groundwater contamination, the degree of contamination will not be addressed. Further, the status of any clean-up or remediation of the site will not be taken into account. Thus, the results may indicate an over-estimation of the potential for impact.

The Importance of the Study

This study has shown that there is a potential for contaminated sites to impact drinking water wells over time. Thus, the state and counties' efforts to protect groundwater resources by requiring investigation and clean-up of chemical contaminated sites is beneficial for the protection of all future uses of the groundwater. In addition, the US EPA's efforts to protect groundwater resources by encouraging and supporting Wellhead Protection Programs is also just as important and beneficial for groundwater protection.

Data from this study will be made available to the Regional Water Quality Control Board for development of their Regional Groundwater Protection

Strategy. The results of this study may be used to designate potential risk areas and facilitate specific policy changes for local agencies to implement wellhead protection strategies to protect these resources and the public health.

CHAPTER TWO

A REVIEW OF THE RELATED LITERATURE

Introduction

The literature search indicated that there are limited publications of successful wellhead protection programs. The majority of participation in US EPA's Wellhead Protection (WHP) Programs have been reported for municipalities that have higher incidence of groundwater contamination related to long term industrial operations. In addition, these municipalities may rely solely or significantly upon the groundwater resources for drinking water and have a more urgent need to develop these WHP programs.

This literature search focused on two areas: the background and development of the US EPA's WHP Programs, and several areas where WHP Programs have been proposed and/or have been implemented.

Guidelines for Delineation of Wellhead Protection Areas

The Amendments to the Safe Drinking Water Act (SDWA), passed in 1986, established the first nationwide program for protection of groundwater resources. Namely, the program is intended to protect public water supplies from potential contamination threats. The State Wellhead Protection (WHP) Programs were intended to be established by the authority of the SDWA to "protect wellhead areas within their jurisdiction from contaminants which may have any adverse effect on the health of persons". To date, only a few states have been active in wellhead protection.

EPA developed technical guidance on the hydrological aspects of this task. **Guidelines for Delineation of Wellhead Protection Areas** (EPA 1987) was developed to meet these needs. One of the major elements of Wellhead Protection Program is to determine what areas or capture zones may need to be protected from chemical contamination. The capture zones, or Wellhead Protection Areas (WHPA) are defined in the SDWA as "the surface and subsurface area surrounding a water well or wellfield, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or wellfield." WHPA delineation policy is generally based upon the analysis of criteria, criteria thresholds, and delineation methods. The goal of the WHPA programs are threefold (EPA 1987):

1. to provide a **remedial action zone** to protect wells from unexpected contaminant release
2. to provide an **attenuation zone** to bring concentrations of specific contaminants to desired levels by the time they reach the wellhead.
3. to provide a **wellfield management zone** in all or part of a well's recent or

future recharge area.

The selection of a method depended upon technical and policy considerations. The selection of an optimal method by taking into consideration the ease of application, extent of use, simplicity of data requirements, suitability for hydrogeologic settings, accuracy and ranking (Table 1).

There are several WHPA Delineation Methods that may be considered. They are based upon the various factors listed and as follows (Reynolds 1991):

1. Arbitrary fixed Radii - generalized method not based on scientific principles but involves drawing a circle of a specified radius around a well being protected. The radius of the WHPA may be arbitrarily selected distance criterion threshold value.

2. Calculated Fixed Radii - generalized method using the a fixed radii calculated using an equation that is based on the volume of water that will be drawn to a well in the specified time.

3. Simplified Variable Shapes - standardized forms are generated using analytical methods selected for hydrogeologic and pumping conditions matching or similar to those found at the wellhead.

4. Analytical Methods - method used through the use of equations to define groundwater flow and contaminant transport taking into account site

Table 1

WHPA Methods Selection Versus Technical Considerations

(Water Table Aquifer in Porous Media for the Hypothetical State Example*)

CRITERIA / METHOD	EASE OF APPLI-CATION L/M/H	EXTENT OF USE L/M/H	SIMPLI-CITY OF DATA REQUIRE-MENTS L/M/H	SUITABIL-ITY FOR HYDRO-GEOLOGIC SETTINGS L/M/H	ACCURACY L/M/H	RANKING (1 - 5)
ARBITRARY FIXED RADII						N/A
CALCULATED FIXED RADII	H	M	H	L	L	4
SIMPLIFIED VARIABLE SHAPES	M–H	L	H	H	L–M	2
ANALYTICAL FLOW TRANSPORT MODELS	L–M	H	M	H	M	5
HYDROGEOLOGIC MAPPING	L–M	M	L–M	H	M–H	1
NUMERICAL FLOW/ TRANSPORT MODELS	L	L–M	L–M	H	M–H	3

L–LOW
M–MEDIUM
H–HIGH
T–TECHNICAL
N–NON-TECHNICAL
N/A–NOT APPLICABLE

NOTE: Ranking (1 - 5): 5 is most desirable, 1 is least desirable.

* The ranking is based on a previous selection of TOT as the criterion. Other criteria selections may influence ranking.

specific hydrogeologic parameters.

5. Hydrogeological Mapping - groundwater flow boundary and time of travel criteria are mapped by geological, geophysical and dye tracing methods.

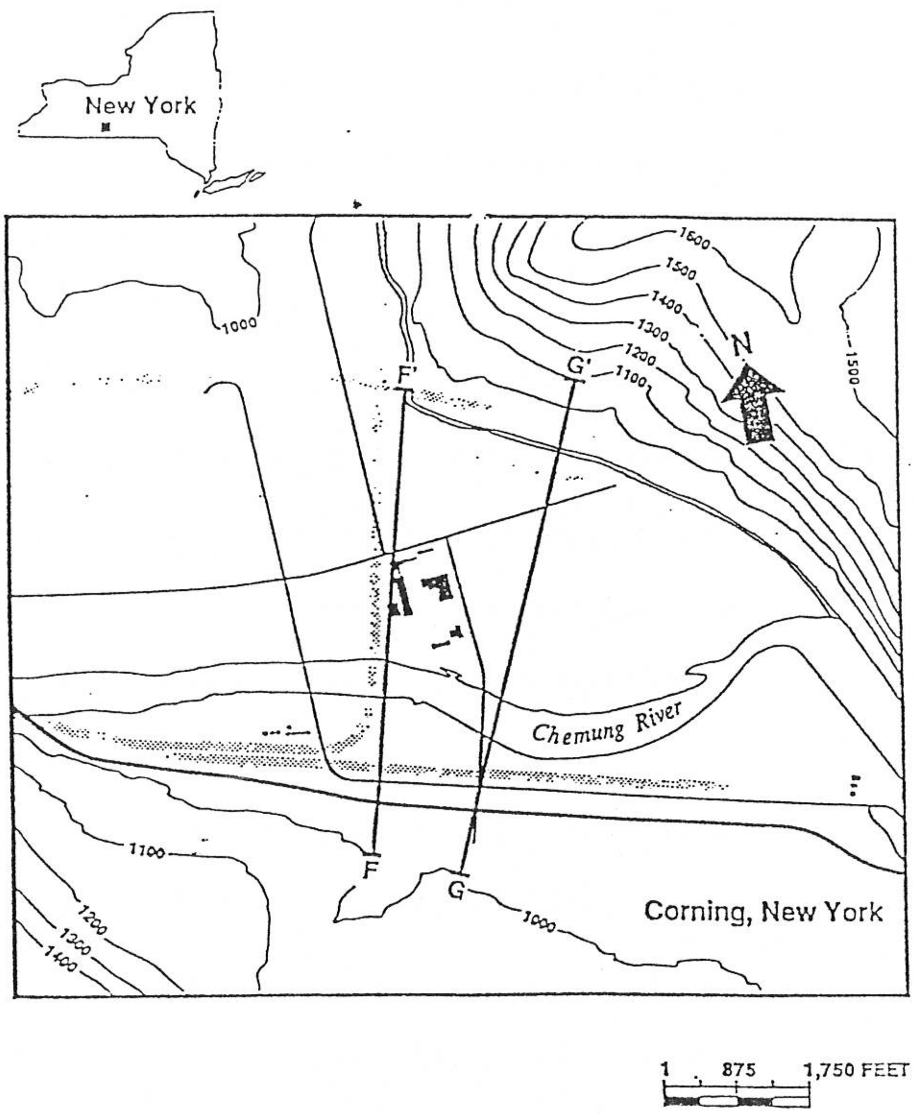
6. Numerical Flow/Transport Models - computer models that approximate groundwater flow and/or solute transport equations numerically.

The most desirable method, analytical flow transport models, ranked 5th, has high applicability for most conditions and appears to be the relative method adapted by the US EPA for the WHPA Model.

A Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas

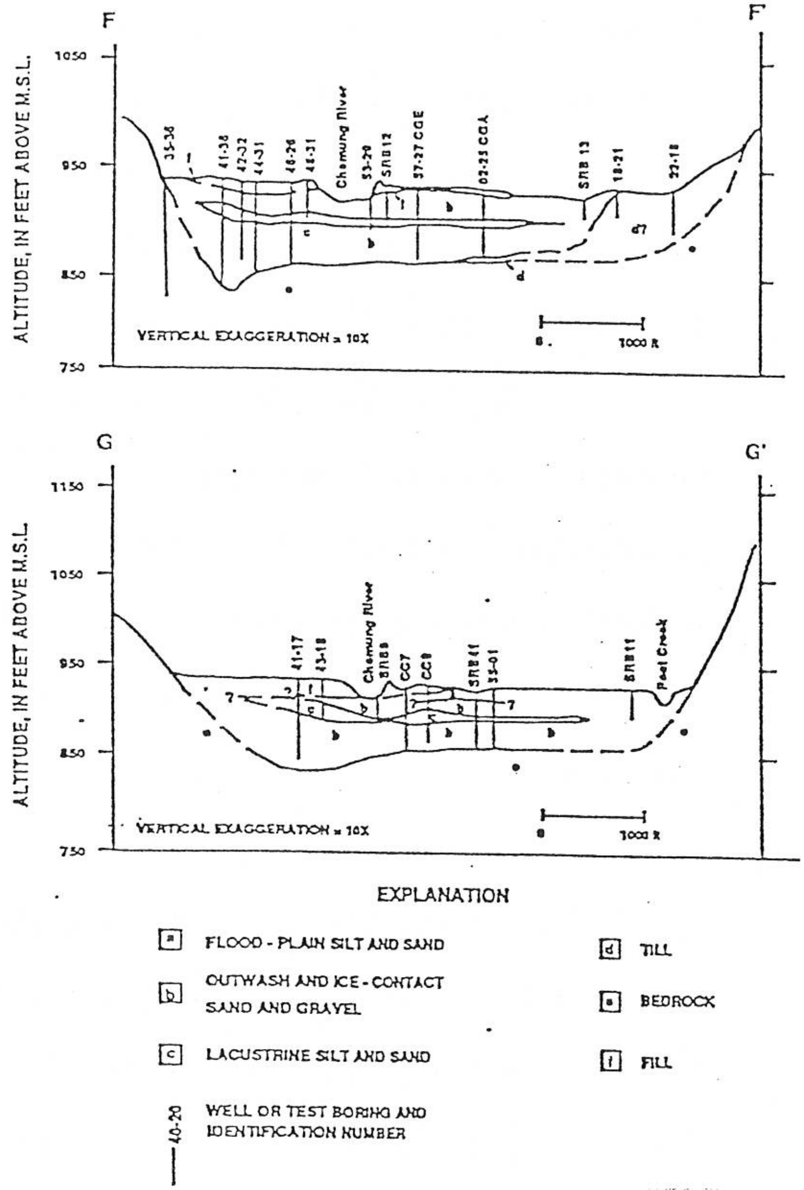
The 2.0 version of the Wellhead Protection Program manual (Blandford and Huyakorn 1991) is a user's guide for a modular, semi-analytical groundwater flow model developed for the US EPA to assist state and local technical staff with the task of WHPA delineation. The WHPA Model contains four major computational modules known as RESSQC, MWCAP, GPTRAC, and MONTEC. The latter three modules were developed specifically for the US EPA Office of Groundwater Protection. These three modules contain semi-analytical capture zones solutions. They are all applicable to homogeneous aquifers that exhibit two-dimensional, steady groundwater flow in an areal plane (Blandford and Huyakorn 1991). The selection of the module for this study will be based on the available information from the wells and hydrogeologic characteristics.

An example of a study area similar to the Daly City groundwater basin is demonstrated with the Corning example. The WHPA model used as an example for drinking wells capture zones in Corning, New York using a 1988 Ballaron study data (Blandford and Huyakorn 1991). The two dimensional RESSQC module was chosen to delineate the capture zone for three pumping wells in that city. The geology and hydrogeology of the study area consists of valley sediments in the vicinity of Corning with stratified glacial drift deposits that are primarily interbedded silty sand to clean sands and gravels. Relatively thin deposits of lacustrine clay, silt, and fine sand exists over much of the valley. This layer separates a surficial, unconfined aquifer from a confined to semi-confined aquifer at depth(Figures 3 and 4). Note that the two deep aquifer zones are confined under a leaky aquitard below a water table aquifer. The three wells were screened in the surficial aquifer. Recharge were considered negligible from three major sources; the Chemung River, precipitation, and leakage from the shallow aquifer to the deep aquifer. The RESSQC module was able to determine the capture zones for the wells but did not include the recharge factor from major sources, thus providing conservative estimates. Results of this study



General Site Map of Chemung River Valley in the Vicinity of Corning, New York

Figure 4 - source: Blandford and Huyakorn 1991



Cross Sections F-F' and G-G' in the Vicinity of Corning
Reproduced from Ballaron (1988)

Figure 5 - source: Blandford and Huyakorn 1991

indicated a capture zone larger in areal extent than if all sources of recharge to the well were incorporated into the analysis.

The five year capture zones for the three pumping wells were delineated by the RESSQC module and interference effects of the three pumping wells were significant (Figure 6). The capture zone of the three wells can be seen to overlap and adjust resulting in odd shapes.

This example, using the RESSQC module, demonstrated that well interference capabilities, simplicity of display, and the suitability of the hydrogeologic setting were effective for the purposes of Corning study. The geologic and hydrogeologic data and contaminated site locations of the Corning example was also similar to the Daly City study area and provided support for its use in this thesis.

Pima Association of Governments Wellhead Protection study

The Pima Association of Governments (PAG) performed a preliminary wellhead protection program for Tucson and Pima County in southern Arizona. The study consisted of identifying contaminated public supply wells, compiling hydrogeologic and geologic data, well construction data, potential sources of contamination, and evaluation of options for wellhead protection (PAG 1992). Forty-four wells were identified in the County which were contaminated with

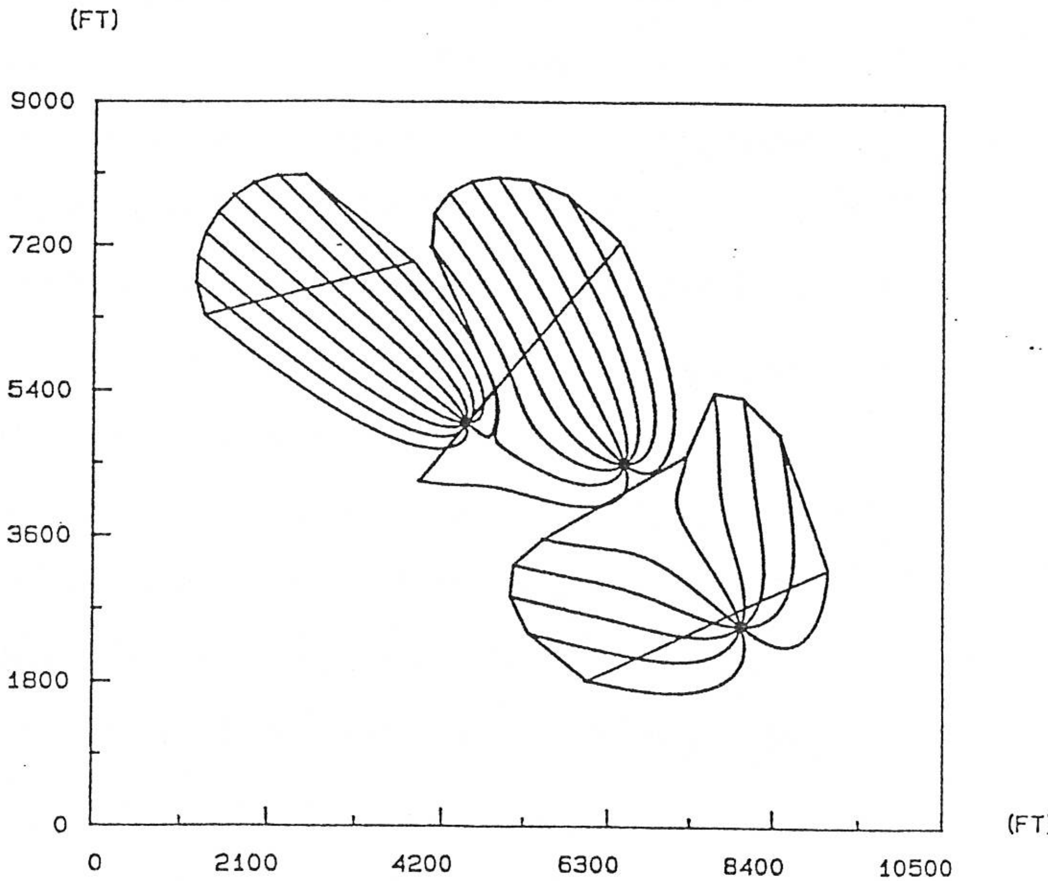


Figure 6 - Five Year Capture Zones for Corning Example Delineated Using RESSQC with One Capture Zone-Time Specified (Blandford and Huyakorn 1991)

volatile organic compounds (VOCs), petroleum products, and nitrates. Nine study areas and their relative geology and hydrogeology were delineated. Contributing factors effecting their potential for contamination were also identified. The sources of contamination were landfills and unrestricted discharges of liquid waste from industrial areas for VOCs; leaking underground pipelines and underground storage tanks for petroleum products; and irrigated agriculture, sewage treatment plants, and septic systems for nitrate contamination (PAG 1992).

The results of this investigation indicated that, in general, the sources of contamination were not adjacent to the wells, but effected recharge areas more than a mile away. Thus the arbitrary fixed radius or a time-of-travel criterion were ineffective or impractical because it was determine that it was politically and economically infeasible to establish the required large wellhead protection areas (WHPAs). Actual remediation times for existing contamination problems were difficult to project and thus time-of-travel estimates were deemed not particularly effective strategies for protection of the Tucson wells (PAG 1992).

The conclusion reached by the PAG was to establish regional wellhead protection areas to protect the areas that are most susceptible to groundwater pollution. These were identified as recharge zones and shallow or perched groundwater areas. Additional regulatory programs were not recommended because most of the groundwater contamination occurred before the existing regulatory programs were in place. They assumed that existing regulatory programs would restrict the type of activities responsible for past contamination (PAG 1992).

A Detailed Work Program for incorporation of wellhead protection strategies into planning operations was subsequently developed to include: identification of wells at risk for contamination; identification of WHP strategies which would be most likely to protect Tucson water wells; implementation of WHP strategies; and implementation of public information/technology transfers. These goals were assigned a milestone and scheduled to be completed by September 1993 (PAG 1992).

In evaluation of the PAG program, it appears that it was inappropriate to use any fixed radius or computer modeling to determine the capture zones in the area immediately surrounding the effected wells because contamination identified in this area did not necessarily contribute to the well contamination. All evaluation of WHPA locations were based upon pre-existing conditions of groundwater contamination. The assumption that current regulatory controls were sufficient to eliminate future releases of contamination to the groundwater appears premature although the proposed wellhead protection plan includes consideration of land use controls throughout the entire aquifer rather than just the recharge areas. Planning and zoning controls as well as modifying existing monitoring and enforcement requirements were also suggested to be implemented to protect sensitive areas designated as WHPAs. In addition, siting of new wells would be based upon the low risk of contamination. This investigation was well researched and appeared to address all major issues thoroughly.

Fernley Wellhead Protection Program

In early 1992, the town of Fernley, Nevada began to develop the "Fernley Town Utilities Wellhead Protection Program". Previously submitted to the US EPA was the "Wellhead Protection Demonstration Project Work Plan" dated November 1991. Ten tasks were described within that Work Plan in a time schedule format from January of 1992 through July of 1994. Public education, contamination inventory, well information, wellhead protection area delineation, quality assurance/quality control, a monitoring program, and a new well hydrogeologic study were some of the tasks of significant interest. An Interim Status Report dated November 1992 reports some of the results of these tasks (Wateresource 1992).

Tasks number 3.0, 4.0, and 5.0 addressed the sources of contamination inventory, well information/data base, and the Wellhead Protection Area delineation. Task 2.0, reported a review of hazardous material reports from the Nevada State Fire Marshall's office. The schedule planned the next step to include site visits to all documented sites by a qualified technician. Task 3.0 included detailed well and hydrogeologic data for each of the six drinking water wells. Task 5.0 discussed the delineation of the Wellhead Protection Areas almost complete, with only minor adjustments to be made (Wateresource 1992).

The results of Task 5.0 discussed the hydrogeology and well data used to create the WHPA. The well system was pumping from two aquifers, one confined and the other unconfined. Well 1/2, Well 9 and Well 9A pumped from the confined aquifer and Well 3 and Well 5 pumped from unconfined aquifers. Modeling of groundwater flow of Wells 1/2, 8, 9, and 9A was performed using GPTRAC, a semi-analytical particle tracking computer module. Well 9 and 9A were delineated as one well. The groundwater flow systems and capture zones of Wells 3 and 5 were performed using RESSQC, a time-related capture zone computer module. A total of five well delineation areas were identified (Figure 7). No detail was provided in the report discussing the rationale for the module selection (Wateresource 1992).

The Interim Report of the Fernley Wellhead Protection program appears to be a brief overview of their program. The well data collected presents some data as averages and assumptions in the aquifer thicknesses, direction of ambient flow, ambient gradient, transmissivity and boundary conditions. It appears that the selection of modules were appropriately based upon the whether the aquifer

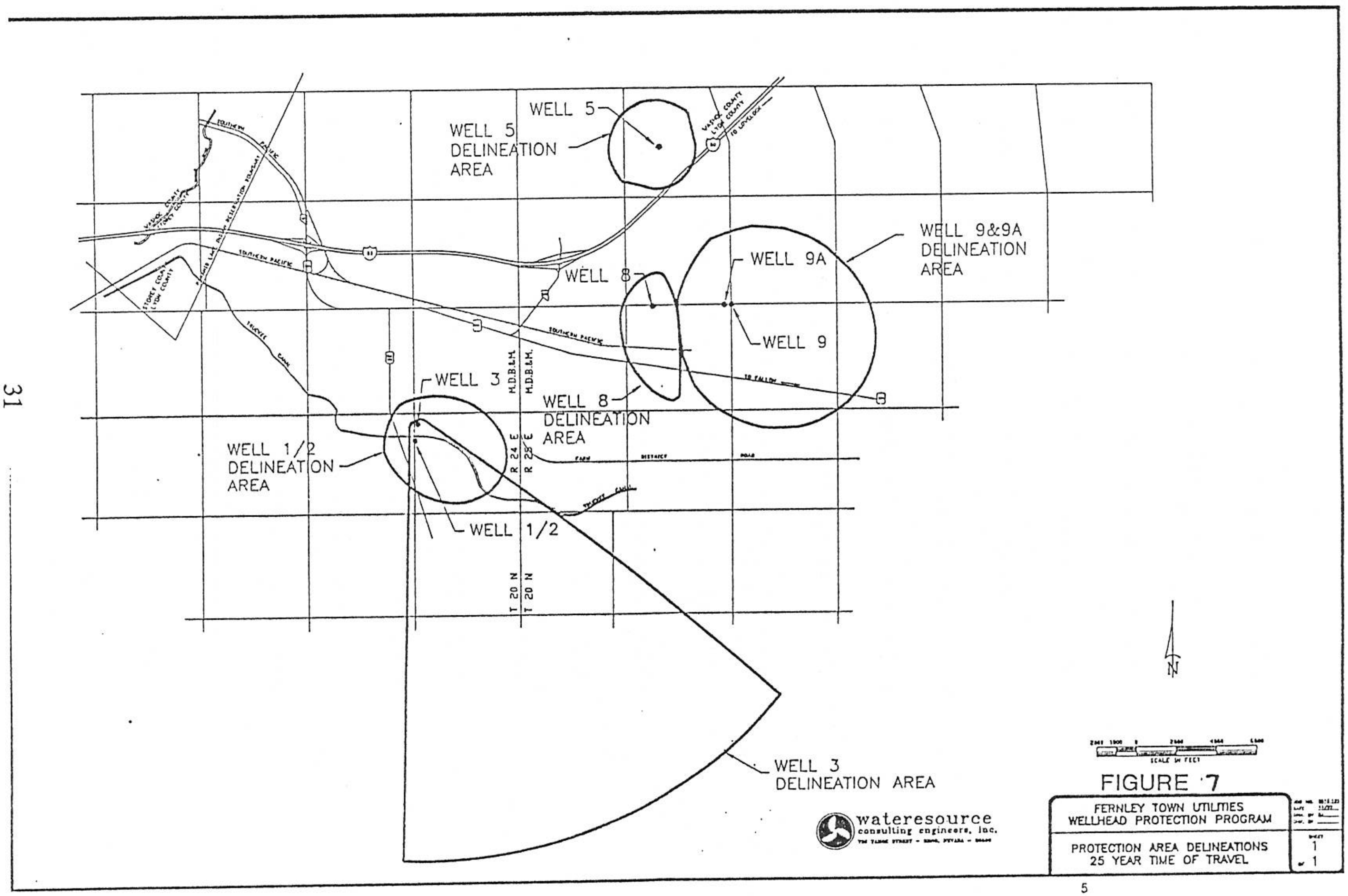


FIGURE 7

FERNLEY TOWN UTILITIES WELLHEAD PROTECTION PROGRAM

PROTECTION AREA DELINEATIONS 25 YEAR TIME OF TRAVEL

5

for each well is confined or unconfined. Because of the variability and estimations, and the capture zone times of 15 and 25 years, these are likely preliminary results requiring some sensitivity analysis. The evaluation of location of contaminants sites and their impact within the capture zones or Zone of Contribution was not performed.

Wellfield Travel Time Model for Selected Wellfields in Dade, Broward and Palm Beach Counties, Florida

In 1979, under the provisions of the SDWA, the US EPA designated the Biscayne aquifer as the sole source of potable water in southeast Florida. In 1981, the US EPA approved a groundwater protection study and awarded the lead role to the 208 Areawide Clean Water Management Programs in Dade, Broward, and Palm Beach Counties (Figure 8). The program consisted of three phases: development of time of pollutant travel contours around selected existing wellfield; identification of land uses and sources of pollution within the contours; and development of wellfield protection ordinances. This report addressed the methodology and procedures used to develop the pollutant travel time contours around approximately 70 existing wellfield in Dade, Brower, and Palm Beach Counties, Florida (Camp, Dresser, and McKee 1982).

The hydrologic setting is one factor that made the modeling of this area

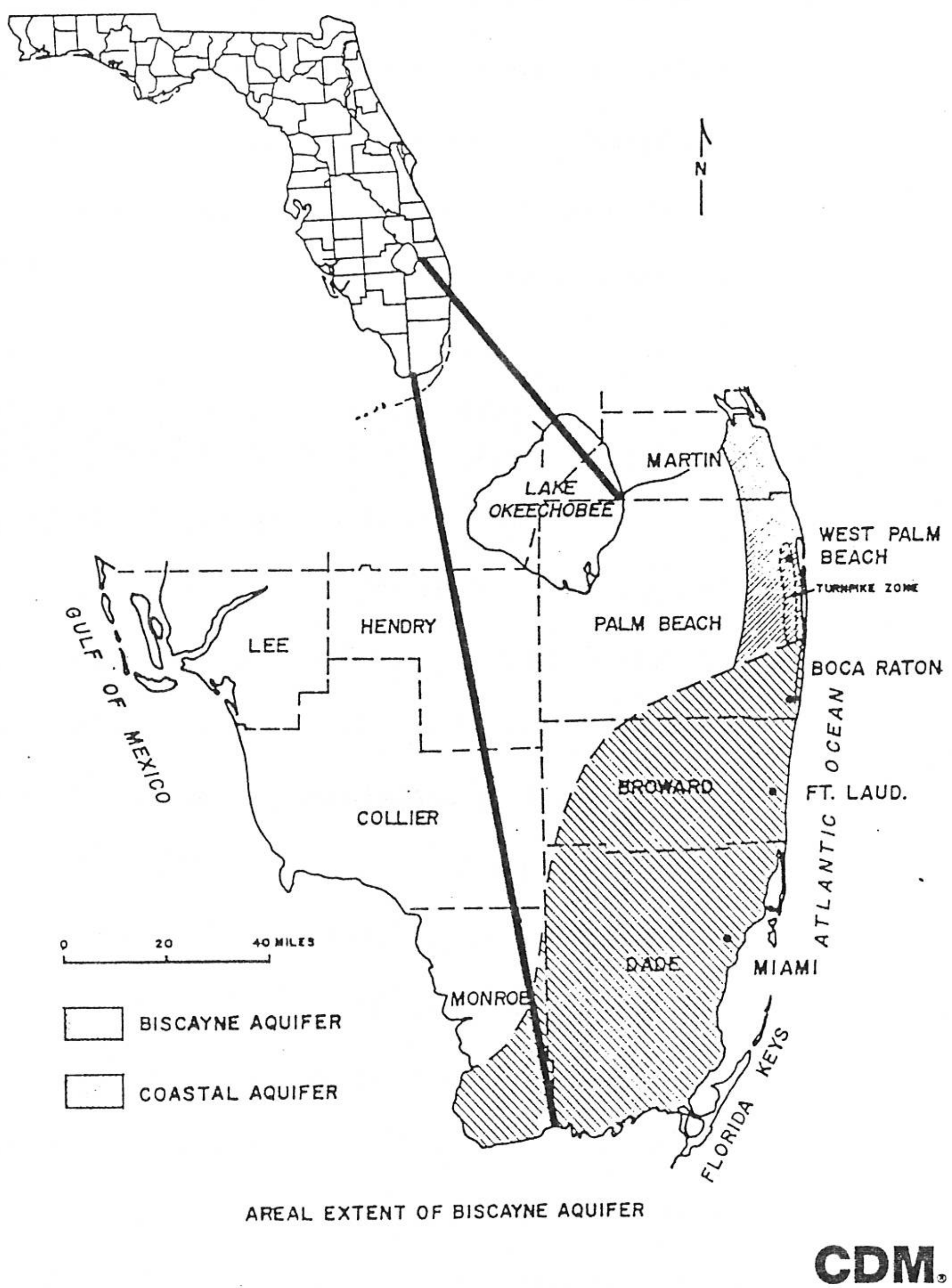


Figure 8. source: Camp, Dresser, and McKee 1982

difficult. The aquifer consisted of highly permeable limestones and sandstones overlain by younger deposits of sand. The aquifer is more than 300 feet thick in coastal Dade and Broward counties and thinned westward to about 70 feet in the central part of the tri-county area, but pinched out near the western county boundaries. Beneath this aquifer was a thick sequence of relatively impermeable clays. Then, beneath these clays lay the saline Floridan aquifer, which is not a usable drinking water supply. To further complicate the picture, the Biscayne aquifer is made of hard limestone zones which contain numerous cavities interspersed with a sand content that makes transmissivity highly variable, ranging from 0.4 to 12 million gallons per day per foot (Camp, Dresser, and McKee 1982).

Prior to development, this region was covered by swamps and shallow rivers. Since that time, a series of canals were constructed for flood control and drainage of the wetlands. Any excess water is directed toward areas such as conservation areas of the Everglades and Lake Okeechobee. The extensive canal system controls water elevations through dams, locks, and saltwater barriers.

The Biscayne aquifer recharge is primarily through precipitation, infiltration from the canals and other surface water bodies, and from the aquifer systems that are adjacent to the Biscayne aquifer. The aquifer discharge is primarily through groundwater outflow into the canals and pumping wells. The

groundwater elevations are directly influenced by the levels in the canals. Thus, groundwater flows either to or from the canals, and is dependent upon local hydraulic characteristics, seasons, and the presence of drought conditions (Camp, Dresser, and McKee 1982).

This report's objective was to determine the zones of influence around major wellfield in Dade, Broward, and Palm Beach Counties. These zones were delineated by travel time contours around the wellfields. The development of the methodology included the delineation of the zones of influence, and automation of the methodology for ready application to a large number of selected wellfields. The model was based upon the probability that once the pollutant slug reaches the groundwater it will reach the wells over time. The model incorporated the pollutant mass reaching the well such that by the time 20% of the pollutant reaches the well it would not likely exceed standard thresholds limits. Chemical reactions or retardation factors were not incorporated into the model (Camp, Dresser, and McKee 1982).

A computer program was developed to compute the travel times of possible pollutants within the Biscayne aquifer to the selected wellfields. The complicating effects of the regional water flow, the aquifer variability, the canals, and nearby wells on the flow near any well required the use of an aquifer simulation model to compute the drawdown near the wellfield. These simulated drawdowns were subsequently used for the mass transport calculations to compute the hydraulic travel times (Camp, Dresser, and McKee 1982).

The first step was the simulation of the drawdown caused by each wellfield. The second step was to compute the travel times from the simulated drawdowns. A numerical dispersion model was used based upon the Random-Walk Solute Transport Program by Prickett, et al. Camp, Dresser, and McKee modified this model to produce the travel time computations for the study area (Camp, Dresser, and McKee 1982).

In the development of the methodology, the main concern was to incorporate the elements associated with groundwater mass transport in a clear and reproducible way by defining the "worst case" conditions. Four overlapping grids were interfaced with 34 local finer grids for higher resolution simulation around the wellfields. The methodology and formal procedure was developed and implemented in the computer model package for the determination of nominal zones of influence around wellfields for the protection of water supplies. The results of this study served as a reliable and reproducible approach for determination of pollutant travel times for wellfields of southeast Florida (Camp, Dresser, and McKee 1982).

This important step in preparation of a wellhead protection program addressed modeling of a difficult hydrogeologic area. Even though this work was critical for a reliable representation, perhaps if the second phase of the study, the location of contaminant sources, was performed first, the study may have actually been limited to a smaller area depending upon where the identified contaminated sources existed. The report did not address this issue, nor did it discuss the other phases of the program. In addition, the report did not address sensitivity analysis or fine-tuning of the model for actual use. It was assumed that once the other two phases of the program were complete, that further fine tuning would be performed.

Wellhead Protection Area Delineation Model Assessment

In 1992, the Michigan Departments of Natural Resources and Public Health (MDNR & PH) completed an evaluation of the US EPA's WHPA model for the cities of Gaylord and Sturgis and the Village of Spring Lake. The purpose of the evaluation was to determine the delineation limits of the WHPA model given Michigan's complex hydrogeology and to determine the most significant data required to properly delineate capture zones. Evaluation of the WHPA model for Gaylord involved a hydrogeologic study and groundwater modeling. The MDNR &PH also evaluated existing groundwater models used for Sturgis and Spring Lake. This report presents the procedures they used to assess the WHPA model's ability to delineate capture zones at all three municipalities followed by the overall recommendations for the state of Michigan (MDNR & PH 1992).

The report began with a summary of three models to be evaluated: the USGS's MODFLOW, the Massachusetts Institute of Technology's (MIT) AQUIFEM, and the US EPA's WHPA model. Within the WHPA model were four modules: RESSQC, MONTEC, GPTRAC, and MONTEC. MONTEC was eliminated because it is an uncertainty analysis used only when data is lacking. The other three were analytical methods. All three assume horizontal flow (no vertical flow), flow in the aquifer is steady state (constant recharge and pumping rate), flow in the aquifer is steady state (constant recharge and pumping rates), and flow in one direction at a constant gradient (uniform flow direction and gradient)(MDNR & PH 1992).

The USGS's MODFLOW can simulate two- or three-dimensional models for many different types of boundary conditions, recharge rates, hydraulic conductivities, aquifer thicknesses, and flow directions. MIT's AQUIFEM is a two-dimensional flow model which addressed different boundary conditions, recharge rates, aquifer horizontal hydraulic conductivity, and aquifer thicknesses. Both these models can examine groundwater flow patterns based upon extensive hydrogeologic data.

Because no previous data was available, a hydrogeologic study of Gaylord was conducted to define the aquifer flow directions, gradients, transmissivities, and porosities. This data was then input into the WHPA model and the MODFLOW to delineate the capture zones of the Gaylord wells. The geology of the Gaylord area is dominated by Pleistocene glacial deposits between 650 and 750 feet thick and underlain by shale. Glacial features consisted of moraine and outwash sands and gravels. Area well logs indicated that the outwash materials consisted of fine to course sands with occasional gravels and sparse clays. A perched water table above a continuous clay layer extending to the southwest of Gaylord was evident by wetlands and water bodies. The Gaylord wells, located to the west of this clay layer, did not intercept any clays and drew from an unconfined aquifer of sands and gravels estimated to be 700 feet thick (MDNR & PH 1992).

Groundwater flow direction and gradient are essential parameters in the delineation of the WHPA. Based upon topographical maps, the direction of flow is to the northeast. A review of groundwater elevations were contoured by MDPH staff to better determine a gradient direction. Overall, a gradient of 0.0008 ft/ft to 0.0026 ft/ft to the east to northeast direction was identified.

To obtain additional information, a groundwater survey of 33 private wells, aquifer pump test of three wells, and soil samples were taken for porosity measurements. The results of this data collection indicated that the aquifer was unconfined and high yielding. The aquifer material was more homogeneous and more stratified near one well than the others (MDNR & PH 1992).

After review of the hydrogeologic data, Gaylord appeared to fit the WHPA model assumptions: the groundwater flow was determined to be at steady state and the aquifer conditions to be basically two-dimensional. In addition, flow direction and gradient were constant. This data was then input into the WHPA model and MODFLOW to delineate the capture zones (MDNR & PH 1992).

The GPTRAC numerical option was tested to delineate a ten year capture zone for Gaylord. It was the only option that can evaluate varying groundwater flow directions and gradients. The model reproduced the general flow directions and gradients, but did not reproduce the exact flow directions up-gradient of the production wells (MDNR & PH 1992).

The MODFLOW model was also applied to Gaylord and required the data obtained from the groundwater survey and transmissivity estimates from the pump test analyses. This option was able to model several horizontal layers with differing hydraulic conductivities (MDNR & PH 1992).

The MODFLOW and AQUIFEM models were previously used at Spring Lake and Sturgis. MDNR & PH evaluated the use of these two more complex models and determined that they were necessary to devaluate the horizontal and vertical components of the complex hydrogeology of the area (MDNR & PH 1992).

In summary, a review of the analytical models, RESSQC, MWCAP, and

GPTRAC was performed. The RESSQC, MWCAP, and GPTRAC Analytical option can be used if several simulations are made covering the range of flow directions and gradients present at a site. A review of the numerical model option for GPTRAC allowed gradient and flow direction to vary across the study area and required hydraulic head contours for the area along with horizontal hydraulic conductivity and porosity. The more complex models, MODFLOW and AQUIFEM were recommended for use where wellfields have complex hydrogeology and significant vertical flow.

This study was able to clarify the requirements and limitation of each of the models reviewed but no model selection was specified. The requirements for each module or model were varied and evaluation of the quality and availability of data is needed to select the most appropriate model. Two of the five models reviewed required extensive and highly detailed hydrogeologic data of the study area. This study also indicated the selection of the module or model is dependent upon the expertise of the modeling staff.

CHAPTER THREE

METHODOLOGY

Introduction

The methodology employed for this research problem required the collection geologic, hydrogeologic, and well data for the capture zone determination; the collection of data confirming soil and groundwater contamination sites; and the evaluation of these contaminated sites that lie within the capture zones. Thus, the potential impact upon the groundwater in the Daly City Groundwater Tributary area can be determined.

Capture Zone Determination

In order to determine the capture zone, specific geologic, hydrogeologic, and well data was obtained and the selection of an appropriate computer model was chosen. Geological maps and reports from the United State Geological Survey, (USGS) were obtained from the USGS Map Center in California or Colorado. Hydrogeological and well reports published about the specific study area were obtained from government agencies such as the San Francisco Bay Regional Water Quality Control Board (RWQCB), the U.S. Geologic Survey(USGS), the County of San Mateo, and the City of Daly City Department of Water and Wastewater Resources.

A thorough review of the geologic and hydrogeologic conditions of the study area was evaluated for the understanding of subsurface conditions of groundwater flow under pumping conditions and for the potential migration of contaminants to the groundwater. Specific hydrological data available regarding the study area was compiled for use in the modeling portion of this report. This data collection included: transmissivity of the aquifer, regional hydraulic gradient, angle of ambient groundwater flow, aquifer porosity, and aquifer saturation thickness.

A thorough review of current well data, such as well construction and operation details was also performed. These details included well discharge rates, and well radii, well depth, and drawdown values obtained from static and pumping groundwater levels within the well.

The model which best fit the geologic and hydrogeologic conditions of the study area was selected after a review of US EPA models, USGS models, and data from the literature. The selection was limited to these models because they are generally well accepted and universal. Such models are generally identified as two or three dimensional models. A two dimensional model program specifically designed for wellhead protection, known as the Wellhead Protection Area (WHPA) Program was selected.

There were indications that a three-dimensional model in a steady groundwater flow state may be a more appropriate model than the two dimensional model. The third dimension, vertical flow from groundwater recharge, has been considered a significant factor due to precipitation and leaky sewer and water pipes (Phillips 1993; and Yates 1993). Significant groundwater recharge into the groundwater basin was reported to occur from Golden Gate Park, Lake Merced and other urban parks north of the study area. Additionally, irrigation from the Lake Merced Golf Club and other nearby golf courses may provide other recharge sources. It is unclear, however, whether groundwater recharge in the immediate study area will effect a two-dimensional model. If this vertical flow provides a significant complicating factor, the use of a two-dimensional WHPA program model will provide a conservative estimate because a two dimensional flow model will likely depict a larger area than a three dimensional model.

In view of this uncertainty, selection and use of one of the WHPA programs should be considered a screening tool to determine the potential for groundwater impact. The results must be considered conservative and preliminary. Further studies may then be performed using the USGS MODFLOW or other similar three-dimensional models for more accurate results.

The WHPA Program selected provided a semi-analytical mathematical solution for determination of the capture zones from pumping wells. This selection was dependent on the available data. To efficiently analyze the study area, the following assumptions about site conditions must be made (Blandford and Huyakorn 1991):

1. homogeneous, isotropic aquifer with ambient flow
2. the aquifer is at steady state (equilibrium conditions)
3. flow is horizontal (two dimensional in areal view)
4. the aquifer is confined, or unconfined if the drawdown-to-initial saturated thickness ratio is small (<0.1)
5. fully penetrating wells
6. vertical flow is ignored
7. steady groundwater flow
8. no stream or barriers

The Daly City Groundwater Tributary Area and well construction criteria generally met these above criteria. The WHPA Program allows for the selection of several modeling modules depending upon specific parameters and assumptions (Table 2).

The RESSQC model was selected for this study because the delineation of the capture zones allowed for multiple, closely spaced pumping wells in a

Table 2 - EPA's WHPA Program Modules

Module Name	Description
RESSQC	Delineates time-related capture zones around pumping wells, or contaminant fronts around injection wells, for multiple pumping and injection wells in homogeneous aquifers of infinite areal extent with steady and uniform ambient groundwater flow. Well interference effects are accounted for.
MWCAP	Delineates steady-state, time-related or hybrid capture zones for pumping wells in homogeneous aquifers with steady and uniform ambient groundwater flow. The aquifer may be infinite in areal extent of the effects of nearby stream of barrier boundaries can be assessed. If multiple wells are examined, the effects of well interference is ignored.
GPTRAC	**Semi-analytical Option:** Delineates time-related capture zones for pumping wells in homogeneous aquifers with steady and uniform ambient groundwater flow. The aquifer may be of infinite areal extent, or it may be bounded by one or two(parallel) stream and/or barrier boundaries. The aquifer may be confined, leaky confined of unconfined with areal recharge. Effects of well interference are accounted for. **Numerical Option:** Delineates time-related capture zones about pumping wells for steady groundwater flow field. Since this option performs particle tracking using a head field obtained from a numerical (finite difference or finite element) groundwater flow code, many types of boundary conditions as well as aquifer heterogeneities and anisotropies may be accounted for.
MONTEC	Performs uncertainty analysis for time-related capture zones for a single pumping well in homogeneous aquifers of infinite areal extent. The aquifer may be confined or leaky confined.

Source: Blandford and Huyakorn 1991

wellfield and for the effects of well interference. None of the other modules in the WHPA Program were quite as appropriate. The minimum numerical data, which was found in the geologic and hydrogeologic review, was available to run the RESSQC module (Blandford and Huyakorn 1991):

1. x and y coordinates for each number of pumping wells
2. transmissivity of the aquifer (ft^2/day)
3. Regional hydraulic gradient (ft/ft)
4. angle of ambient groundwater flow (0-360°)
5. aquifer porosity (dimensionless)
6. aquifer saturation thickness (ft)
7. maximum amount of time for calculation the trace of a pathline
8. number of time-related capture zones to be calculated for each pumping well (max - 7)
9. time value for capture zone (days)
10. well discharge rates (ft^3/d)
11. well radii (ft)
12. ratio of number of pathlines to the number plotted (1=all, 2=every other)
13. number of pathlines to be computed (default - 20)

RESSQC ignores vertical flow and groundwater recharge from various sources, and in this problem, it was assumed not be a significant factor. After the capture zones were determined for the two time intervals, a comparison of the capture zone maps, while changing saturated thicknesses, provided further sensitivity analysis to the study.

Additional fine tuning was performed, to provide more meaningful results. This sensitivity analysis was performed to adjust actual conditions which were not possible using the limitations of the model. Further adjustments were needed because the RESSQC model assumes fully penetrating wells, and the actual wells were not fully penetrating. The saturated thickness for each well was then considered the aquifer thickness. After review of the data, it revealed that the range of saturate thicknesses varied. Since several of the wells were clustered in the same areas had similar saturated thicknesses, an average saturated thickness was calculated for each well cluster. Four maps were then run, one each for the different average saturated thicknesses found in each well cluster. The four maps were spliced together to represent the relative saturated thickness of each of the well clusters. This was necessary to allow well interference factors to be included in the map representation.

Location of Contaminated Sites

Confirmed soil and groundwater contaminated site information was obtained from the files of San Mateo CROP, the SFRWQCB files, and Cal/EPA DTSC files for all sites in the City of Daly City. Data from files with confirmed and documented soil and groundwater contamination within the study area was collected. The location of contamination in the soil, the shallow aquifer, and the deep aquifer was recorded. Then, the location of these sites were compared to the map of the Daly City Groundwater Tributary Area to verify their potential location within the capture zones.

Evaluation of the Contaminated Sites within the Capture Zones

After the sensitivity analysis was performed, an overlay of the previously identified contaminated sites was placed over the five and ten year capture zones for the twelve pumping wells within the study area. A review of the extent of the contamination for each site was then addressed to determine whether actual or potential impact to these sites was possible.

There were three levels of contamination reported and recorded for site that lie within the Daly City Tributary Area. Those that have deep aquifer impact, shallow aquifer impact and unknown. Unknown assumes that soil have been impacted but shallow or deep aquifer impact has not yet been confirmed. Some contaminated sites were identified to have confirmed deep aquifer impact and have the greatest potential to impact the drinking water wells because the twelve wells pump from the deep aquifer. Some contaminated sites were identified to have confirmed shallow aquifer impact and have moderate potential to impact the drinking water wells. Some contaminated sites were identified that have unknown impact and have unknown potential to impact the drinking water wells. In addition, if the contaminated site is underlain by a shallow aquifer, the potential may be moderate, but if underlain by permeable soils and only the deep aquifer beneath it, the potential may be high. There may also be a question whether once the shallow aquifer is impacted, will the deep aquifer be impacted. Unless specific investigation is performed to determine this, it is not known.

CHAPTER FOUR

DATA COLLECTION AND ANALYSIS

Capture Zone Determination

In order to fully evaluate the impact of contamination upon the Daly City municipal wells specific data was collected. Collection of specific regional geology and hydrogeology and well construction data in the study area was performed and the computer modeling of the capture zone of each Daly City municipal well was completed. Secondly, the location of abandoned well sites and contaminated sites with the confirmation of impact upon the soil, the shallow aquifer, or the deep aquifer was performed. Lastly, the location of contaminated sites and abandoned well sites were identified in relation to the capture zone model to evaluate whether these contaminated sites and abandoned wells sites will have the potential to impact the deep aquifer used for drinking water.

Geology and Hydrogeology

It is important to understand the geology and hydrogeology of the study area and well construction data to better select the most appropriate wellhead protection model for the area. In addition, the potential for contaminant migration through the soil to the groundwater can better be assessed. Once the milieu of the area is understood, further analysis of selected hydrogeologic data will be utilized in a computer program to determine whether drinking water will be impacted by chemical contamination.

The Extent of the Groundwater Basin

The study area is known as the Daly City groundwater basin located from southern San Francisco County through northern San Mateo County. This continuous body of permeable, water bearing sediments known as a groundwater basin supplies Daly City's ten wells. This basin extends from the City of San Bruno northward six miles along the coast to Daly City, under Lake Merced, to the San Francisco Zoo. The basin covers about a two mile wide valley that extends from southern edge near Daly City along the San Andreas Fault, which lies three and a half miles offshore, to the northern edge, beneath Lincoln Park in San Francisco. It is bounded to the east by Mount Sutro, Mount Davidson and San Bruno Mountain and to the south by the Santa Cruz Mountains. The total on-shore area which covers approximately 40 square miles of which 16 square miles lies in San Francisco (Applied Consultants 1991) (Figure 2).

The coastal hills to the south of Daly City merge with San Bruno Mountain to form the low saddle area that cuts across the valley floor near San Pedro Road (Figure 3). This saddle acts as a local drainage divide with two surface drainage basins to either side. The surface drainage to the north feeds into Lake Merced and the Pacific Ocean, and south into Colma Creek Basin and into the San Francisco Bay (Carroll/Resources Engineering & Management 1972).

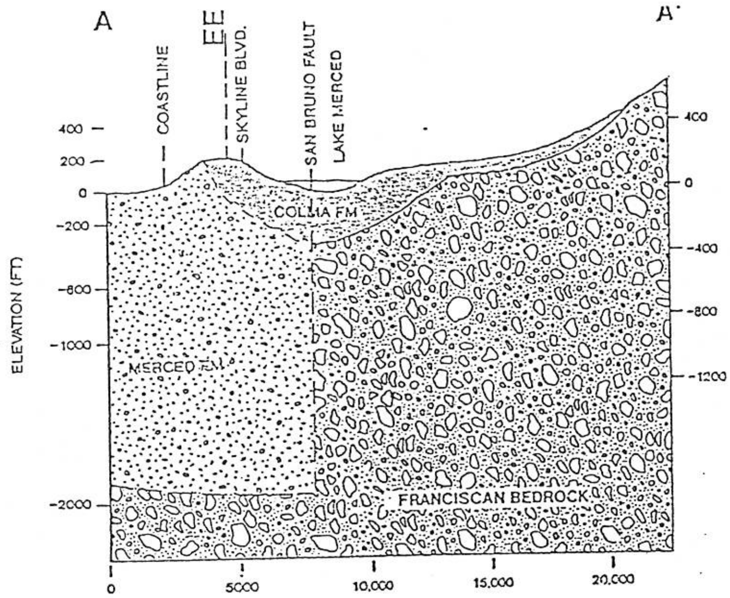
Geology

The Daly City groundwater basin lies above a trough-shaped bedrock formation of the Franciscan Complex. This trough is roughly two miles wide running from the northwest from the San Francisco Bay to the Pacific Ocean along the northeast side of the San Andreas Fault. The depth to the bedrock was estimated to be 2500 feet based upon aeromagnetic and gravity survey data (Bonilla 1971).

The movement of water is controlled by hydraulic conductivity and storage coefficient of the geological materials. In bedrock, the hydraulic conductivity is very low compared to the overlying sediments. The presences of springs indicate that there may be fractures in the bedrock that allow groundwater flow, but to simplify this study, bedrock will be considered an impermeable boundary for the groundwater basin (Yates, Hamlin, and McCann 1990).

In the study area, sediment stratification from Plio-Pleistocene marine and non-marine sources known as the Merced and Colma formations were deposited into this bedrock trough over the past 2 million years. These sediment deposits form the existing layers of soil types that created the two aquifers systems in the Daly City groundwater basin. Of the two formations, the Merced formation covers a wide area that reaches from Lake Merced and Mussel Rock along the coast, to the western edge of the San Andreas fault near San Bruno Mountain. The Colma Formation lies along a narrower outcropping over the Merced formation from Lake Merced and southeast toward the eastern portion of the valley. It ends near the southern base of San Bruno Mountain. Cross sections in Figure 2 show the variations in the extent and depths of these formations (Figures 9, 10, and 11).

The larger formation, the Merced Formation consists of shallow marine and estuarine sediments such as poorly consolidated sands, clays, sandy shales, sandstones, pebble conglomerates, and shell beds which cover the Franciscan Bedrock Complex in unconforming layers. In some areas, the Merced Formation is estimated to be 5000 feet thick. Stratigraphically, there is significant variation in the sediments and the course-grained materials are not vertically extensive. There are indications that the water bearing zone in this formation is overlain by 10 to 50 feet of low permeability clay and silty interbeds. This will likely act as a localized confining aquifer condition. Thicker fine-grained layers from 10 to 60 feet typically occur every 300 to 600 feet. In addition, some tilted fine-grain strata was considered to significantly impede horizontal flow of groundwater (Yates,



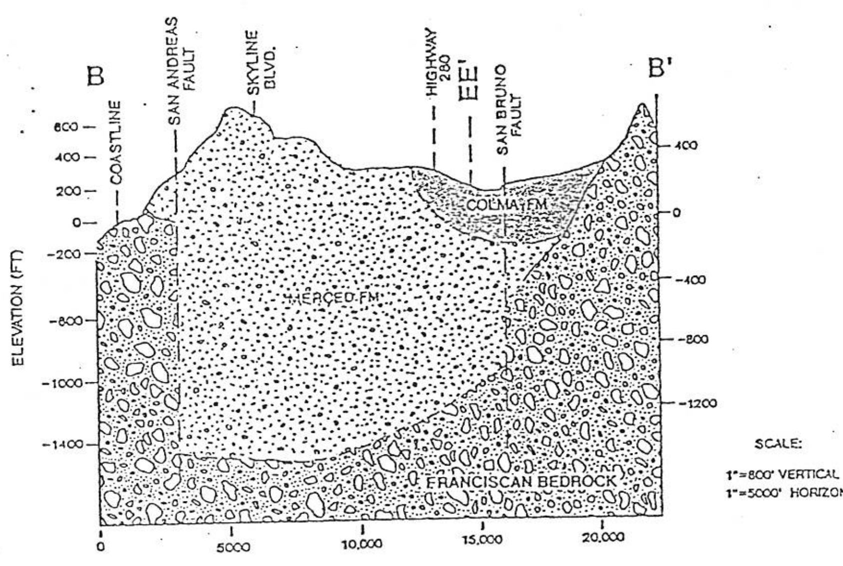


Figure 9. Geologic Cross-sections A-A' and B-B'(Applied Consultants 1991)

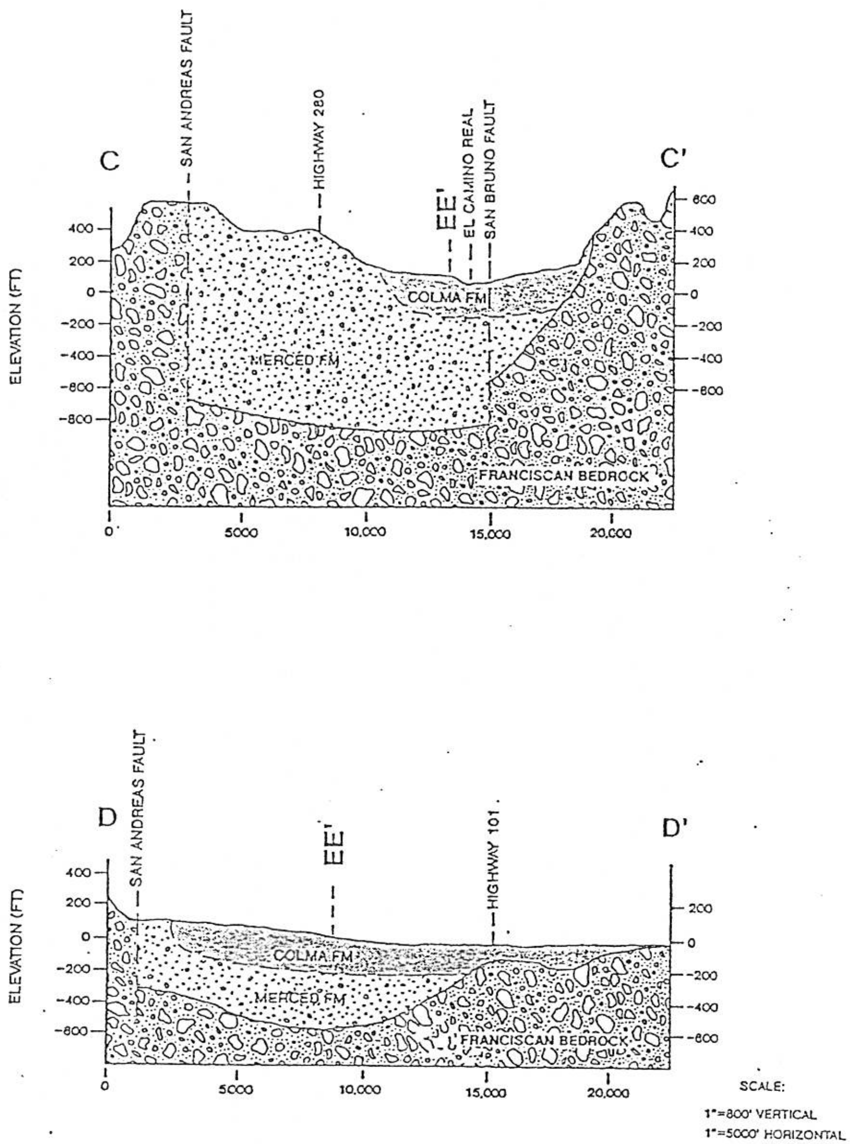


Figure 10. Geologic Cross Section C-C' and D-D' (Applied Consultants 1991)

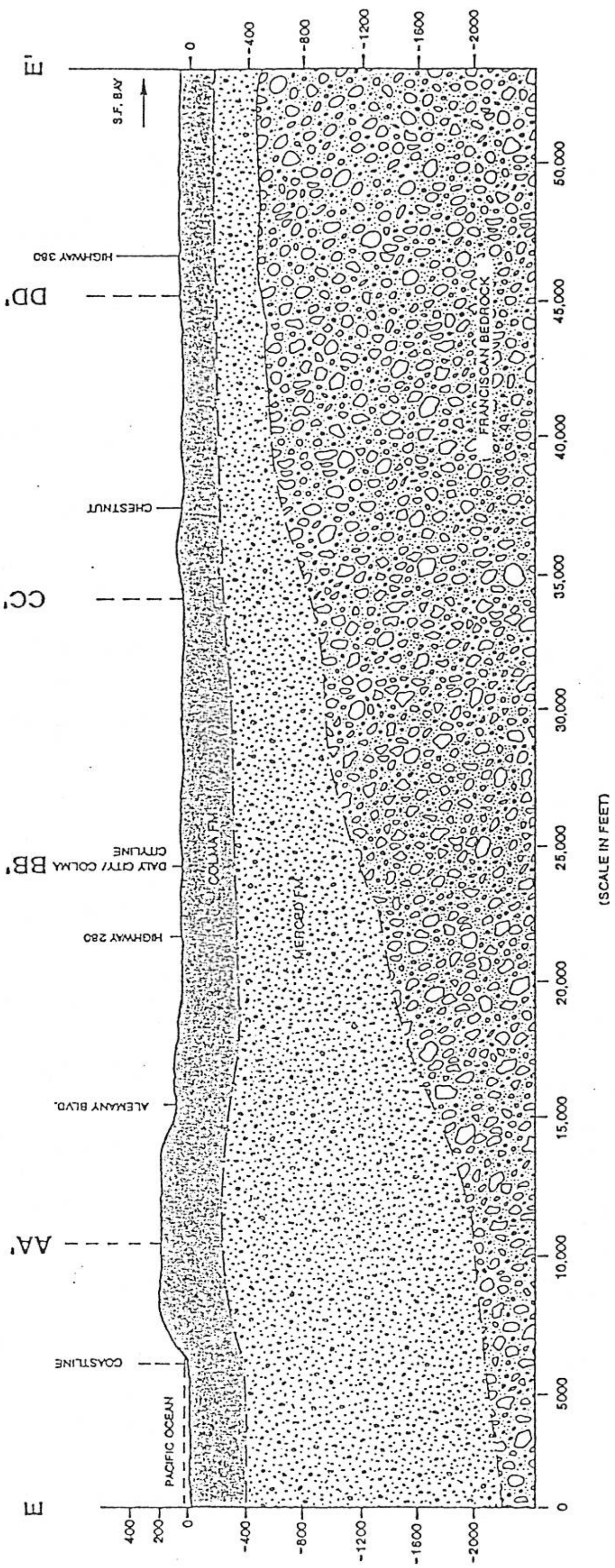


Figure 11. Geologic Cross-section E-E'
(Applied Consultants 1991)

Hamlin, and McCann 1990). Dipping of bedding planes increase from more than 40 degrees in the older strata exposed between San Bruno and Daly City to 10 to 15 degrees in the youngest strata exposed at the beach near Lake Merced (Bonilla 1971).

The upper formation, lying above the Merced Formation, is the Colma Formation. It consists of yellowish to reddish brown sand to silty sand with a few thin beds of clay (up to five feet thick) and fine gravels. This layer of sediments, ranging from 0 to 200 feet thick, is horizontally stratified and cross bedded. In someareas, shallow deposits of recent alluvium, dune sand, and bay mud overlie this formation (Applied Consultants 1991).

The Aquifer System

The Daly City groundwater basin consists of two aquifers. These two unconsolidated water-bearing zones lie within the Merced and Colma Formations. Course grained materials such as sand and gravel bear water in each of these formations. The full lateral extent of these formations beneath the Pacific Ocean and the San Francisco Bay has not been fully defined. The hydraulic connection between the aquifer and the ocean or bay is also not fully understood. The many fault zones which may impede groundwater flow further complicate the picture. These factors limit complete definition of the groundwater flow regime in this study area. A well near Fort Funston in the northwestern part of the study area indicates little evidence of salt-water intrusion has occurred*. It is known that the aquifer system is multilayered yet it does not appear as typical textbook examples of confined and unconfined aquifers. The shallow aquifer does not appear to demonstrate any significant gradient effects due to the surface drainage from the saddle which transects the basin as previously noted. In addition, the deeper aquifer appears semi-confined in some areas with the confining layer(s) discontinuous in thickness and lateral extent. This deeper aquifer of the Merced Formation appears to receive infiltration or recharge through the sometimes discontinuous aquitard from the overlying unconfined shallow aquifer of the Colma Formation (Applied Consultants 1991).

An aquifer test at the Alvord well indicated that horizontal hydraulic conductivity in the depth interval between 170 and 240 ft ranged from 12 to 24 ft/day (Woodward-Clyde 1984). Another aquifer test gave a value of 8 ft/day for the interval between 175 and 475 feet below land surface (CH2M-Hill 1989). Horizontal hydraulic conductivity in the top several hundred feet of the groundwater basin was estimated from drawdown data obtained during 1 to 2 hour well-efficiency tests conducted for the Yates study on June 28, 1988. Hydraulic conductivity ranged form 5 to 31 ft/day and average 17 ft/day (Yates,

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* personal communication with Steven Phillips

Hamlin, and McCann 1990).

A generalized version of the northern part of the Basin shows aquifer layers and the associated aquitard layer. The estimated hydraulic conductivity, leakance, transmissivity are also shown (Yates 1993)(Figure 12).

Lake Merced

In the Lake Merced area, water level trends in the shallow aquifer have been noted to be related to water levels in the lake complex. Lake Merced creates a plateau in the water table by causing a path of low resistance for the shallow groundwater flow. There is also a downward and southward gradient caused by deep pumping at the three golf courses (Harding Park, San Francisco Golf Club, and Lake Merced Golf Club) and other locations south of the Lake Merced area (Yates, Hamlin, and McCann 1990). Yet, the natural movement of groundwater in the Lake Merced area appears to be towards the west.

Significant declines in all deep water wells were noted during 1940 to 1970 but data indicated that levels have generally remained stable during the 1970's (Yates, Hamlin, and McCann 1990). Recently, in the past 10 years, however, water levels have slowly declined. Water levels trends in the deep aquifer have also been noted to be related to water levels trends in the Daly City municipal wells.

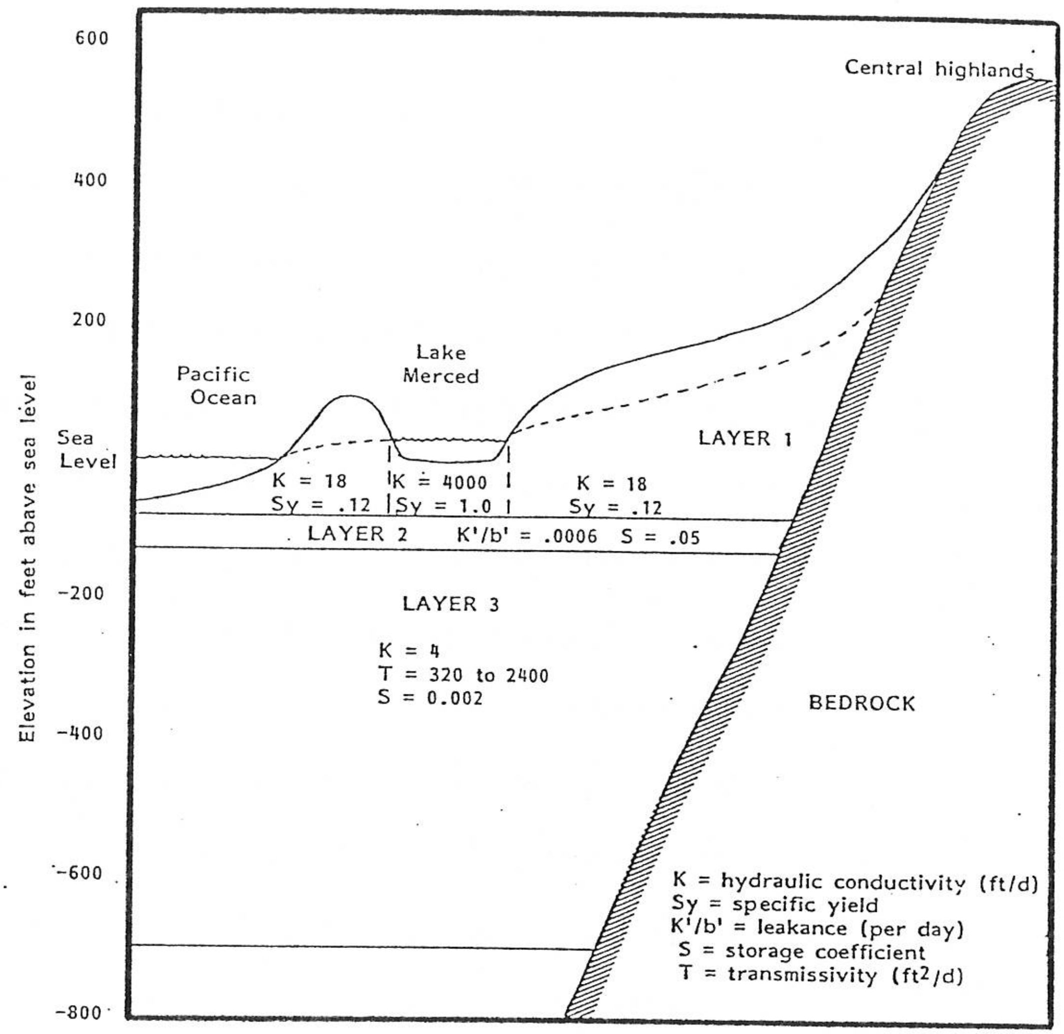

Figure 12. Schematic cross-section of model layer and aquifer characteristics in the northern part of the basin (Yates 1993)

Groundwater Recharge

Groundwater recharge in various water budgets studies have only been estimated. The recharge occurs with rainfall, irrigation water, and leaky pipes and sewer lines which percolates downward from the surface to the water table. Only water that percolates past plant roots can reach the water table. Rainfall recharge also only occurs where there is exposed soil and not in areas covered by pavement and buildings. Surface runoff with discharge to the San Francisco Bay, evapo-transpiration, and depression storage (puddles, ponds, etc) are other complicatingfactors.

Kirker, et al represented the Daly City Groundwater Tributary Area with surface drainage and groundwater flow directions (Figure 13). The boundary to the east of the aquifer area is dashed signifying an undetermined contribution of groundwater through a portion of the eastern boundary which drains water from the subsurface valley. The northern boundary is a groundwater divide to signify groundwater moving north toward the San Francisco and Olympic Golf Club wells and Lake Merced. The southern boundary is a groundwater divide with groundwater flowing towards the Colma cemetery wells. The eastern and western boundaries are the limits of the aquifer (Kirker, et al 1972).

After the extensive review of the Daly City groundwater basin's geologic

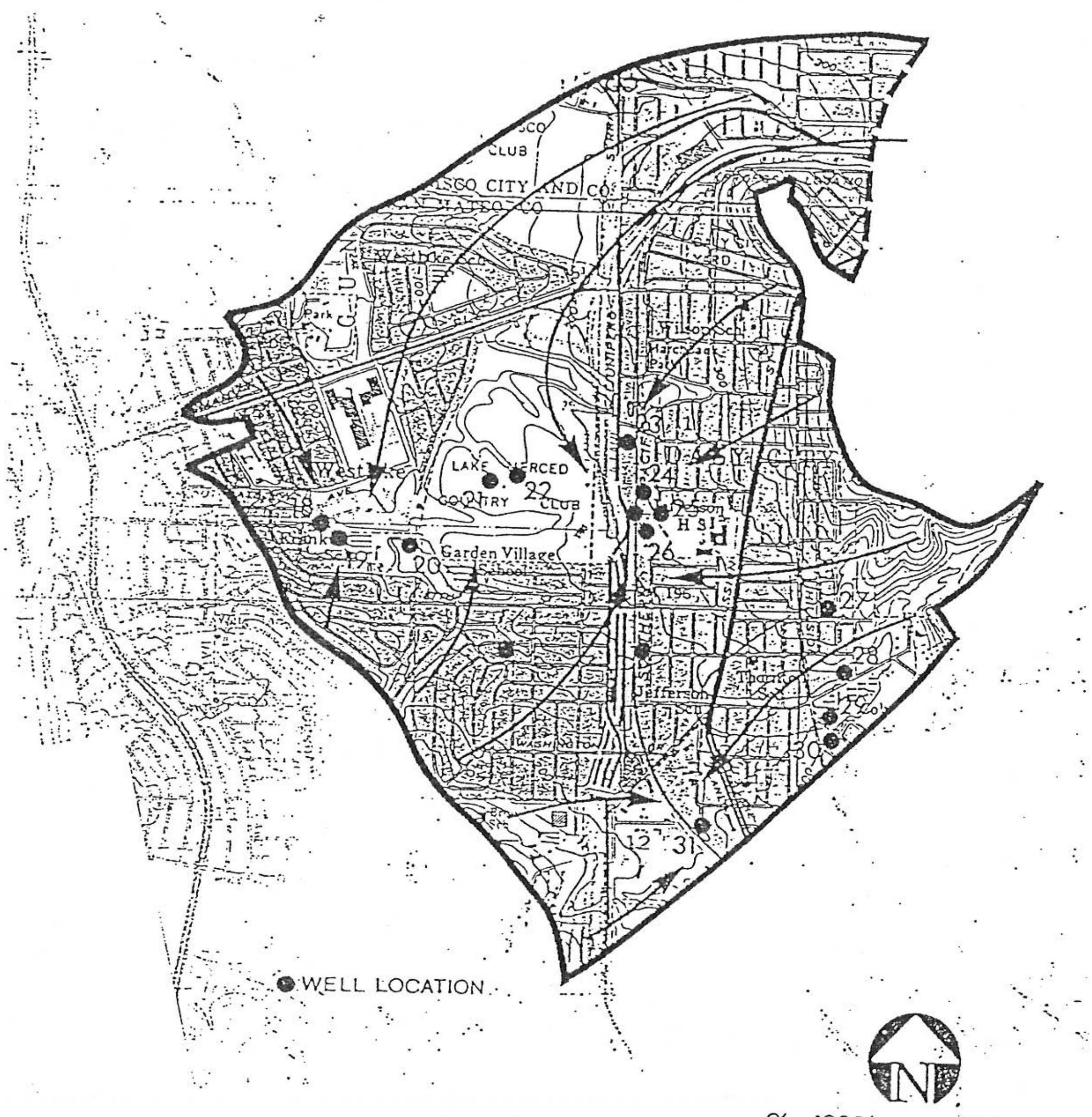

Figure 13. Map of Daly City Groundwater Tributary Area and groundwater flow directions(Kirker, et al 1972).

and hydrogeologic conditions, it was discovered and documented in two recent studies (Phillips 1993; and Yates 1993) that groundwater recharge as a result of precipitation and leaking sewer and water pipes may be significant factors in this study area. Groundwater recharge in the Lake Merced area was estimated to contribute about one-third of the total annual inflow to the groundwater system (Yates, Hamlin, and McCann 1990). Significant groundwater recharge has also been attributed to irrigation from the Golden Gate Park* .

Although there is a certain amount of uncertainly from year to year depending upon precipitation, average annual recharge at the present level of development is approximately 5,630 acre-feet per year (af/yr) in the area of 10188 acres covered by the Yates groundwater model (Yates 1993). Overall, the groundwater recharge from infiltration in the immediate tributary/drainage basin of the Daly City municipal water wells appear to be limited.

Gradient and Groundwater Levels

The natural gradient in the Daly City deep groundwater aquifer is generally assumed to flow toward the ocean. The Yates, Hamlin and McCann report assumed that gradient to be only 0.005 ft/ft seaward because of the effects of the pumping wells at the inland locations. The natural gradient in the shallow

* personal communication with Stephen Phillips

aquifer appears to be towards the east. but, actual shallow and deep gradients have be altered due to constant groundwater pumping wells in the area. Yates represents a map with generalized groundwater levels contours of the shallow and deep aquifers in 1990 (Yates 1993) (Figures 14 and 15). The gradient direction was measured as a perpendicular line to the potentiometric surface in the area of the Daly City groundwater drainage basin and was estimated to be 255° North.

The trough and depressions show the potentiometric surface of the ground water during active well pumping. The potentiometric lines are water levels at equal elevations depicted relative to Mean Sea Level (MSL). These groundwater levels are presented with some averaging due to static water levels taken from intermittent pumping irrigation wells versus the continuous pumping municipal wells.

The potentiometric surface of the deep groundwater is shown in Yates study from data taken during active pumping wells(Figure 15). Note that although the major pumping wells all draw from the deep aquifer, the drawdown propagates upward through the clay confining layer and effects water levels in the shallow aquifer as well as exhibited by potentiometric measurements. This is shown in the difference of 1.5 feet between the levels of water in the South Lake Merced and Impound Lake Merced due to the deep pumping wells near the South Lake (Yates 1993). No known continuous or significant pumping is aquifer appears to be towards the east. but, actual shallow and deep gradients have be altered due to constant groundwater pumping wells in the area. Yates represents a map with generalized groundwater levels contours of the shallow and deep aquifers in 1990 (Yates 1993) (Figures 14 and 15). The gradient direction was measured as a perpendicular line to the coastal edge of ocean in the area of the Daly City groundwater drainage basin and was estimated to be 255° North.

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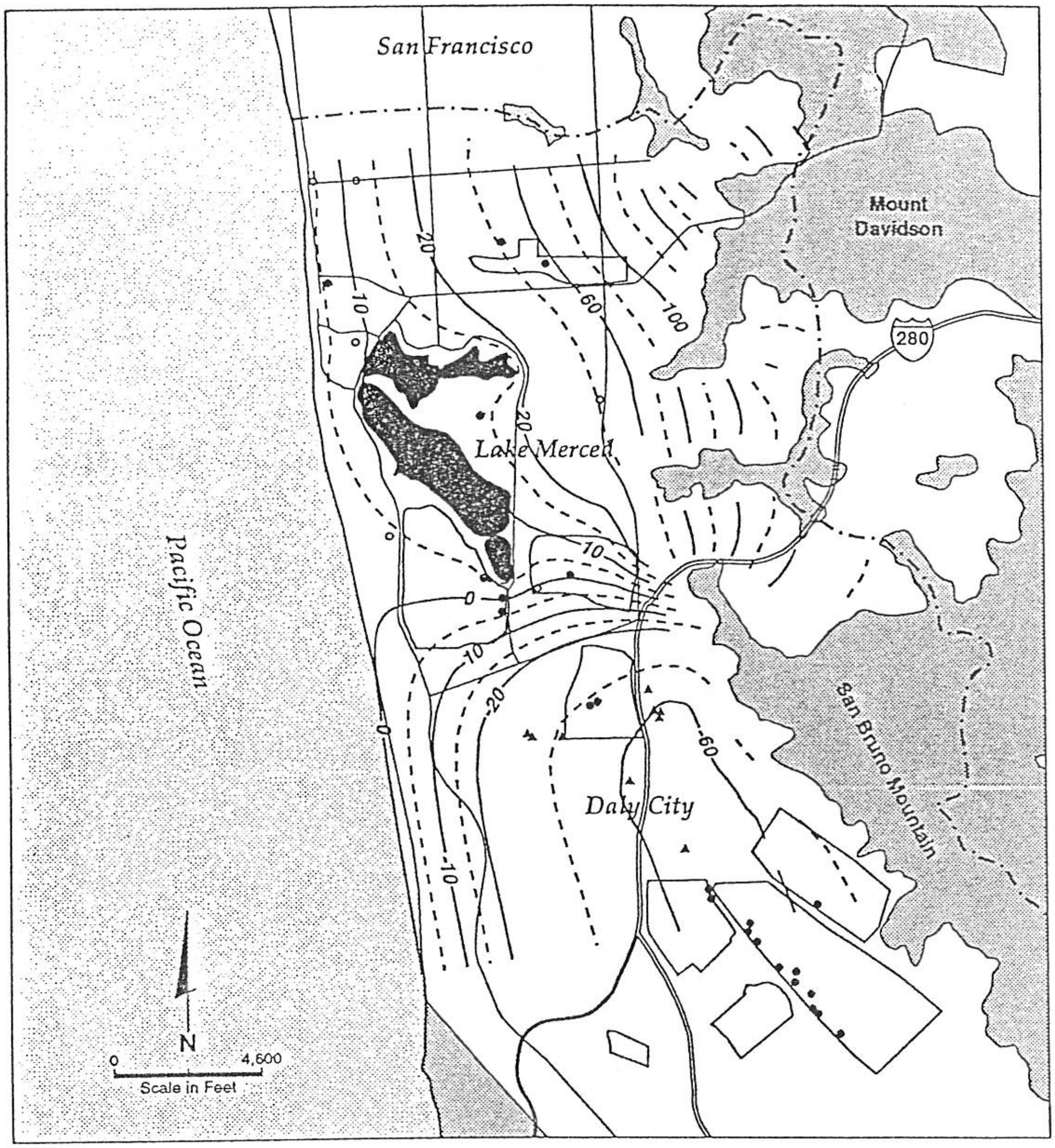


EXPLANATION

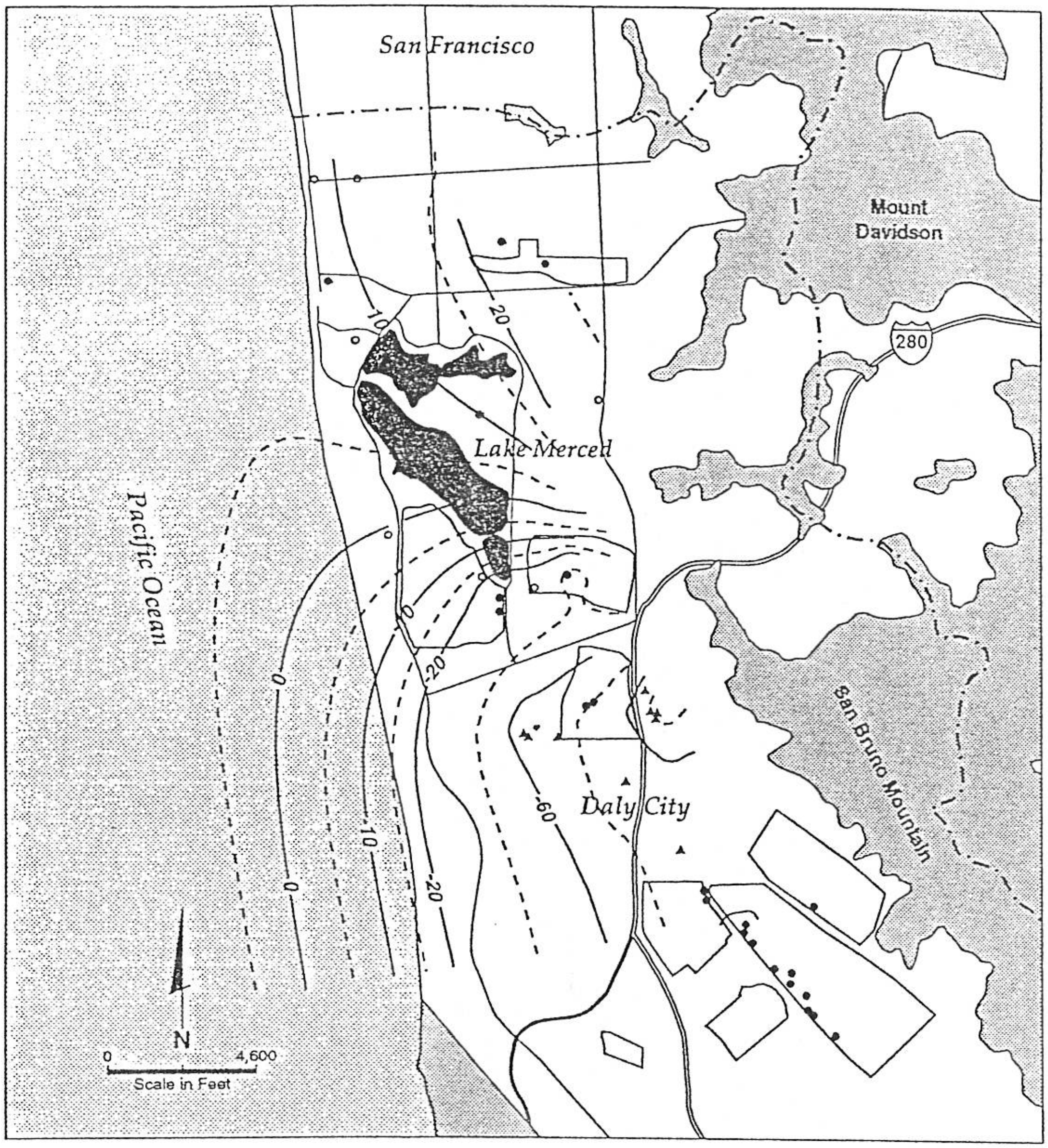
- o Monitoring Well
- ▲ Municipal Well
- • Irrigation Well
- Bedrock Outcrop
- ..— Surface Drainage Divide
- — Contour of Simulated Water Levels in Feet Above Sea Level (contour interval varies)

Figure 14 - source: Yates 1993

Measured Water Levels and Contours of Simulated Water Levels in the Shallow Aquifer in September 1990

Jones & Stokes Associates, Inc.

Merced-5



EXPLANATION

- ○ Monitoring Well
- ▲ Municipal Well
- ● Irrigation Well
- ▒ Bedrock Outcrop
- ..— Surface Drainage Divide
- —— Contour of Simulated Water Levels in Feet Above Sea Level (contour interval varies)

Figure 15 - source: Yates 1993

Measured Water Levels and Contours of Simulated Water Levels in the Deep Aquifer System in September 1990

Jones & Stokes Associates, Inc.

Merced-7

occurring in the shallow aquifer to influence the groundwater flow direction. This shallow aquifer gradient south of Lake Merced appears to be toward the east (Figure 14).

Historical water level data show that levels for years 1959, 1966, 1971, 1980, and 1988 demonstrate significant declines in static water levels up to 1971. These levels have remained relatively stable since that study (Yates, Hamlin, and McCann 1990). Water levels in the deep aquifer system near the southern part of Lake Merced were 30 to 60 feet lower than the shallow aquifer in 1990. Farther south, near the Daly City pumping wells and cemeteries, water levels were even deeper, about 100 to 130 feet below Mean Sea Level (Yates 1993).

Modeling of the Capture Zone

The capture zones from the Daly City drinking water wells and the nearby Lake Merced Golf Club irrigation wells was determined from previously collected data. The pumping well data includes the 10 Daly City (DC) drinking water wells, and two Lake Merced Golf Club (MC) irrigation wells (Table 3). The MC wells were included in the study because of the possible overlap and interference of their capture zones upon the DC wells. Through the use of the RESSQC module, hydrogeologic and well data obtained from the first subproblem was entered into the model and the results evaluated (Table 4 and 5). X and Y

Table 3 - PUMPING WELL DATA - 1993 data from City of Daly City Department of Water & Wastewater Resources and Lake Merced Golf Club

well#	Year Install-ed	Depth (ft)	Pump capacity (gpm)	Saturated thickness (ft)	Pump Rate (gpm)
DC1	1954	380	259	129	110
DC2	1955	389	370	140	233
DC3	1962	375	215	135	210
DC4	1981	480	519	191	445
DC8	<1940	479	350	98	297
DC10	1950	516	395	159	335
DC11	1953	550	300	141	154
DC12	1959	550	425	370	233
Vale	1991	700	825	384	704
Jeff	1991	700	650	350	565
MC1	1986	700	1000	300	500*
MC2	1964	450	500	130	100*

*averaged over a year

source: City of Daly City, Department of Water and Wastewater Resources, 1993.
Lake Merced Golf Club, personal communication with Lou Tenelli, Golf Superintendent

Table 4 - RESSQC Input Values for Daly City Municipal Wells For the study area:

IUNIT (units of input parameters)	ft & day
NWP (number of pumping wells)	12
NWI (Number of Recharge wells)	0
XMIN (min x-coordinates of area)	0 ft
XMAX (max x-coordinates of area)	10500 ft
MIN (min y-coordinates of area)	0 ft
YMAX (max y-coordinates of area)	10500 ft
TRANSM (transmissivity of aquifer)	2150-3200 ft^2/d (Applied Consultants 1991) 320-2400 ft^2/d (work in progress, Yates 1993)
GRADNT (regional hydraulic gradient)	0.005 ft/ft (work in progress, Yates 1993)
ALPHA (Angle of ambient GW flow)	est 255 degrees
POR (aquifer porosity)	34% Colma formation (Kirker, et al 1972)
HEIGHT (Aquifer saturated thickness)	average 300 ft (Daly City 1993)
DL (largest allowable step length)	45 ft
TMAX (max amount of time for calculating trace of a pathline)	1825 days
NCAPZ (# of time-related capture zones for each well)	2
NRPATH (# of reverse-tracked pathlines started at arbitrary locations within the study area)	0

For Each capture zone:

DATE(I) (time value for capture zone)	1825 and 3650 days

Table 5 - Input values for each pumping well from 1993 City of Daly City and Lake Merced Golf Club data:

Well#	X (ft)	Y (ft)	QPWELL (ft^3/d) (well discharge rate)	RADW (ft)* (well radius)	ITRW (ratio of path lines)	NPATH (number of pathlines)
DC1	2600	5850	20598	1.17	1	5
DC2	2350	6050	26758	1.17	1	5
DC3	3550	5750	40425	1.17	1	5
DC4	4850	4350	85663	1.17	1	5
DC8	6800	6500	57365	1.0	1	5
DC10	6550	7150	65065	1.17	1	5
DC11	7050	6200	30415	1.17	1	5
DC12	7600	2000	44275	1.17	1	5
Vale	6750	4350	136098	1.33	1	5
Jeff	6650	6250	107225	1.33	1	5
MC1	4400	6700	721875	1.17	1	5
MC2	4600	6600	144375	1.17	1	5

*source: City of Daly City, Department of Water and Wastewater Resources, 1993.
Lake Merced Golf Club, personal communication with Lou Tenelli, Golf Superintendent

coordinates were arbitrarily selected using a grid of the Tributary Area.

Sixteen runs were performed using a range of parameters to determine optimal results with two time intervals (Table 6). Two values for transmissivity and four values for aquifer thicknesses were used over two time periods to see the range of area covered by the capture zones. This sensitivity analysis of the models, using a range of transmissivity values and aquifer thicknesses was performed to provide more accurate results. Included in this analyses, an average pump rate for the Lake Merced Golf Club wells was used because these wells only operates for 7.5 hours a day from mid-May to mid-November. During that time, MC1 generally operates alone at an average of 800 gpm. During maximum usage, MC1 operates at capacity of 1000 gpm with MC2 or MC3 pumping at 200 gpm for a total of 1200 gpm. In this study, Lake Merced Golf Club was assumed to pump from MC1 and MC2 at the total rate of 1200 gpm.

Throughout the entire basin, the transmissivity values range from 320 to 2400 ft^2/d (Yates, Hamlin, and McCann 1990). Data taken specifically from the vicinity of the Daly City wells indicate transmissivities of 2150 to 3200 ft^2/d (Applied Consultants 1988). For data entry, transmissivity values of 2150 and 3200 ft^2/d were used.

A comparison of the capture zones was also made with different aquifer thicknesses. Since none of the wells fully penetrate the aquifer as required by the

Table 6 - Modeling Run Criteria

Run for 5 yr capture zone	Run for 10 yr capture zone	Transmissivity	Well Cluster Representation	Aquifer Saturation Thickness
DC105	DC110	2150	DC#1,2,3	195
DC205	DC210	2150	DC#8,10,11,12, Jeff	366
DC305	DC310	2150	DC#4,MC1, MC2	248
DC405	DC410	2150	Vale	456
DC505	DC510	3200	DC#1,2,3	195
DC605	DC610	3200	DC#8,10,11,12, Jeff	366
DC705	DC710	3200	DC#4, MC1, MC2	248
DC805	DC810	3200	Vale	456

The computer modeling from these runs are presented in Appendix B.

The capture zone models were run with the following conditions:

Time periods (1895 and 3650 days)
Regional hydraulic gradient of 0.005 ft/ft
Angle of Ambient flow - 255 degrees of North
Aquifer porosity - .34 (dimensionless)
Aquifer saturation thickness - 195, 248, 366, & 456 ft
Transmissivity - 2150 and 3200 ft^2/d
MC#1 and MC#2 pumping rate averaged over one year

model parameters, the length of water column, or saturated thickness, at static non-pumping conditions, was considered the aquifer thickness. The average saturated thickness of the wells in the study area was estimated at 300 ft but range from 130 to 456 feet. Because the model cannot distinguish differing saturated thicknesses for each well, average saturated thicknesses for four well cluster areas were used. The average of DC1, DC2, and DC3 was 195 ft. The average of DC4, MC1, and MC2 was 248 ft. The average of DC8, DC10, DC11, DC12, and Jeff was 366 ft. The Vale well had the longest saturated thickness of 456 feet and was considered one well cluster. The capture zones of each of these clusters are indicated with their respective thicknesses on the final map overlay for each time period (Figures 16, 17, 18, and 19). See Appendix B for model run outputs.

A map of known groundwater contaminated sites was then overlain over the map of the Daly City Groundwater Tributary Area to see whether these contaminated sites lie within the capture zones. The potential for the contamination can then be identified. These sites were identified if soil or groundwater in the shallow or deep aquifer was confirmed to have been contaminated. The results were then evaluated to determine whether existing groundwater contamination will have the potential to impact the drinking water aquifer over time.

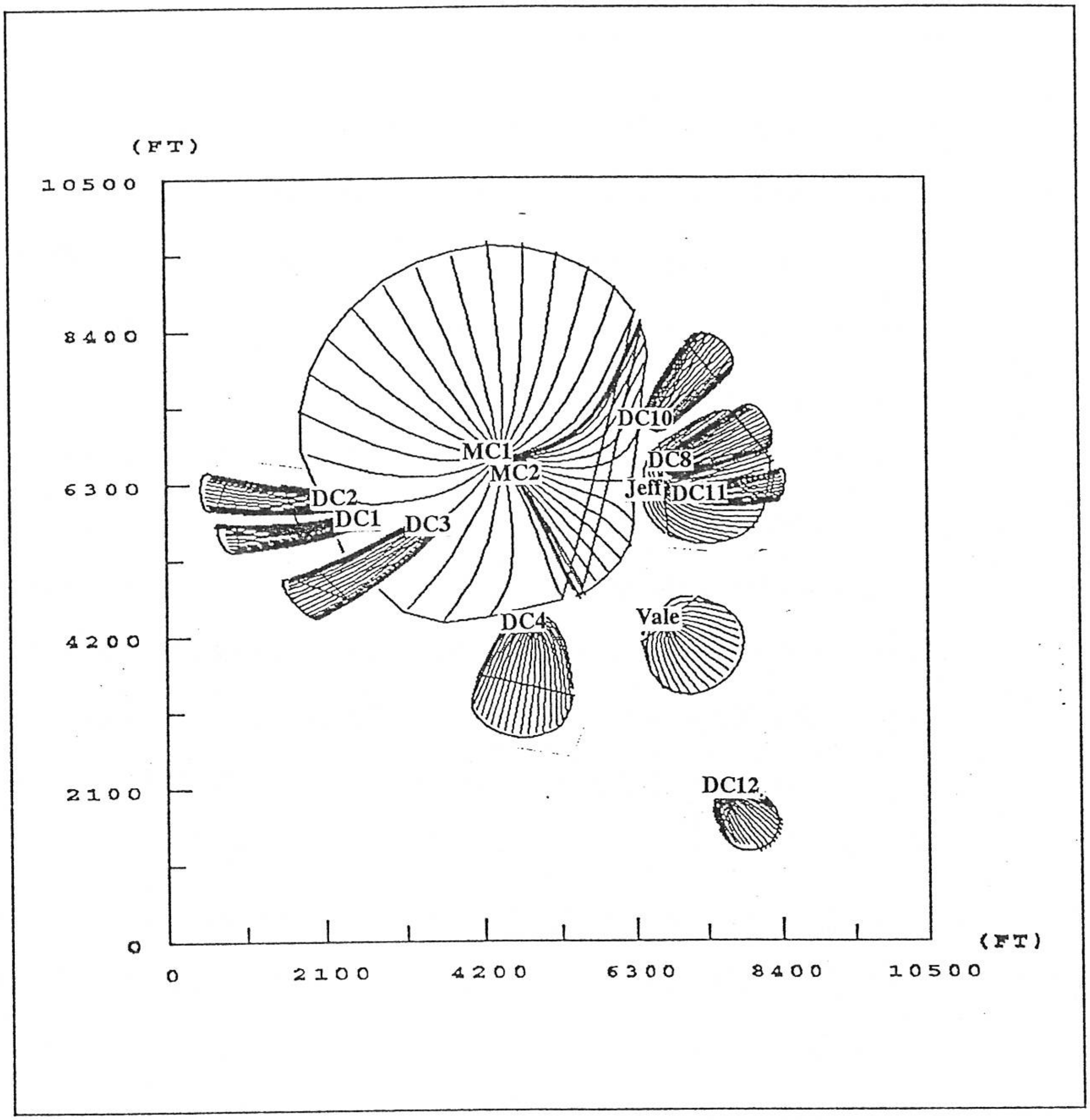


Figure 16. 5 year capture zones for a transmissivity value of 2150 ft^2\d.

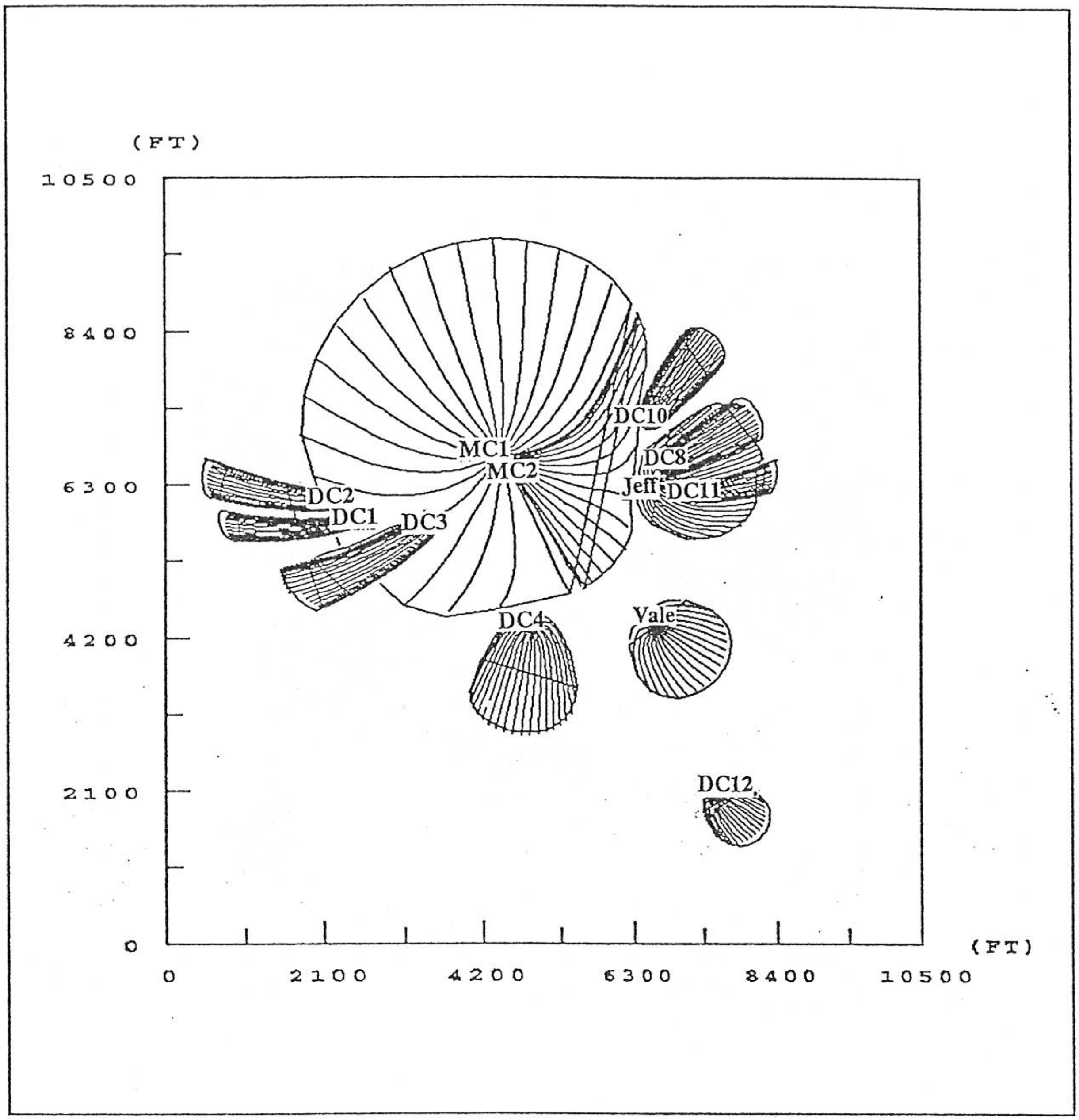


Figure 17. 5 year capture zones for a transmissivity value of 3200 ft^2/d

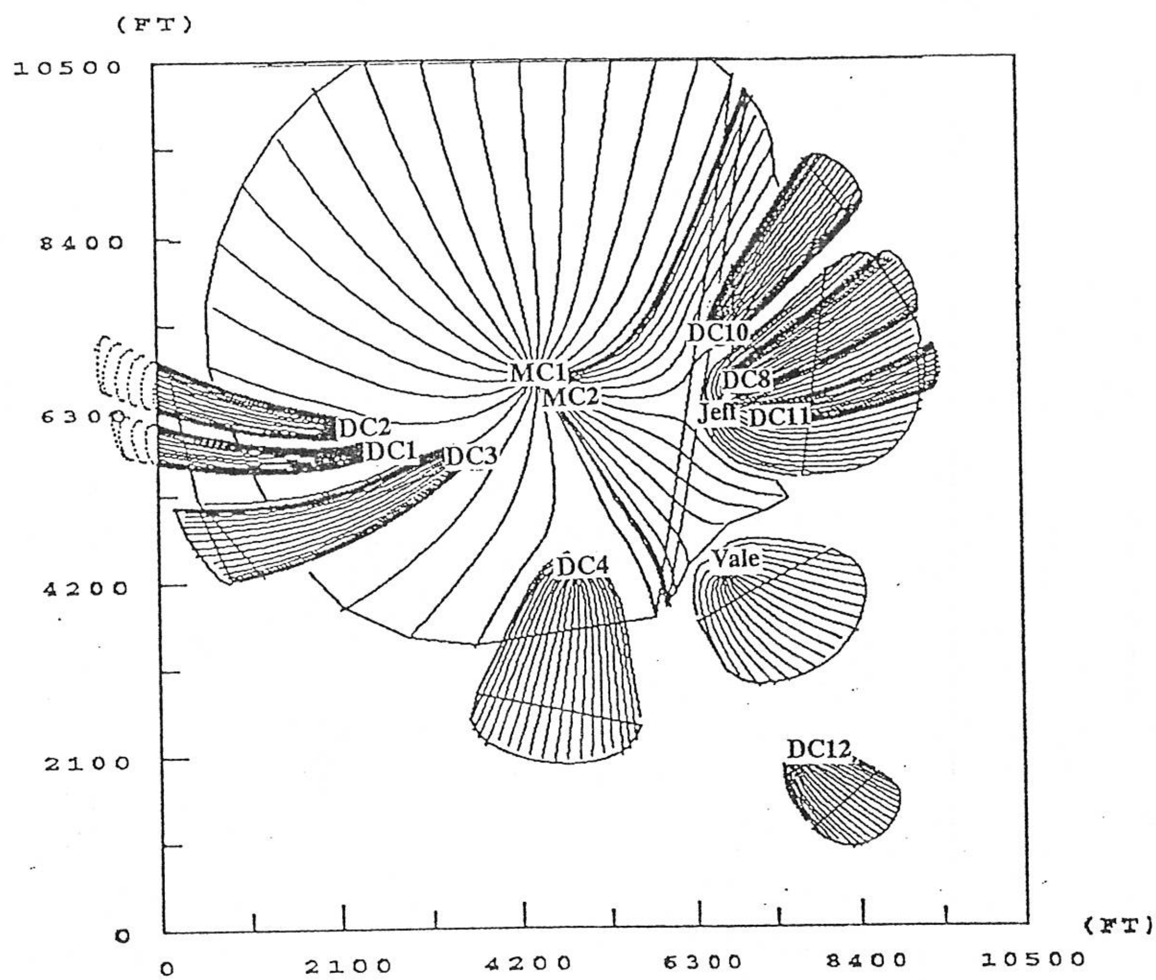


Figure 18. 10 year capture zones for a transmissivity value of 2150 ft^2/d

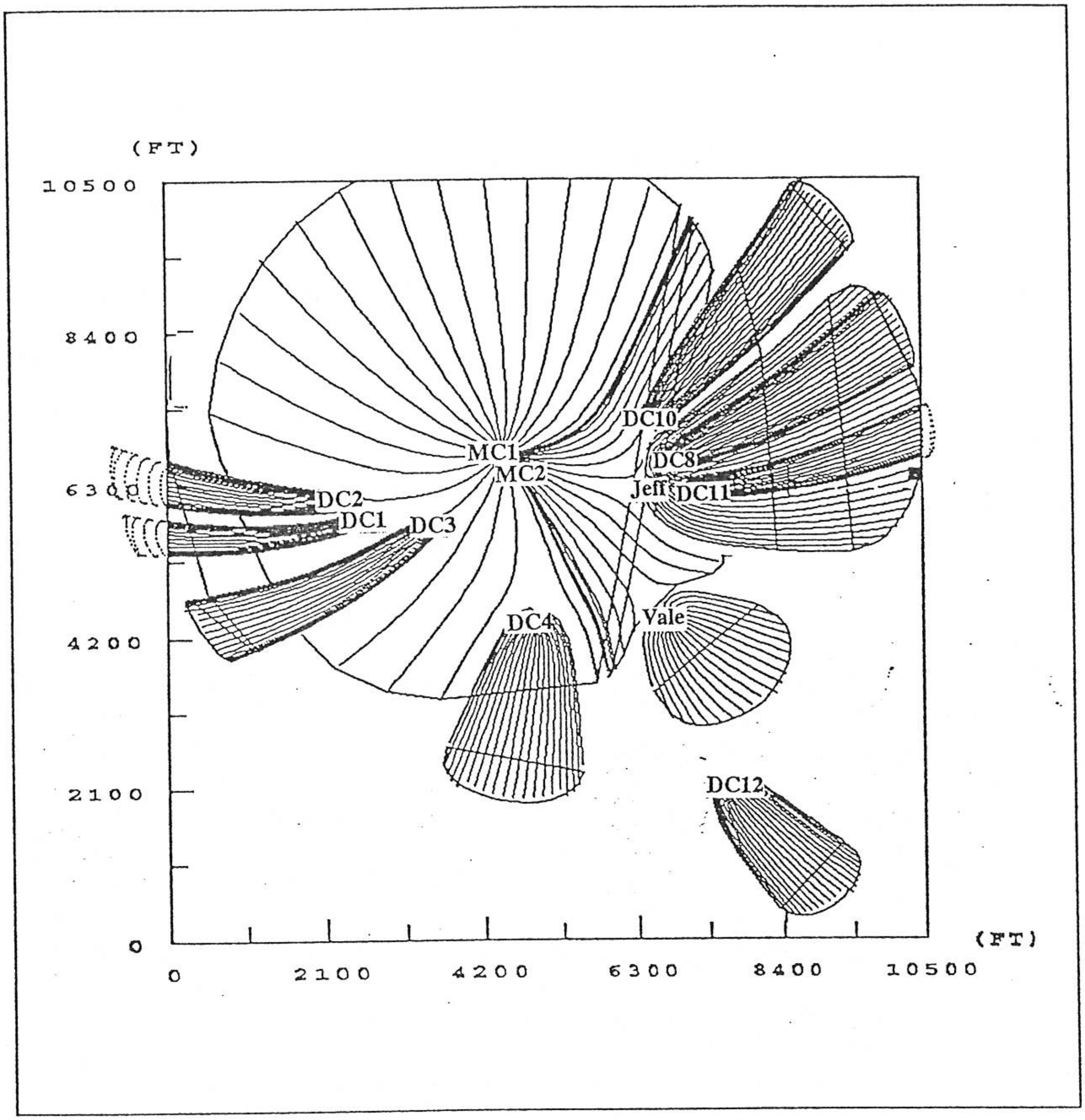


Figure 19. 10 year capture zones for a transmissivity value of 3200 ft^2/d

Contaminated Sites and Abandoned Well Sites

Review of goverment agency files identified contaminated sites and abandoned wells sites in the Daly City Tributary Area. Many were considered potential sources of contamination to the deep drinking water aquifer. If they lie within the Daly City Groundwater Tributary Area, they were considered to have the potential for impacting the Daly City drinking water wells.

Contaminated Sites

The following sites were determined to have confirmed soil and/or groundwater contamination (Table 7 and 8). Note that a distinction has been made whether the shallow (**S**) or deep (**D**) aquifer has been impacted. Soil (**s**) contaminated sites indicated that soil only has been impacted. Unknown (**unk**) indicates that soil hs been impacted but it is unknown whether the shallow or deep groundwater has been impacted.

This research model is most relevant when contamination has already impacted the deep aquifer. Otherwise, the contamination must move through the soil, the shallow aquifer, and the leaky aquitard, before it enters the deep aquifer. At the point the contaminants reach the deep aquifer, then the model can depict contaminant movement towards the pumping wells over a five and ten year time interval.

Table 7 - Confirmed Contaminated Sites in the City of Daly City

Site Name	Site Address	Contaminant	S/D	# wells
Shell Oil	4968 Callan Blvd	TPH-gas	unk	0
Fire Station #7	444 Gellert Blvd	TPH-diesel	unk	0
Shell Oil	390 Hickey Blvd	TPH-gas	unk	0
Chevron	892 John Daly Blvd	TPH-gas	S	0
Chevron	2089 Junipero Serra	TPH-gas	s	1
BP	3001 Junipero Serra	TPH-gas	S	3
Daly City Wastewater	153 Lake Merced Blvd	TPH-diesel	unk	0
Venturino Trust	5975 Mission Blvd	TPH-gas	S	1
Daly City Texaco	6098 Mission Blvd	TPH-gas, diesel	S	7
Winston Tire Co.	6492 Mission Blvd	TPH-gas	s	0
Stump Property	6800 Mission Blvd	TPH-gas	S	3
Daly City Service	7200 Mission Blvd	TPH-gas	unk	0
AAMCO Dealer	7360 Mission Blvd	TOG, trace PCB	unk	0
Daly City Corp Yard	798 Niantic St	unk	unk	0
Unocal	137 Serramonte Blvd	TPH-gas	S	6
Serramonte Olympian	501 Serramonte Blvd	TPH-gas	S	7
ARCO	151 Southgate	TPH-gas	D	5
Mobil	1404 Southgate	TPH-gas	S	1
Exxon	1690 Sullivan Rd	TPH-gas, VOCs	S	3
Pacific Bell	359 Washington Ave	TPH-diesel	unk	0
ARCO	295 Washington Ave	TPH-gas	S	3

Legend for Table 7:

PCB	Poly-chlorinated biphenols
TPH-gas	Total Petroleum Hydrocarbons as gasoline
TPH-diesel	Total Petroleum Hydrocarbons as diesel
TOG	Total Oil and Grease
VOC	Volatile Organic Carbons (ie: solvents,etc)
S	Confirmed shallow groundwater impact
D	Confirmed deep groundwater impact
s	Soil only impact
unk	Confirmed soil contamination but unknown shallow or deep groundwater impact
# wells	Number of monitoring wells to identify if contaminants were detected in groundwater

Table 8 - Contaminated Sites that lie within the DC Groundwater Tributary Area

These sites are identified on Figure 20 by the location codes below:

Location code	Contaminated site by name/street	X (ft)	Y (ft)
a	Chvron/John Daly Blvd	2300	8150
b	Chevron/Junipero Serra	6500	7500
c	BP/Junipero Serra	6650	2750
d	DC Water Resources	2350	8600
e	Stump Property	8300	7050
f	Unocal/Mission	8400	6500
g	DC Service/Mission	7900	4850
h	AAMCO/Mission	7700	4000
i	ARCO/Southgate	2700	6550
j	Exxon/Sullivan	5750	2400
k	Pac Bell/Washington	5700	2900
l	ARCO/Washington	5900	2900

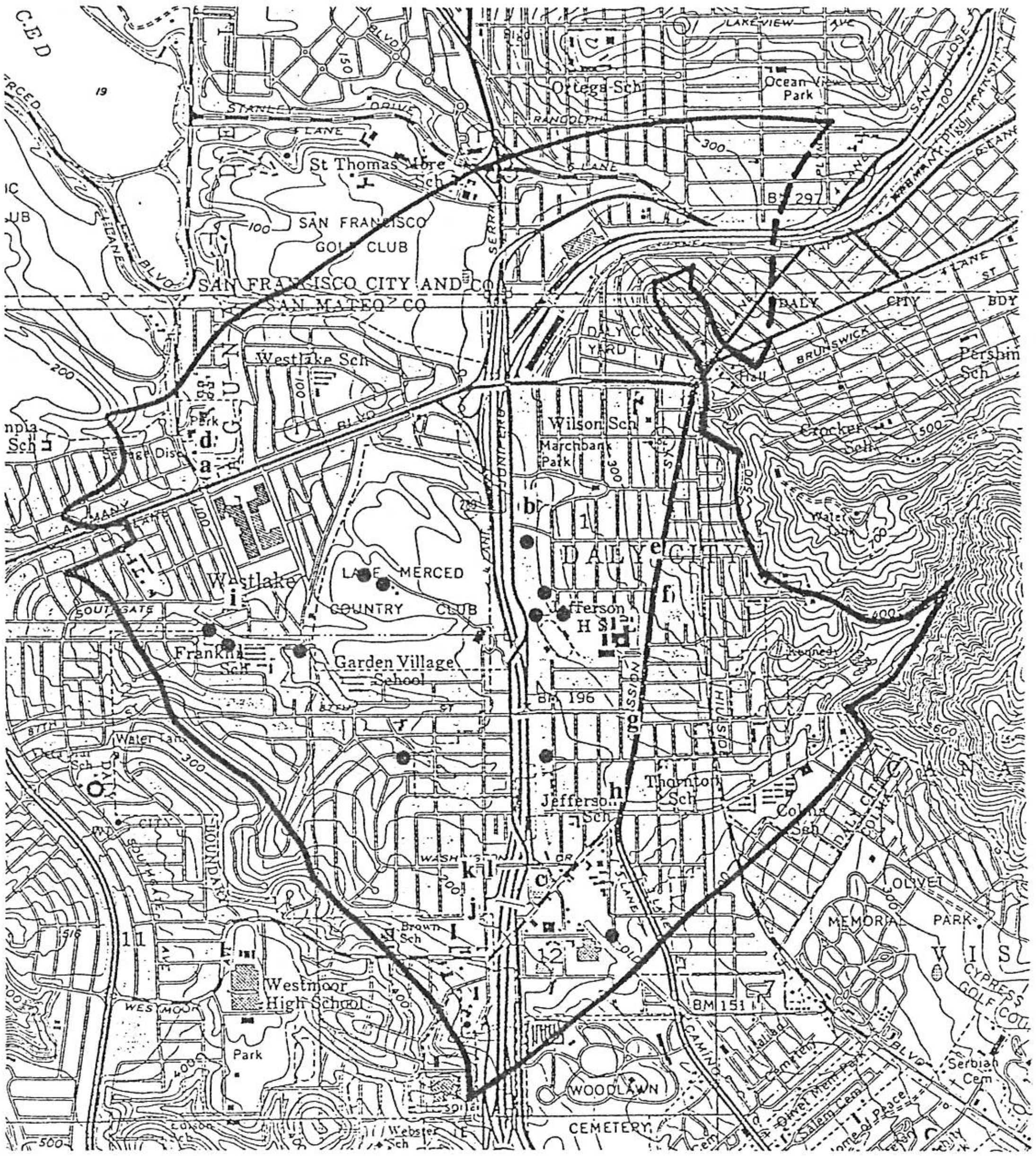


Figure 20. Site Map of Confirmed Contaminated Sites that lie within the Daly City Groundwater Tributary area.

Abandoned Wells

Abandoned wells were located and considered potential conduits for contamination from the surface or upper geological strata to be drawn down to the drinking water aquifer (Kirker, et al 1972). These abandoned wells may have been left unprotected from deliberate contamination, left in disrepair, or unmaintained so that cracks or breaches in the well or well seal may carry surface contamination downward into either two water bearing zones. It may also provide a route for contaminated shallow groundwater to move into the deeper groundwater. Upon further investigation, it appears that these abandoned wells do not lie within the Daly City Groundwater Tributary Area and therefore, the potential impact of abandoned wells as conduits for contaminant transport to the deep aquifer near the Daly City municipal wells is limited (Table 9 and Figure 21).

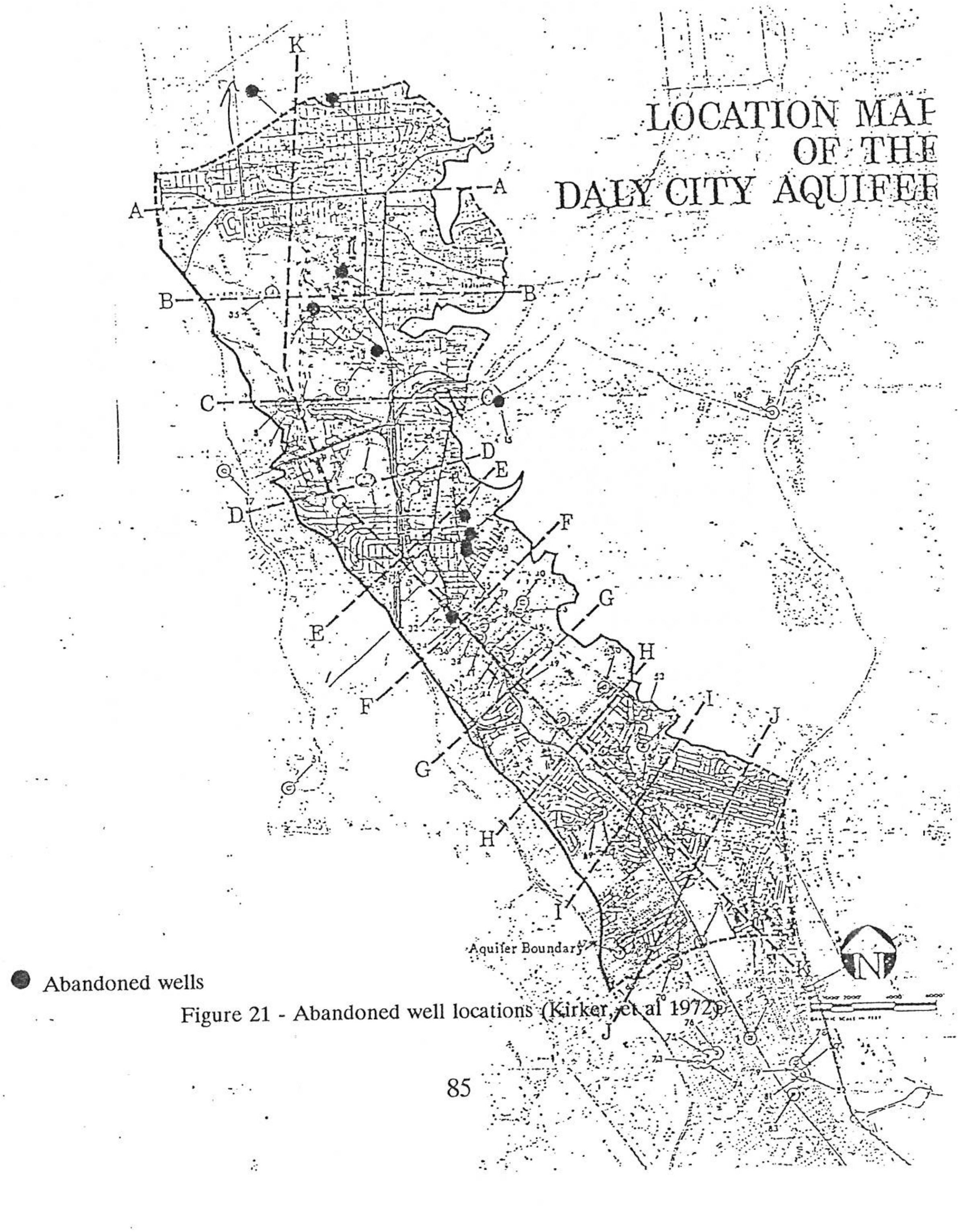
Table 9 - Abandoned wells as potential contaminant conduits in the Daly City Study Area

Well #	Owner	Location (APR#)	Drill date	Well type	Depth to water	well depth
4	IT & TE	44.73E-77.96N	1950	test hole	none	55
5	IT & TE	45.95E-77.85N	1950	test hole	none	60
6	IT & TE	45.85E-74.73N	1948	test hole	none	40
7	IT & TE	45.58E-74.72N	1950	test hole	none	30
14	IT & TE	46.49E-74.18N	1949	test hole	none	45
15	Daly City	48.21E-73.34N	1918	municipal	unk	200
29	Micheletti*	47.67E-71.31N	unk	irrigation	unk	unk
30	Piedamonte#	47.68E-71.25N	unk	agric	350	450
33	Woodlawn	47344E-70.25N	unk	unk	unk	unk
27	Pacini	47.67E-71.72N	1950	irrigation	225	445
28	Micheletti	47.73E-71.46N	1950	irrigation	45	395

*Used by Colma Elemementary School until 1960

#Pumped water to Pig Ranch above Cypress Lawn Golf Club until 1969

*source: Kirker, et al 1972



Abandoned wells

Figure 21 - Abandoned well locations (Kirker, et al 1972)

Evaluation of Contaminated Sites Within the Capture Zones in Five and Ten Years

Afer the location of the contaminated sites was identified within the capture zones, the determination was made whether the contamination may impact the drinking water wells. The location of the contaminated sites was superimposed onto the map of the Daly City municipal wells and the Lake Merced Golf Club wells and their respective capture zones to determine their impact (Figure 22 and 23). Only results from capture zone models using a transmissivity value of 3200 ft^2/d was used because the difference between the two values used were very similar. The contaminated site locations are indicated by an alphabetical location code from Table 8. The wells are denoted by the well code used in Table 5.

If a contaminated site lies within the capture zone of any of the wells, it has the potential to impact the groundwater well. A determination must first be made as to the extent of the contamination. Although this study does not address the degree of contamination of each site, it does indicate whether the soil, the shallow aquifer, or the deep aquifer has had detectable levels of contaminants.

It must be noted that during the geologic and hydrogeologic investigation,

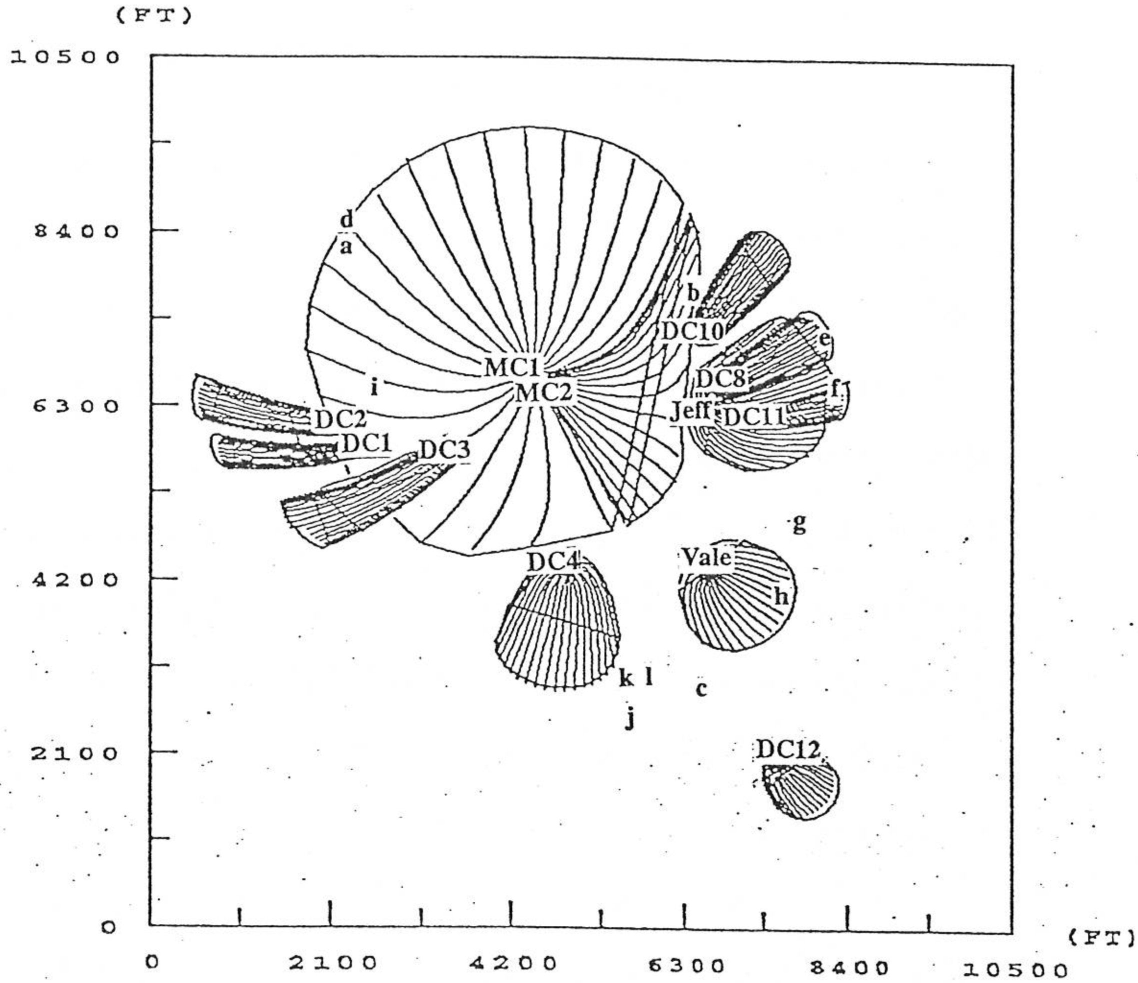


Figure 22. Five year capture zone models with contaminated sites identified within the Daly City Tributary Area

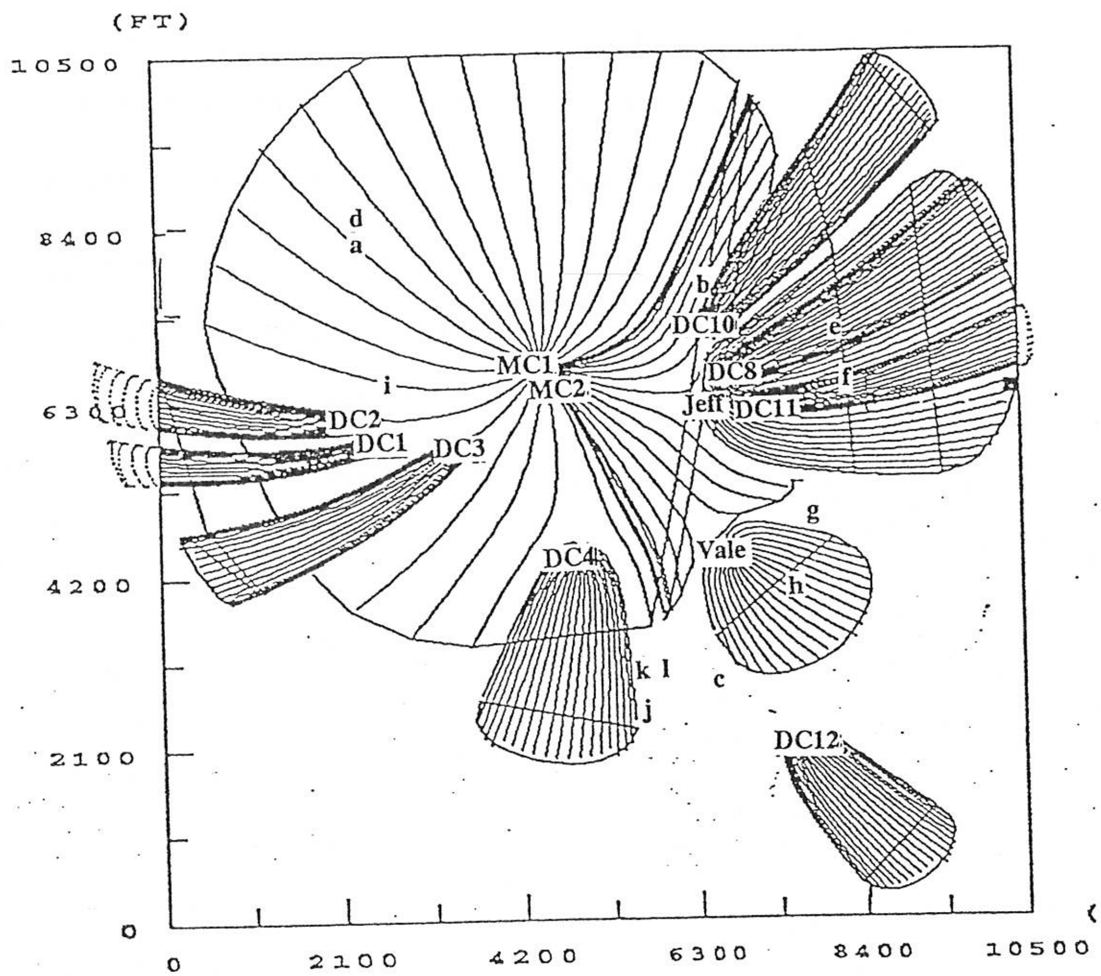


Figure 23. Ten year capture zone models with contaminated sites identified within the Daly City Tributary Area

there were areas that reported discontinuous clay or leaky aquitard layers, which indicated that some areas do not have a shallow aquifer perched above it. This would indicated relatively permeable materials from the surface down to the deep aquifer. This can allow soil contamination from the surface area to percolated down to the deep aquifer fairly uninhibited. In other cases, the contamination may have to migrate through the soil, the shallow aquifer, and the clay or leaky aquitard layer before it can impact the deep aquifer.

CHAPTER FIVE

CONCLUSION

The purpose of this investigation was to evaluate the geology and hydrogeology, locate contaminated sites in the Daly City Groundwater Tributary Area, and provide modeling of the Daly City drinking water wells to determine the potential impact. Results of the study may then be used to further consider Wellhead Protection activities. These results were able to demonstrate that confirmed contamination in soil, shallow, and deep aquifer may eventually impact the Daly City municipal wells over time.

The first subproblem required review of geology, hydrogeology, and well data to determine the capture zones of the Daly City drinking water wells over a five and ten year period. The results indicated that well interference of many of the wells created unusual shapes and covered much area within the Daly City Groundwater Tributary Area.

The second subproblem required review and documentation of government agency files to obtain confirmed soil and groundwater contaminations in the Daly City area and further locate those that lay within the Daly City Groundwater Tributary Area. Twenty-one sites were identified in the City of Daly City. Twelve such contaminated sites were found to lay within the Daly City Groundwater Tributary Area and seven sites lay within the capture zones of the Daly City drinking water wells. These seven sites have the potential to impact the drinking water wells.

The third subproblem required the evaluation of the contaminated sites within the capture zones of the Daly City drinking water wells. Out of the seven contaminated sites within the five or ten year capture zones, one had confirmed deep aquifer impact, three had confirmed shallow aquifer impact, one had soil only impact and two had unknown impact. All of the twelve sites have the potential to impact the drinking water wells, but only one had confirmed deep aquifer contamination, and thus the greatest potential to impact the drinking water wells.

The hypothesis and subhypotheses were all proven to be correct. Chemical contaminated sites lie within the capture zone and may impact the groundwater resources within five or ten years was proven to be correct. The geology and hydrogeology of the study area is of relatively permeable sands and silty sands and susceptible to contaminant transport down to the deep aquifer. There are contaminated sites that lie within the Daly City Groundwater Tributary Area and within the pumping well capture zones close to potentially impact the drinking water wells. Computer modeling determined the capture zones for each municipal wells and confirmed that contaminants from the previously identified contaminated sites may impact these wells over time.

A combination of all the wells with the various averaged saturated thicknesses based upon well clusters are with various transmissivities and time intervals were modelled (Figures 16, 17, 18, and 19). Figure 16 and 18 assumes a transmissivity of 2150 ft^2/d and Figure 17 and 19, assumes a transmissivity of 3200 ft^2\d. The four well clusters with their relative saturated thicknesses are represented.

Three contaminated sites lie within the capture zones of and contaminants may be drawn into the wells over a five or ten year period. Three sites lie within the capture zones of DC8, DC11, Jeff and Vale and have the potential to reach the wells in a five to ten year time period, if and when the contamination reaches the deep aquifer. Four sites lie within the capture zones of MC1 and MC2, indicating that at current pumping rates, the contaminants from these four sites, if and when the contamination reached the deep aquifer, has the potential for reaching these irrigation wells within five to ten years. Note that the source of contamination north of and closest to DC1, DC2, & DC3, the ARCO/Southgate site (**i**) has been drawn into the capture zone for MC1 rather than DC1 or DC2. These results may need to be adjusted to account for the well pumps not operating six months during the rainy season. Note also that any groundwater contamination at Chevron/Junipero Serra (**b**) will also be drawn into MC2 instead of DC10. Because this location is so close to the border of capture zones for both wells, a more detailed study is needed to verify this. A close look at other contaminated sites that lie very close to the edges of captures zones indicate that a more detailed study of the area for more accurate representation.

It appears that there is relatively little difference in the results with a change in 1100 ft^2\d transmissivity values as shown in Figures 16 and 17, and 18 and 19. Generally, the higher transmissivity, the faster contaminants can move through the groundwater medium.

Caution must be taken in assuming the location of a contaminated site lying within the capture zone of a the pumping well as modelled is representative of actual conditions. Only sites where deep (**D**) aquifer contamination has been confirmed in monitoring wells will actual municipal wells have the greatest potential for impact over the designated times. The only site where this condition applies in the ARCO/Southgate site (**i**).

The sites that have confirmed shallow (**S**) groundwater contaminant impact must add additional time needed for the contamination to be drawn down through the clay aquitard into the deep aquifer. Because of the demonstrated propagation and downward influence of deep aquifer pumping, unabated contaminant movement over time may eventually reach the deep aquifer. At that point, the contaminant may move as demonstrated in the models. There are nine sites in the study area that this condition applies.

Similarly, with confirmed soil contamination only (s), the contaminant must move through the soil to impact the shallow aquifer, and through the aquitard to reach the deep aquifer. Additional time for this travel of contaminants must be included prior to the model representation. There are three sites that this condition applies. To estimate these conditions, concentration of the contaminant, soil type, porosity, and gradient must be taken into account.

As can already be inferred, the concentration and amount of contaminants at each site is a major factor in whether the contaminant will actually move into the deep aquifer. The model does not take this into account, nor does it take into account any adsorption or absorption effects or movement of contaminants through the soil media nor remedial activities. Thus, the results shown in the models are very conservative estimates of groundwater flow due to the pumping wells and are very conservative estimates of contaminant movement in the aquifers. Additional work is needed to more accurately represent site conditions and groundwater movement. A more complex three dimensional model may be better equipped to take these factors into account.

In conclusion, these results indicate that the potential for municipal well contamination may exist. This will likely depend upon the amount of contaminants released, the rate of movement through soil and water, and the proximity to the pumping wells. Perhaps this possibility will initiate priority clean-up and remediation enforcement or funding, or changes in zoning of contaminant storage facilities. This study does indicate that further studies are needed to better understand these potential impacts of contaminants upon municipal groundwater supplies in the Daly City area. Future protection of these precious groundwater resources and a regional groundwater management program may be needed to preserve these resources for generations to come.

APPENDIX A

Definition of Terms

aquifer - a formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield sufficient, economical quantities of water to wells and springs. Rock or sediment in a formation, group of formations, or part of formations that is saturated and sufficiently permeable to transmit economic quantities of water to wells and springs.

bedrock - a general term for the rock, usually solid, that underlies soil or other unconsolidated material.

capture zone - the area surrounding a pumping well that encompasses all areas or features that supply groundwater recharge to the well.

confined aquifer - an aquifer bounded above and below by confining units of distinctly lower permeability than the aquifer media. An aquifer in which groundwater is under pressure significantly greater than atmospheric and its upper limit is the bottom of a bed of distinctly lower hydraulic conductivity than that of the aquifer itself.

groundwater - part of the subsurface water in the saturated zone. The water contained in interconnected pores located below the water table in an unconfined aquifer or located in a confined aquifer.

groundwater basin - general term used to define a groundwater flow system that has defined boundaries and may include more than one aquifer underlain by permeable materials that are capable of storing or furnishing a significant water supply. The basin includes both the surface area and the permeable materials beneath it. A rather vague designation pertaining to a groundwater reservoir that is more or less separate from neighboring groundwater reservoirs. A groundwater basin could be separated from adjacent basins by geologic boundaries or by hydrologic boundaries.

groundwater model - a simplified conceptual or mathematical image of a groundwater system, describing the feature essential to the purpose for which the model was developed and including various assumptions pertinent to the system. Mathematical groundwater models can include numerical and analytical models.

hydraulic conductivity - proportionality constant relating hydraulic gradient to specific discharge, which for an isotropic medium and homogeneous fluid, equals the volume of water that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. The rate of flow of water in gallons per day through a cross section of one square foot under a unit hydraulic gradient, at the prevailing temperature(gpd/ft^2) In the Standard International System, the units are $m^3/day/m^2$ or m/day. A coefficient or proportionality describing the rate at which water can move through a permeable medium. The density and kinematic viscosity of the water must be considered in the determining hydraulic conductivity.

hydraulic gradient - slope of a water table or potentiometric surface. More specifically, change in static hear per unit of distance in a given direction, generally the direction of the maximum rate of decrease in head. The rate of change in total head per unit of distance of flow in a given direction. The change in total head with a change in distance in a given direction. The direction is that which yields a maximum rate of decrease in head. The difference in hydraulic head(h_1-h_2),divided by the distance (L) along the flow path

$$i = (h_1 - h_2)/L$$

impermeability - characteristic of geologic materials that limit their ability to transmit significant quantities of water under the pressure differences normally found in the subsurface environment.

leaky aquifer - a artesian or water table aquifer that loses or gains water through adjacent semipermeable confining units.

leaking underground fuel tanks (LUFT) - as regulated by the county agencies in an agreement with the State Resource Control Board. Typical contaminants resulting form these include total petroleum hydrocarbons as gasoline or diesel, waste oil, chlorinated hydrocarbons, and metals.

permeability - ability of a porous medium to transmit fluids under a hydraulic gradient. The property or capacity of a porous rock, sediment, or soil for transmitting a fluid; it is a measure of the relative ease of fluid flow under unequal pressure.

point source - any discernible, confined, or discrete conveyance from which pollutants are or may be discharged, including (but not limited to) pipes, ditches, channels, tunnels, conduits, wells, container, rolling stock, concentrated animal feeding operations, or vessels.

potential beneficial uses - almost all groundwater has potential beneficial uses for agricultural, industrial or drinking waters.

potentiometric surface - a surface that represents the level to which water will rise in tightly cased wells. If the head varies significantly with depth in the aquifer, then there may be more than one potentiometric surface. The water table is a particular potentiometric surface for an unconfined aquifer.

radius of influence - the radial distance from the center of a well bore to the point where there is no lowering of the water table or potentiometric surface(the edge of its cone of depression).

recharge area - area in which water reaches the zone of saturation by surface infiltration. An area in which there are downward components of hydraulic head in the aquifer. Infiltration moves downward into the deeper parts of an aquifer in a recharge area.

saturated zone - portion of the subsurface environment in which all voids are ideally filled with water under pressure greater than atmospheric. The zone in which the voids in the rock or soil are filled with water at a pressure greater than atmospheric. The water table is the top of the saturated zone in an unconfined aquifer. Also called the phreatic zone.

semiconfined aquifer - an aquifer that had a "leaky' confining unit and displays characteristics of both confined and unconfined aquifer

spring - discrete place where groundwater flows naturally from rock or soil onto the land surface or into a surface-water body.

superfund sites - as designated by the US Environmental Protection Agency by placement on the National Priority List for clean-up oversight provided by Superfund monies. The clean-up for these sites are overseen by State Department of Health. The costs are to be reimbursed by the responsible parties.

time of travel (TOT) - Rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. it is equal to an integration of the hydraulic conductivities across the saturated part of the aquifer perpendicular to the flow path. The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Transmissivity values are given in gallons per minute though a vertical section of an aquifer 1 foot wide and extending the full saturated height of an aquifer under a hydraulic gradient of one in the English Engineering system; in the Standard International System, transmissivity is given in cubic meters per day though a vertical section of an aquifer 1 meter wide and extending the full saturated height of a aquifer under a hydraulic gradient of one. it is a function of the properties of the liquid, the porous media, and the thickness of the porous media

transmissivity - the distance of groundwater movement through the media (unit width of aquifer) under a hydraulic gradient.

unsaturated zone - The zone between the land surface and the deepest or regional water table. It includes the root zone, intermediate zone, and the capillary fringe. The pore spaces contain water, as well as air and other gases at less than atmospheric pressure. Saturated pressure within these may be greater than atmospheric. Same as vadose zone.

water table - upper surface of a zone of saturation, where that surface is not formed by a confining unit; water pressure in the porous medium is equal to atmospheric pressure. The surface between the vadose zone and the groundwater; that surface of a body of unconfined groundwater at which the pressure is equal to that of the atmosphere. The surface in an unconfined aquifer of confining bed at which the pore water pressure is atmospheric. it can be measured by installing shallow wells extending a few feet into the zone of saturation and then measuring the water level in those wells.

wellhead protection area (WHPA)- the surface and subsurface are surrounding a water well or well field, supplying a public water system, through which contaminants are reasonably likely to more toward and reach such water well or well field.

APPENDIX B

Appendix B contains the raw data for Chapter Four collected from sources other than those listed in the Reference list.

They are as follows:

1. City of Daly City well data presented by City of Daly City Department of Water and Wastewater Resources.

2. Computer models results from Table 5 parameters

City of Daly City
Water System Information

PARAMETER	Descriptor	Well Numbers									
		1	2	3	4	8	10	11	12	Vale	Jeff
Date of Test	date	1/93	1/93-2/93	1/93	1/93	3/93	1/93	1/93	1/93	1/93-3/93	1/93-3/93
Static Water Level	Feet from top	251	249	240	289	381	357	359	N/A	316	350
Pumping Water Level	Feet from top	255	256	322	347	423	379	365	N/A	386	455
Discharge Elevation	MSL	112	114	110	133	234	221	229	180	175	208
Bowl Setting	Feet from top	297	309	328	410	425	435	400	532	569	512
Static elevation	MSL	-139	-135	-130	-156	-147	-136	-130	N/A	-141	-142
Pumping elevation	MSL	-143	-142	-212	-214	-189	-153	-136	N/A	-211	-247
Drawdown	feet	-4	-7	-82	-58	-42	-22	-6	N/A	-70	-105
Well Radius(inches)	Dia/2	7	7	7	7	6	7	7	7	8	8
1991 Pumping Rate	gpm(avg)	148	248	246	489	320	372	211	297	741	New-3/92
1992 Pumping Rate	gpm(avg)	128	197	232	453	312	351	177	254	722	543
1993 Pumping Rate	gpm(avg)	110	233	210	445	297	335	154	233	704	565
Depth of Well	feet	380	389	375	480	479	516	500	550	700	700
Bottom Elevation	MSL	-268	-275	-265	-347	-245	-295	-271	-370	-525	-492
Static Column	feet	129	140	135	191	98	159	141	370	384	350
Pumping Column	feet	125	133	53	133	56	137	135	370	314	245

Vale Well Production Began September 15, 1991
Jeff Well Production Began March 19, 1992
Well #2 Impellers Adjusted in January, 1993

Updated: 17-Mar-93

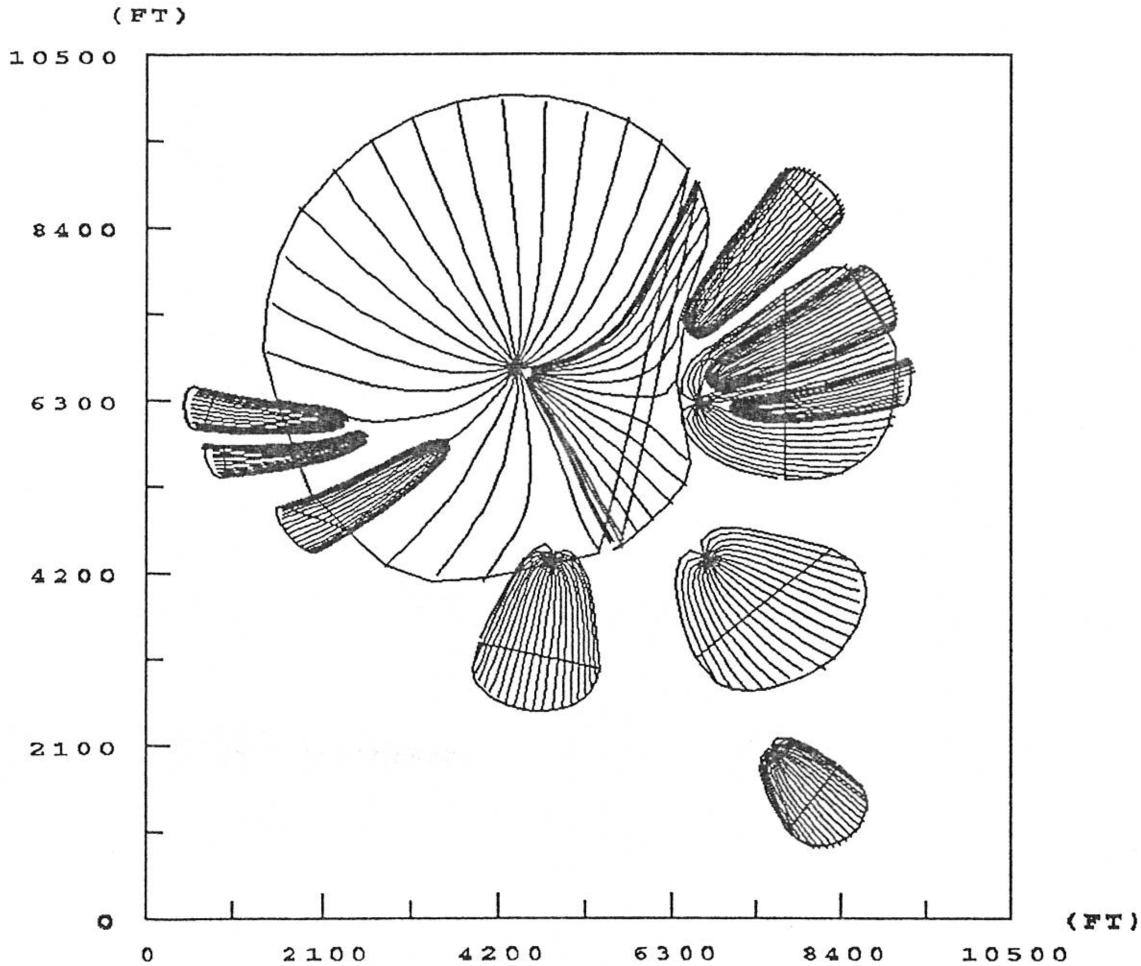


Figure 1 - Five year Capture Zone with transmissivity of 2150 ft^2/d and saturated thickness of 195 ft

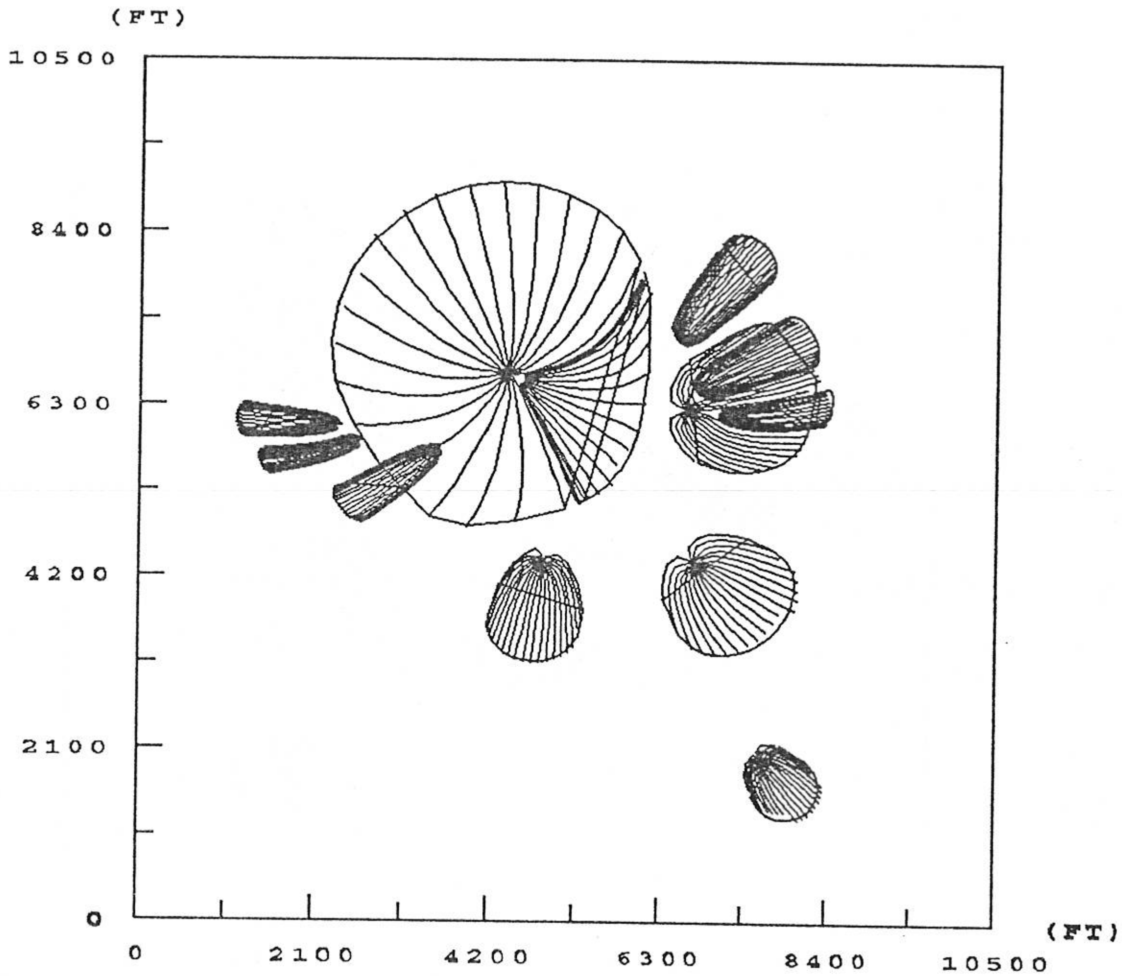


Figure 2 - Five year Capture Zone with transmissivity of 2150 ft^2/d and saturated thickness of 366 ft

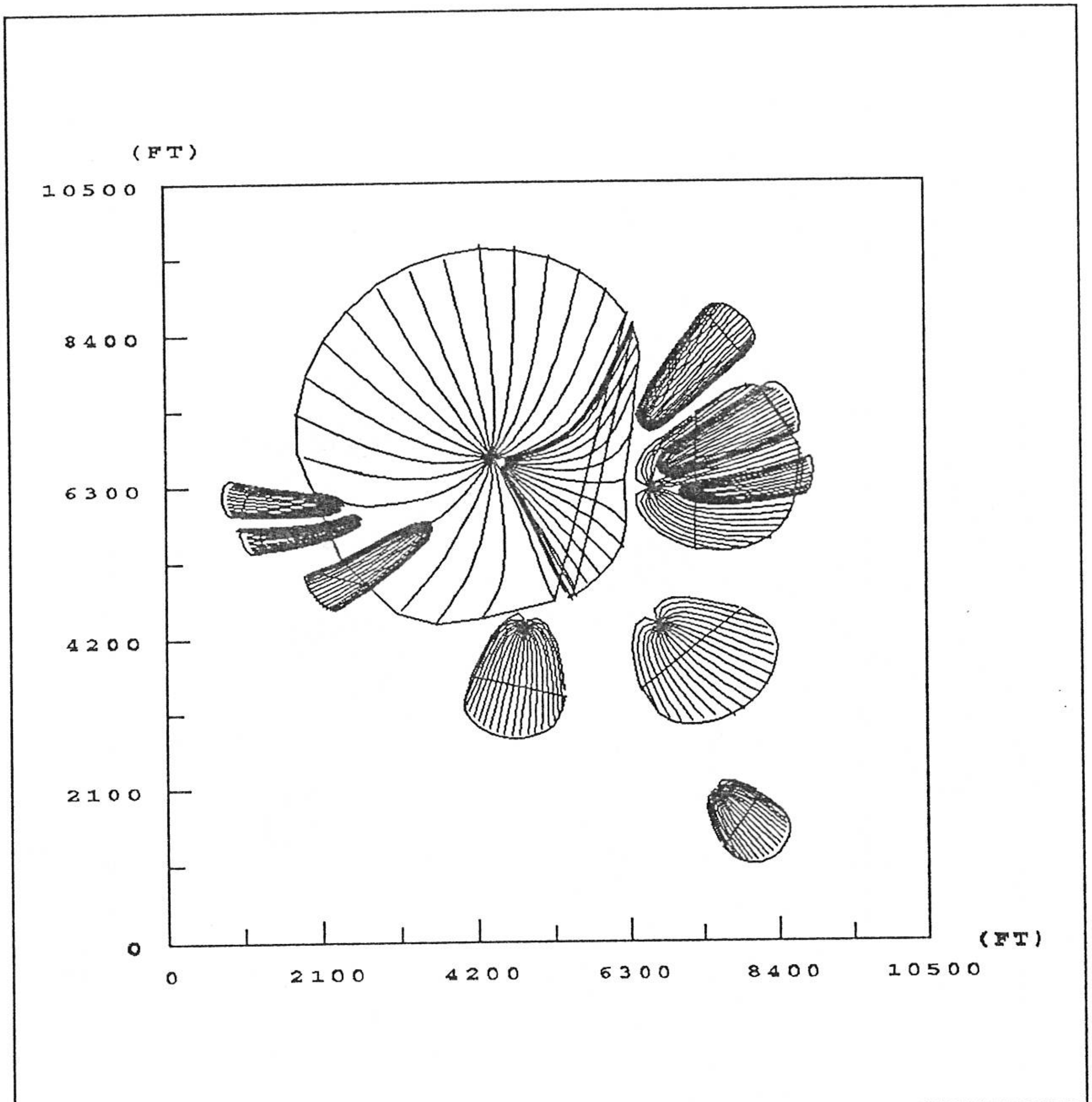


Figure 3 - Five year Capture Zone with transmissivity of 2150 ft^2/d and saturated thickness of 248 ft

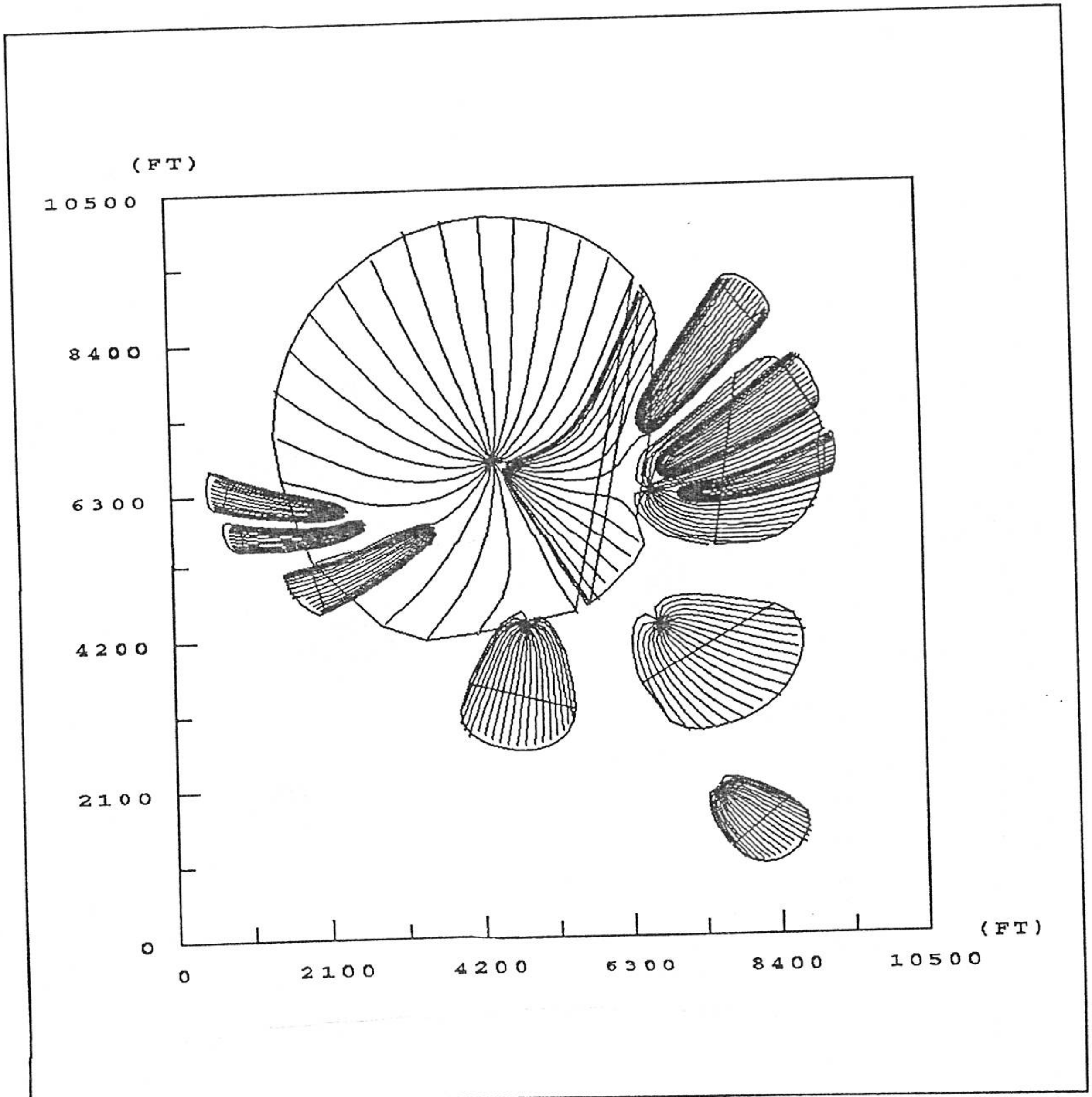


Figure 5 - Five year Capture Zone with transmissivity of 3200 ft^2/d and saturated thickness of 195 ft

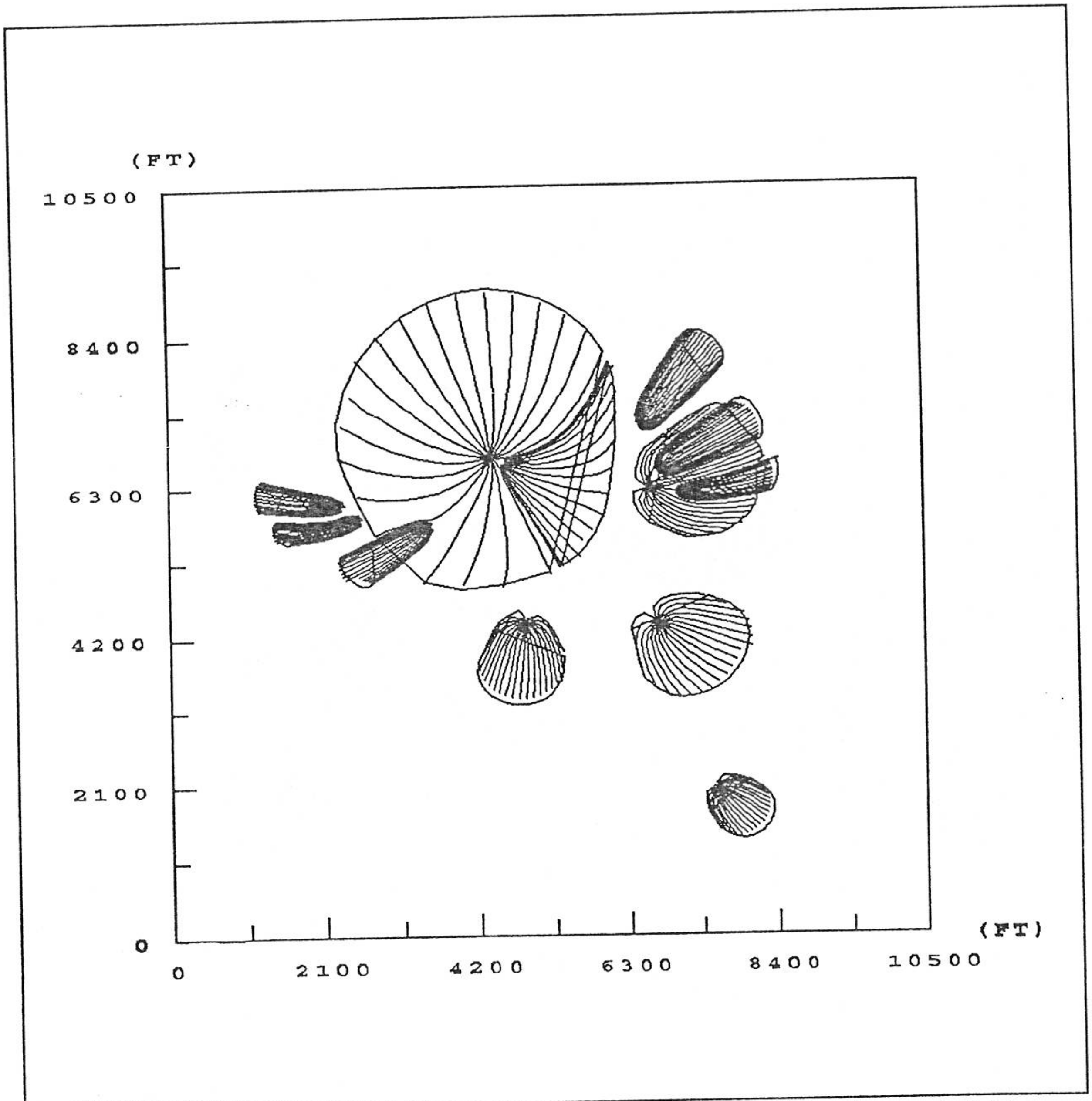


Figure 6 - Five year Capture Zone with transmissivity of 3200 ft^2/d and saturated thickness of 366 ft

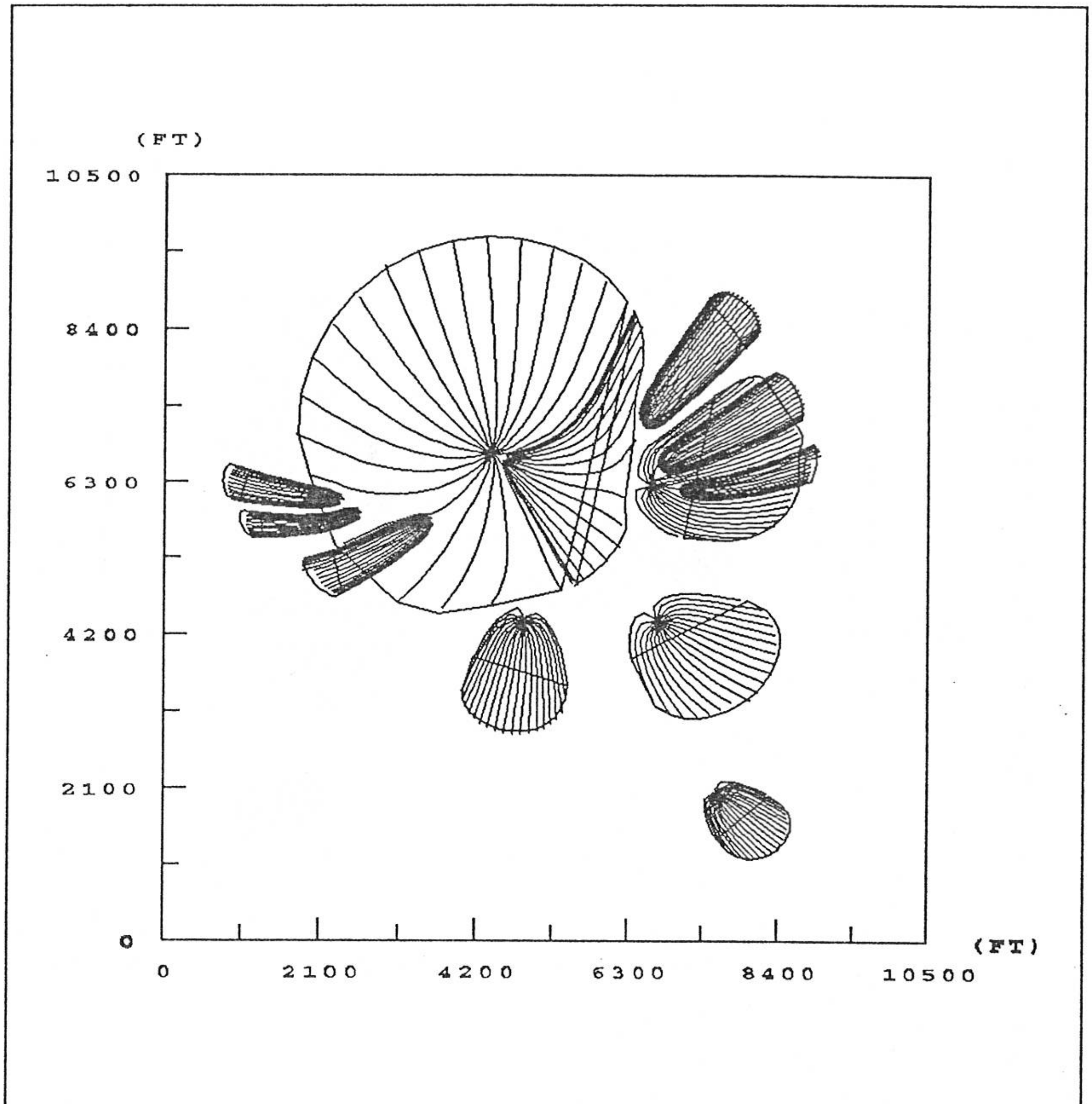


Figure 7 - Five year Capture Zone with transmissivity of 3200 ft^2/d and saturated thickness of 248 ft

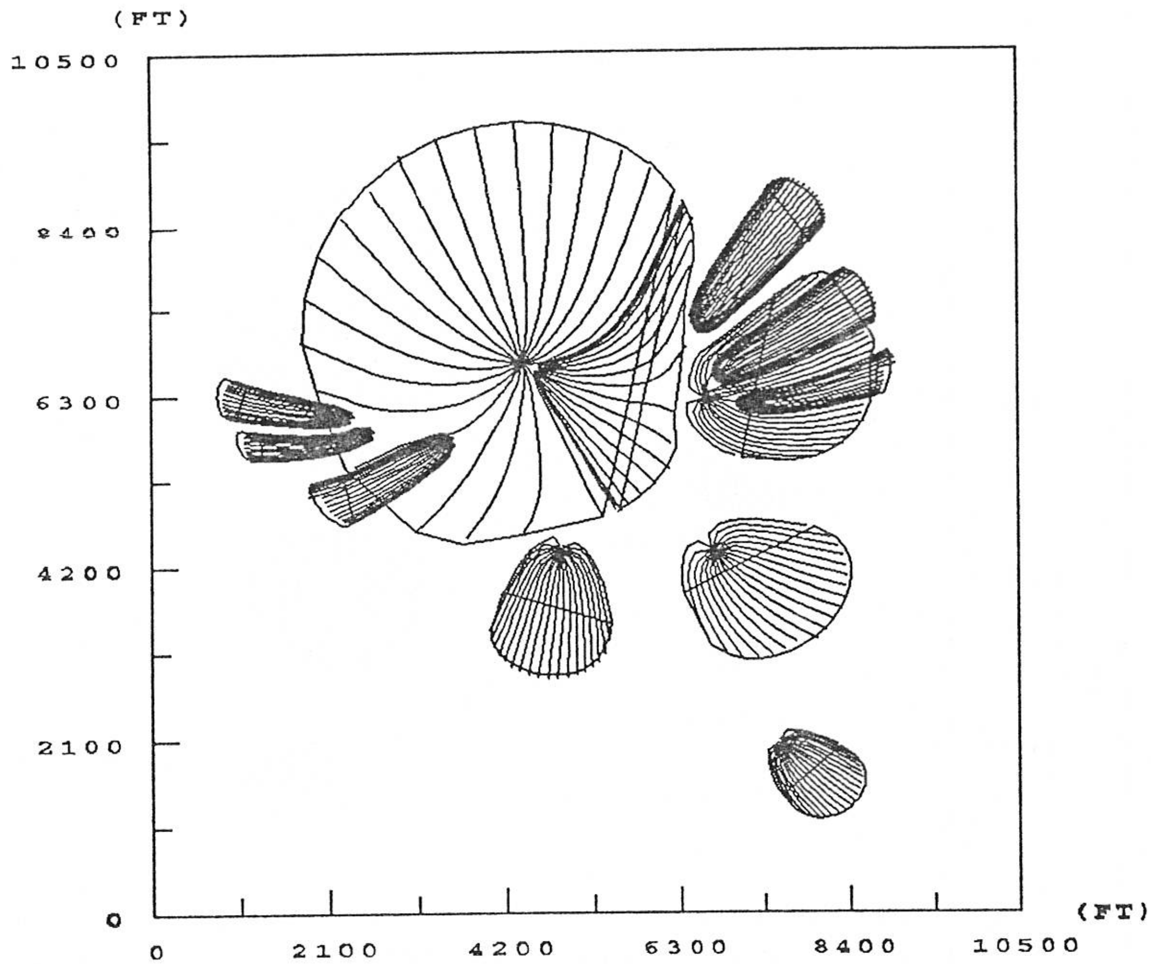


Figure 8 - Five year Capture Zone with transmissivity of 3200 ft^2/d and saturated thickness of 456 ft

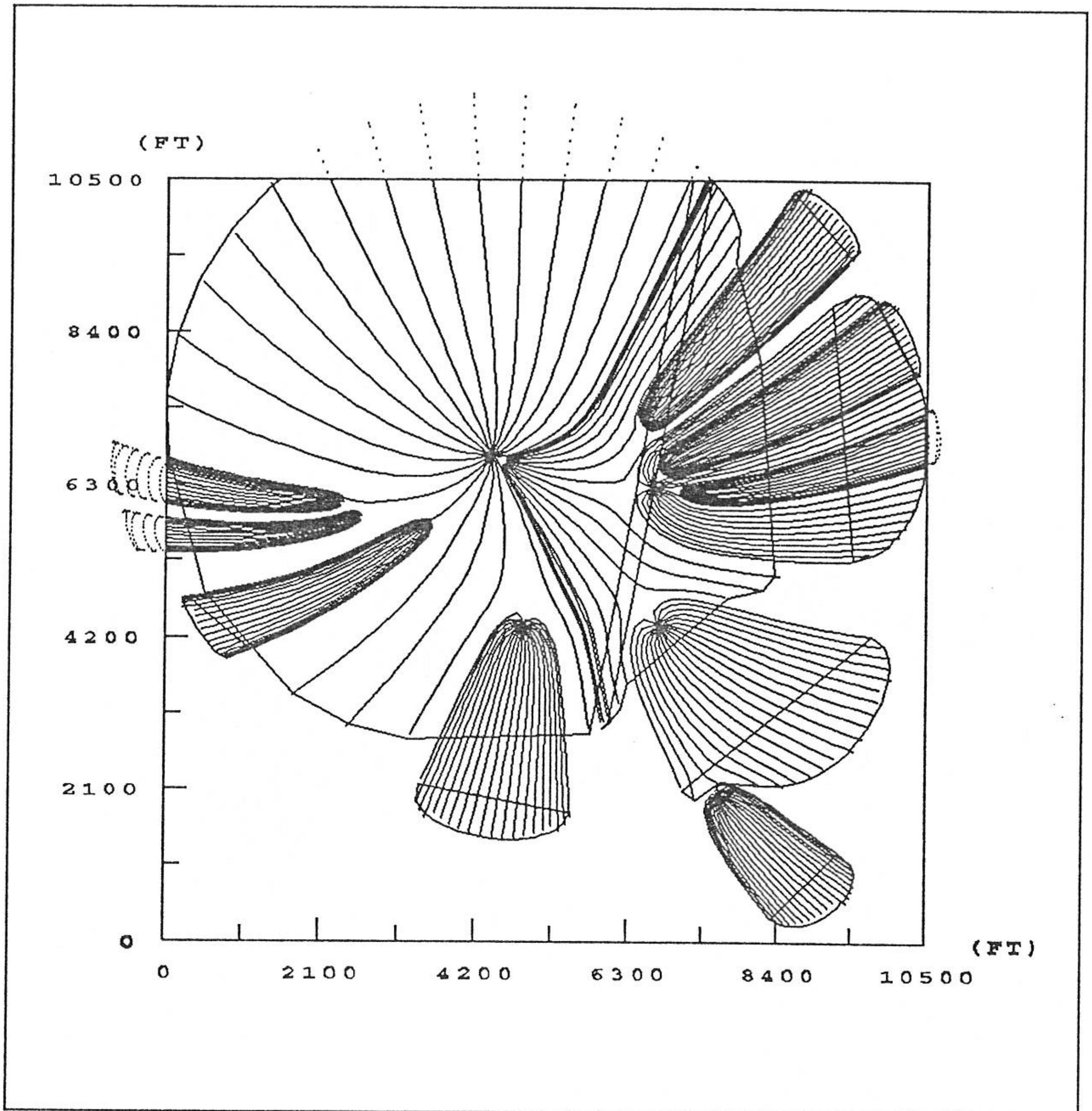


Figure 9 - Ten year Capture Zone for transmissivity of 2150 ft^2/d and saturated thickness of 195 ft

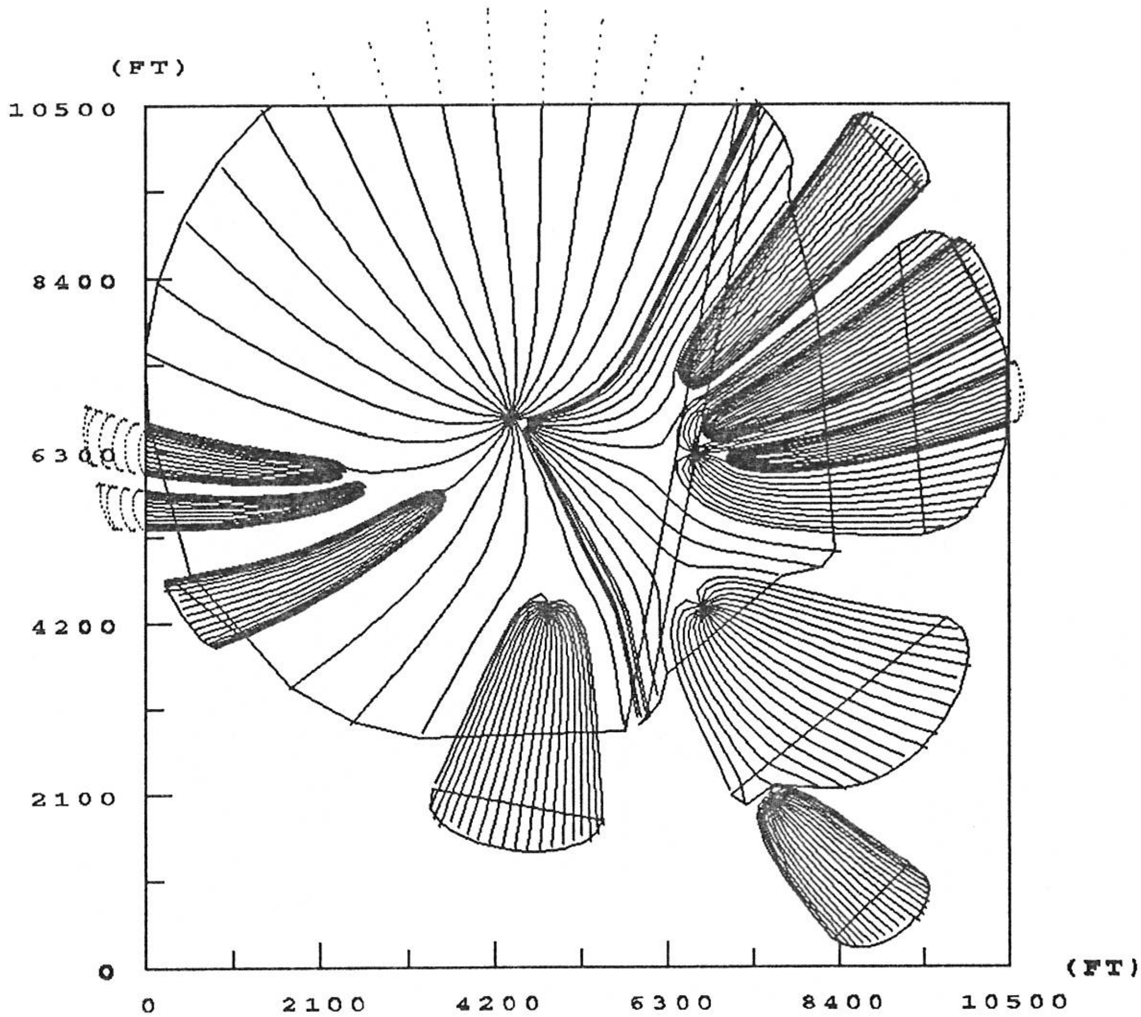


Figure 10 - Ten year Capture Zone with transmissvity of 2150 ft^2/d and saturated thickness of 366 ft

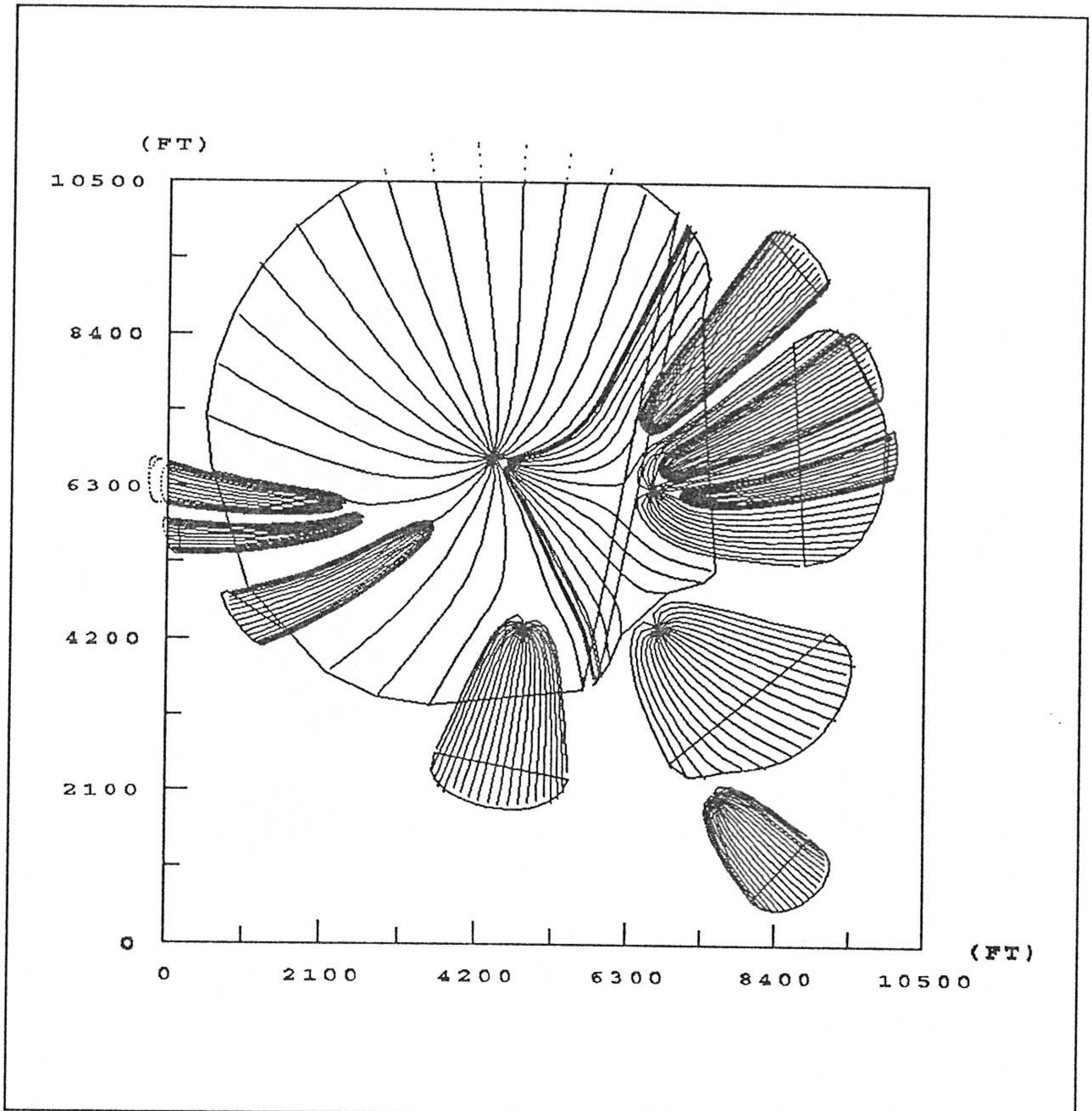


Figure 11 - Ten year Capture Zone with transmissivity of 2150 ft^2/d and saturated thickness of 248 ft

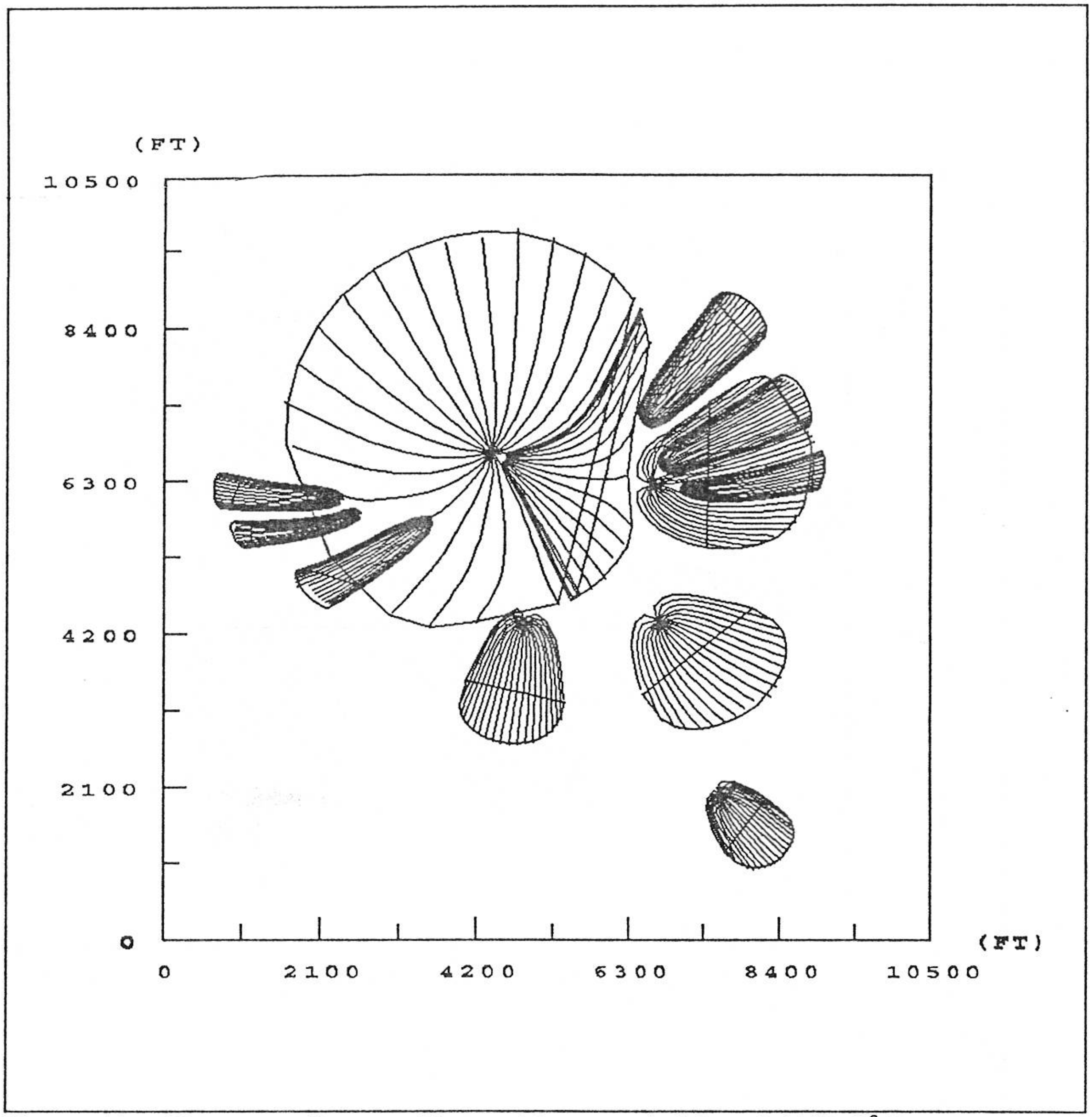


Figure 12 - Ten year Capture Zone with transmissivity of 2150 ft^2/d and saturated thickness of 456 ft

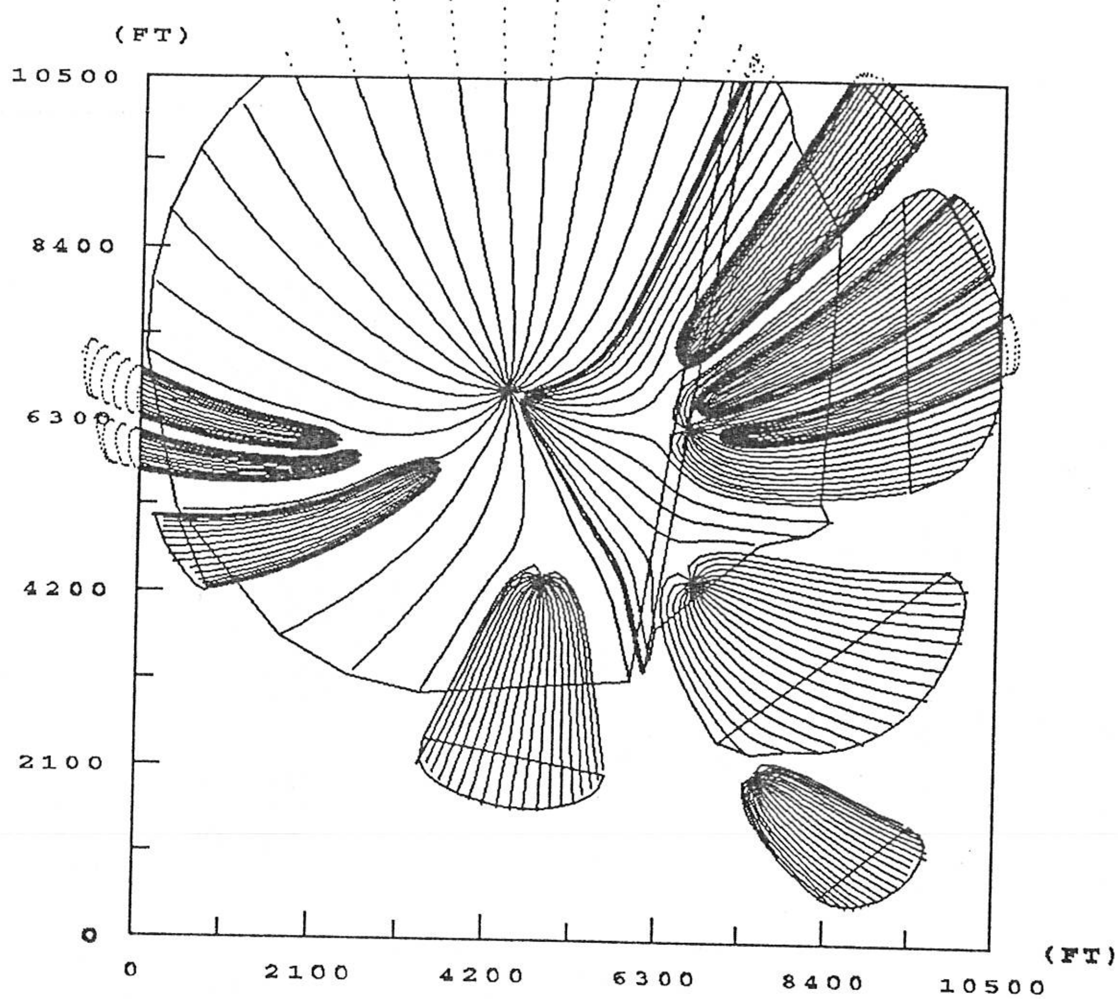


Figure 13 - Ten year Capture Zone with transmissivity of 3200 ft^2/d and saturated thickness of 195 ft

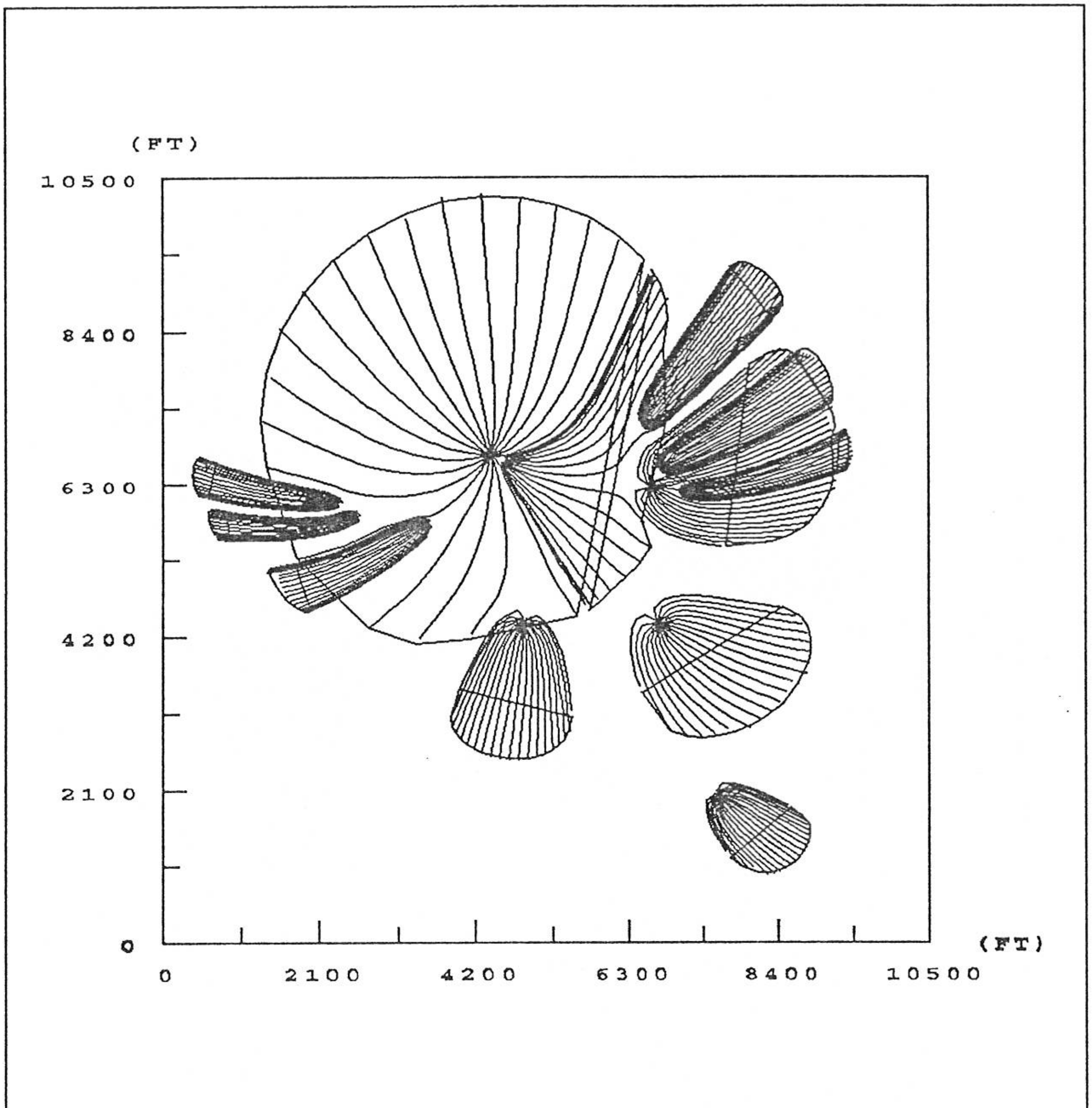


Figure 14 - Ten year Capture Zone with transmissivity of 3200 ft^2/d and saturated thickness of 366 ft

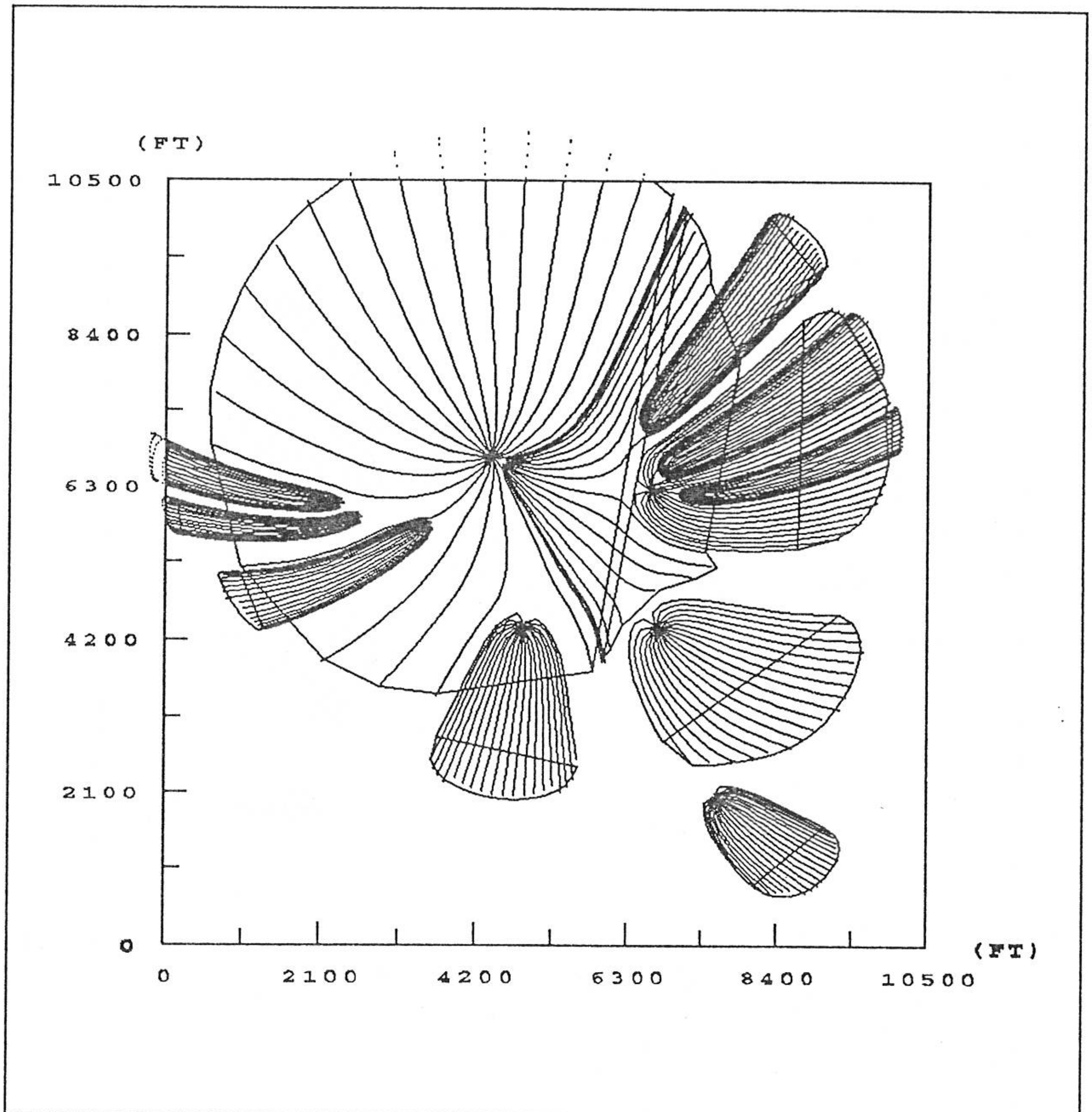


Figure 15 - Ten year Capture Zone with transmissivity of 3200 ft^2/d and saturated thickness of 248 ft

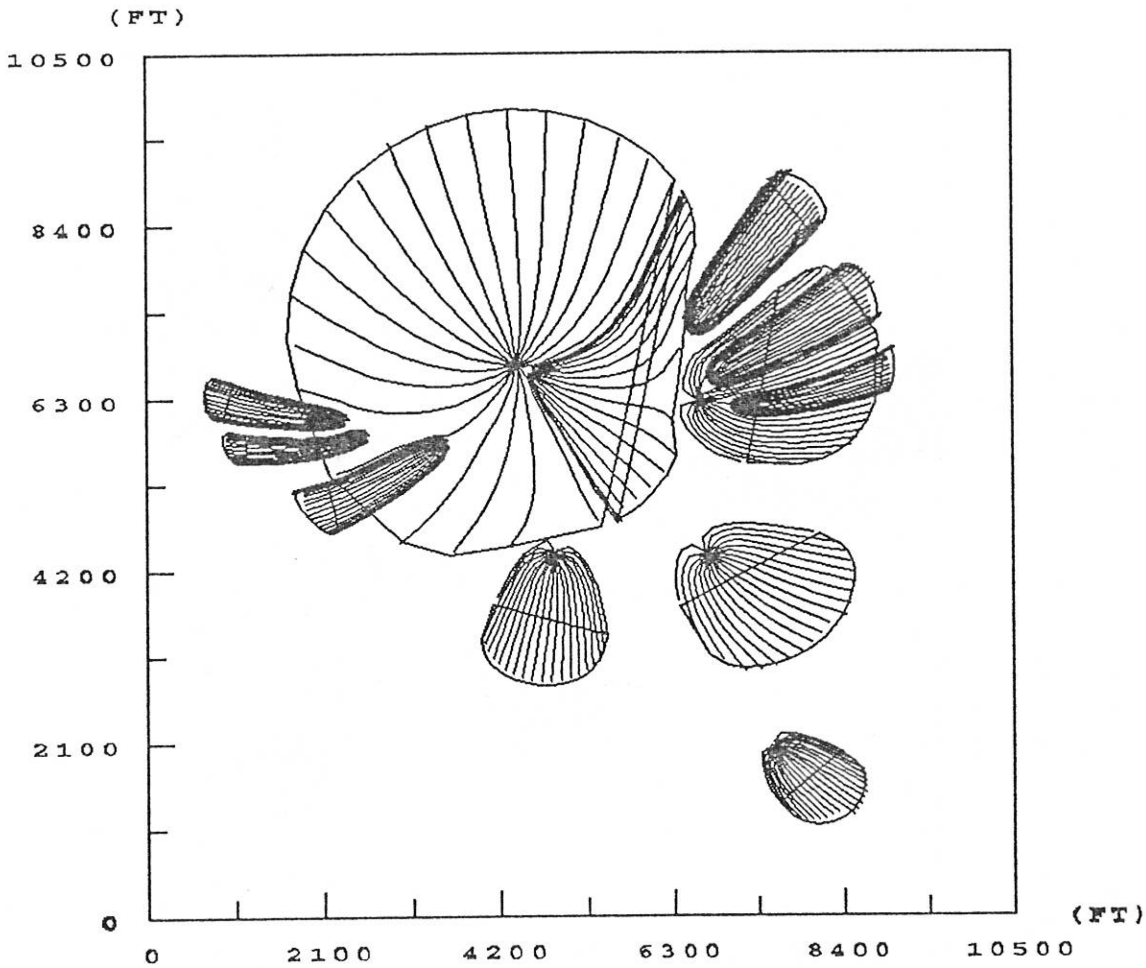


Figure 16 - Ten year Capture Zone with transmissivity of 3200 ft^2/d and saturated thickness of 456 ft

LIST OF REFERENCES

Applied Consultants. 1991. Daly City ground-water investigation and model. City of Daly City, Department of Water and Wastewater Resources.

Bader, J.S. 1971. *Groundwater data as of 1967, San Francisco Bay subregion, California.* U.S. Geological Survey, Water Resources Division Report, Menlo Park, California.

Blandford, T.N. and Huyakorn, P.S. 1991. *WHPA: A modular semi-analytical model for the delineation of wellhead protection areas, Version 2.0.* Document for U.S. Environmental Protection Agency.

Bonilla, M.G. 1971. *Preliminary geologic map of the San Francisco south quadrangle and part of the Hunter;s Point quadrangle, California.* U.S. Geologic Survey Miscellaneous Field Studies Map MF-311, scale 1:24000.

Camp, Dresser, & McKee Inc. 1982. Wellfield travel time model for selected wellfields in Dade, Broward, and Palm Beach Counties, Florida. Dade, Broward, and Palm Beach Counties, Florida.

Carroll/Resources Engineering & Management. 1987. Untitled report of alternative sources of supply for irrigation water at the Golden Gate National Cemetery. Veterans Administration, Palo Alto, California.

CH_2M-Hill. 1989. Technical memorandum for Oceanside Water Pollution Control Plant groundwater development study: Emeryville, California. San Francisco Clean Water Program, San Francisco, California.

Cleary, R.N. 1991. *Groundwater pollution and hydrology.* Princeton Course Syllabus, Princeton, New Jersey.

Fetter, C.W. 1988. *Applied hydrogeology.* Second edition. Oshkosh: Macmillan Publishing Company.

Hamlin, S.N. 1987. Hydraulic/chemical changes during ground-water recharge by injection. *Groundwater.* 25:267-274.

Kirker, Chapman and Associates, and Todd, D.F. 1972. Daly City ground-water investigation: Kirker, Chapman, and Associates. Daly City, California.

McCann, L.J. 1989. "The hydrogeology and an annual water budget for Lake Merced, San Francisco, California". Master of Science thesis, University of California, Davis.

Phillips, S.P.; Hamlin, S.N.; and Yates, E.B. 1993. Geohydrology, water quality, and estimation of groundwater recharge in San Francisco, California. Water Resources Investigation Report (draft). U.S. Geological Survey. Sacramento.

PIMA Association of Governments. 1992. Application of Historic Well Closure Information for Protection of Existing Wells, Final Technical Report. PIMA County, Arizona.
California.

Rantz, S.E. 1972. *A summary view of water supply and demand in the San Francisco Bay region, California.* U.S. Geological Survey, Water Resources Division, Menlo Park, California.

Rantz, S.E. 1971. *Mean annual precipitation and precipitation depth-duration-frequency data for the San Francisco Bay region, California.* U.S. Geologic Survey, Water Resources Division, Menlo Park, California.

Reynolds, S.D. 1991. Wellhead protection modeling. Syllabus for University of California Extension, Davis, California.

San Francisco Water Department. 1990. Groundwater management report. Public Utilities Commission, San Francisco, California.

Schlocker, J. 1974. *Geology of the San Francisco north quadrangle, California.* U.S. Geological Survey Professional Paper 782.

University of California at Berkeley and San Francisco Bay Regional Water Quality Control Board. 1987. *San Francisco Bay regional groundwater resources study.* Volume 10.

U.S. Environmental Protection Agency. 1987. *Guidelines for delineation of wellhead protection areas.* Office of Ground Water Protection, Washington, DC.

U.S. Environmental Protection Agency. 1987. *Guidelines for groundwater delineation of wellhead protection areas.* Office of Groundwater Protection, publication no. EPA 440/6-87-010. Washington D.C.

U.S. Environmental Protection Agency. 1988. *Guidelines for groundwater classification under the EPA groundwater protection strategy.* Office of Groundwater Protection, Washington D.C.

U.S. Environmental Protection Agency. 1992. *Survey of local groundwater/wellhead protection efforts in California.* Ground Water Protection Section, San Francisco, California.

Wateresource Consulting Engineers, Inc. 1992. Interim status report for Fernley wellhead protection program. Fernley Town Utilities, Fernley, Nevada.

Wood, P.R. 1975. *Sources of emergency drinking water supplies in San Mateo County, California.* US Geological Survey, Water Resources Division, Menlo Park, California.

Woodward-Clyde Consultant, 1984. Report in testing of Alvord Lake irrigation well, Golden Gate Park, San Francisco, California. San Francisco, Department of Public Works, San Francisco, California.

Yates, E.B., Hamlin, S.N., and McCann, L.S. 1990. *Geohydrology, water quality, and water budget of Golden Gate Park and the Lake Merced area in the western part of San Francisco, California.* U.S. Geological Survey, Water-Resources Investigation Report 90-4080. Menlo Park, California.

Yates, E.B. 1993. Untitled work in progress. Jones & Stokes Associates, Incorporated. Sacramento, California.