4-17-1995

Evaluating the effectiveness of a delineated wellhead protection area : the north west wellfield in Dade County, Florida

Jose H. Olivo Jr.
Florida International University

DOI: 10.25148/etd.FI15101200

FLORIDA INTERNATIONAL UNIVERSITY

Miami, Florida

EVALUATING THE EFFECTIVENESS OF A DELINEATED WELLHEAD PROTECTION AREA: THE NORTH WEST WELLFIELD IN DADE COUNTY, FLORIDA

A thesis submitted in partial satisfaction

of the requirement for the degree of

MASTER OF SCIENCE

IN

CIVIL ENGINEERING

by

JOSE H. OLIVO, JR.

1995

To: Dean Gordon R. Hopkins
College of Engineering and Design

This Thesis, written by Jose H. Olivo, Jr., and entitled "Evaluating the Effectiveness of a Delineated Wellhead Protection Area: The North West Wellfield in Dade County, Florida," having been approved in respect to style and intellectual content, is referred to you for judgement.

We have read this thesis and recommended that it be approved.

Dr. Shonali Laha

Dr. Vassilios A. Tsihrintzis, Co-Major Professor

Dr. Hector R. Fuentes, Major Professor

Date of Defense: April 17, 1995

The thesis of Jose H. Olivo, Jr. is approved.

Dean Gordon R. Hopkins
College of Engineering and Design

Dean Richard L. Campbell
Division of Graduate Studies

Florida International University, 1995

Dedicated to my parents

ACKNOWLEDGEMENTS

First of all, I would like to thank my parents for their contribution throughout my work. Their love, trust, and support have helped me achieve my goals.

This thesis study was possible thanks to an Environmental Protection Agency Grant awarded to me by Professor Hector R. Fuentes, Florida International University, EPA/GEM Project Director. For that respect and acknowledgement, I would like to give special thanks to my professor and advisor Hector R. Fuentes for his constant support, guidance and encouragement, which made it possible to complete this thesis

I would also like to thank my Co-advisor Professor Vassilios A. Tsihrintzis for having served on my thesis committee, and for having the timely effort in providing critical advice, valuable ideas, and editing.

I would also like to thank Professor Shonali Laha for her assistance and for serving as my committee advisor.

I would like to very specially recognize, Mr. Sashi Nair, Hydrogeologist, and Ms. Nancy Seith, Hydrogeologist of the Department of Environmental Resources and Management, for providing most needed technical assistance, pertinent data and timely suggestions throughout the completion of this study.

Last but not least, I would like to give thanks to my peers Rao Gadipudi, Rizwan Hamid, Rahul Shrotriya, and Leonardo Rodriguez for their support.

ABSTRACT OF THE THESIS

EVALUATING THE EFFECTIVENESS OF A DELINEATED WELLHEAD PROTECTION AREA: THE NORTH WEST WELLFIELD IN DADE COUNTY, FLORIDA

by

Jose H. Olivo Jr.

Florida International University, 1995

Professor Hector R. Fuentes, Major Professor

Professor V.A. Tsihrintzis, Co-Major Professor

Methods for the evaluation of the effectiveness of the Wellhead Protection Program (WHPP) in the North West Wellfield, Dade County, Florida are presented. This is done through application of two computer programs developed by the Environmental Protection Agency: WHPA (Version 2.2), a Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas, and WHAEM, the Wellhead Analytical Element Model. In addition the Calculated Fixed Radius Method for capture zone delineation is also used. Wellhead delineation results from the afore mentioned three methods are obtained for both present and future water demands, based on population predictions done for the years 2010, 2015, and 2025. Conclusions are drawn regarding the impact of current land uses and zoning criteria; and factors and barriers that affect or hinder the effectiveness of current protection activities are pointed out.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

Groundwater contamination in the United States has been an ongoing problem where the presence of more than 200 chemical substances in groundwater, including organic and inorganic chemical substances, are indicative of the severity and extent of groundwater contamination (Barcelona et al., 1988). Groundwater contamination can be defined as the degradation of the natural groundwater quality as a result of man's activities. Volatile Organic Compounds (VOCs) are compounds commonly found in drinking water supplies, these are, for example: halogenated hydrocarbon solvents, aerosol propellants, and refrigerants. Groundwater contamination is typically associated with dense populated areas where groundwater is used as a drinking water supply. Therefore, the Environmental Protection Agency (EPA), through the Safe Drinking Water Act (SDWA) provisions, has made every State responsible for the protection of groundwater through the implementation of a Wellhead Protection Program (WHPP).

The protection of areas that contribute water to public wells is commonly known as a Wellhead Protection Area (WHPA). The zone of the aquifer, where water is drawn toward a pumping well or wellfield, is known as the zone of influence (ZOI) or cone of influence. The delineation of zones of influence form an essential part of a WHPA. These zones of influence must therefore be defined. Implementation of a WHPP is indeed necessary to protect the wellfield area. A WHPA can be managed and monitored by placing strict regulations on existing sources of contamination, and restricting the appearance of other developments, which may prove to be potentially hazardous to the

wellfield. WHPP must have land use restrictions in order to reduce the risk of contaminating public water supply wells.

Land use restrictions and environmental regulations are placed on zones of development that lie within the delineated area. Such enforcement rules are for instance, restrictions on the use of septic tanks, industrial waste generators, rockmining activities, and any others which may contaminate surface or subsurface water.

In a WHPP, the hydrologic, geologic and topographic characteristics of the area are essential to obtain a clear understanding on how solute moves around and near a wellfield. How groundwater moves near and around a wellfield depends on local or regional flow regimes, aquifer properties, and wellfield design, construction, and operation. Solute transport is governed by diffusion and the mechanical mixing caused by the water flow, known as advection. The effect of advection usually is more critical than diffusion. However, in the absence of water flow or when velocities are very small, solute is transported by molecular diffusion. Additional processes, such as degradation (e.g., chemical or biological) and adsorption to the soil, also affect fate and transport of solutes in porous media. Groundwater modeling is one of the management tools used in WHPPs. A groundwater model helps relate the aquifer system with rates and location of pumping and recharge. Selection of a groundwater model is critical in maximizing the objectives of a WHPP (Bear et al., 1992).

Various public agencies have made efforts in developing water supply protection programs, which involve both surface and groundwater. It seems that surface water is more vulnerable to pollution than groundwater sources, and if the case, then water protection programs must emphasize on protecting uncontaminated groundwater sources by developing wellhead protection areas. Also, groundwater sources can be used instead of a surface water source which is contaminated and requires treatment. This indicates that the cost of surface water treatment is not feasible in comparison with using and protecting a groundwater source (Caswell, 1993). Small communities seem to believe that the cost of such Wellhead Protection Programs may not seem feasible, because they attach expenses such as installing observation wells, conducting pumping tests, technical support and other hydrogeological investigations. The point is that a Wellhead Protection Program can be reasonably developed to assist small communities as well, without the high expense. For example, EPA offers a variety of case studies on WHPP already in practice in small communities. These programs are examples, which show how simple methods for delineating wellhead areas and the use of some hydrogeolgical expertise can prove beneficial and feasible for low community budgets. This is the case for some small areas in New England (Caswell, 1993).

Every local government has specific goals which define their WHPP. Input from qualified hydrologists can provide assistance to drinking water purveyors in obtaining specific goals in developing a WHPP. For example, some specific goals are: delineation of wellhead protection areas, identification and management of potential contaminant

sources and establishment of groundwater monitoring plans, and contingency plans for water supply protection (Beckwith, 1993). In essence all these goals describe the importance of running certain activities, such as identifying past, present and future land activities that may pose a potential threat to well contamination, testing and monitoring groundwater. This identification assists in preparing a remediation plan in the event of well contamination or in establishing different levels of emergency response depending on the extent of contamination. Note that it is equally important for private water wells to also adhere to some sort of WHPP.

Dade County, located in the southeastern portion of Florida, is faced with increasing demands for potable water, and the potential threat of groundwater contamination from the ever-increasing industrial and commercial growth as well. Therefore in an effort to protect groundwater resources, Dade County has developed a WHPP to protect the quality of its sole provider of potable water, the Biscayne Aquifer. The County's WHPP goes hand in hand with existing and proposed land use planning, zoning and environmental regulations. In Dade County, the water quality problem is associated with the presence of Synthetic Organic Chemicals (SOCs) in the drinking water supply. SOCs are man-made chemicals which contain carbon and are toxic at low concentrations. VOCs are the volatile subgroup of SOCs, which mean that the chemical substances can easily transfer from a liquid phase to a gas phase. Detection of organic chemicals in old wellfields of Dade County, led to the construction of the newest wellfield, the Northwest Wellfield, constructed in 1983. Thus, ensuring the high quality of water and making sure that the

Northwest Wellfield does not suffer the same fate of older wellfields, is the current objective.

1.1 Need for Proposed Study

The Northwest Wellfield is a resource of uncontaminated water supply. Presently, however, due to the extent of the wellfield's cone of influence, there is some possibility of contaminants encroaching the eastern periphery of the cone. This cone of influence extends east of the Turnpike and Snapper Creek Extension Canal. Therefore, it is necessary to retract the cone of influence, so that the eastern periphery does not encompass contaminated areas. There are other wellfields such as the Hialeah/Preston and Miami Springs, which also influence nearby groundwater flow; these wellfields serve the municipalities of Hialeah and Miami Springs. On the east part of the HEFT, there are commercial/industrial activities, which pose as a potential threat to groundwater if proper land use restrictions are not imposed. The Hialeah/Miami Springs Wellfields are clear examples of poor water quality; proven by the presence of hazardous vinyl chloride concentrations as well as other suspected carcinogens.

1.2 Objective

Due to increases in pumping rates, the Northwest Wellfield cone of influence has extended easterly to a point where contact has occurred with contaminants from the 58th Street landfill and resource recovery facility. Therefore, **the ultimate objective is to evaluate the WHPP of the Northwest Wellfield by using the county's time of travel**

contaminant criteria of 30, 210, and 500-day, with current EPA wellhead protection models, and the Calculated Fixed Radius Method. Thus, protection boundary established by the County can be further verified and compared. Specific objectives are the following:

- Delineate wellfield area.
- Overlay delineation and map zones.
- Investigate future impact of increased pumping rates on current land uses.
- Present comparative results of area delineation.

Once the delineation of a WHPA is accomplished, it is important to zone areas according to the type of potential contaminating activity with respect to water quality (USEPA, 1988). Finally, a WHPP facilitates the implementation of pollution prevention programs, where costs of prevention means less than costs of remediation.

1.3 WHPA Criteria for Delineation.

WHPA delineation can be based on distance, drawdown, travel time, flow boundaries and the capacity of the aquifer to assimilate contaminants. These delineation criteria are followed by state agencies, and small communities, in order to reach a desired degree of protection. After choosing the appropriate delineation criteria, a mapping method must be selected. The mapping methods are Arbitrary Fixed Radius, Calculated Fixed radius, Simplified Variable Shapes, Analytical Models, Hydrogeologic Mapping, and Numerical Flow/Transport Models (USEPA, 1994).

The delineation zone terminology and zone properties used in a WHPA is shown in Figure 1. In the unconfined aquifer a pumping well creates a cone of depression termed the zone of influence (ZOI); the ZOI lies within the zone of contribution (ZOC). The ZOC represents all the area that contributes water to the well. Illustrated in Figure 1, is the zone of transport of a contaminant. This is the time it takes for a contaminant to reach the well, also known as zone of transport (ZOT); contours of equal travel time are isochrones. The ZOT is also part of the ZOC (USEPA, 1987).

1.3.1 Distance.

This concept uses a radius from a pumping well to an arbitrary point, which will encompass the area of concern. The distance criterion does not include much technical consideration with regards to groundwater flow and physical processes of contaminant transport. The distance criterion could be selected as a preliminary step to a more technically WHPP.

1.3.2 Drawdown.

For a water-table aquifer, the lowering of the water table due to pumpage is known as drawdown. The extent of the drawdown reach is known as the ZOI. Drawdown is greatest at the well and decreases as distance increases to a point where the drawdown is negligible (see Figure 2).

Figure 1. Terminology for Wellhead Protection Area Delineation
(Source: USEPA, 1987)

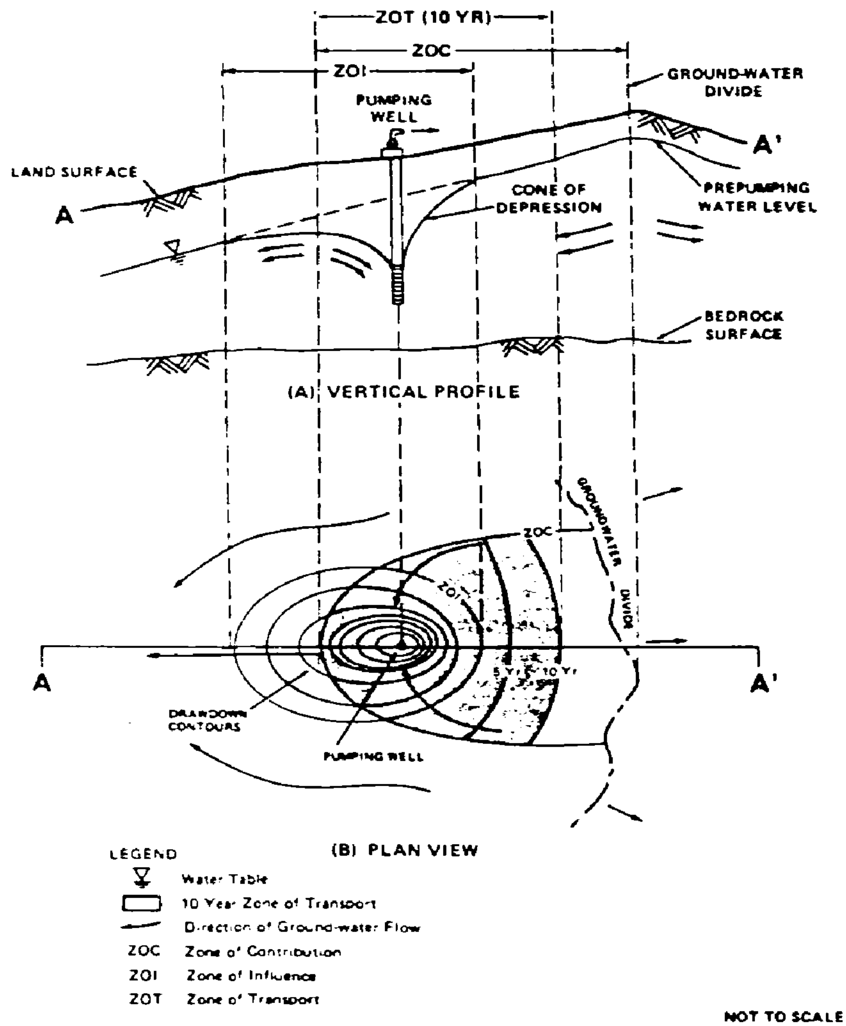
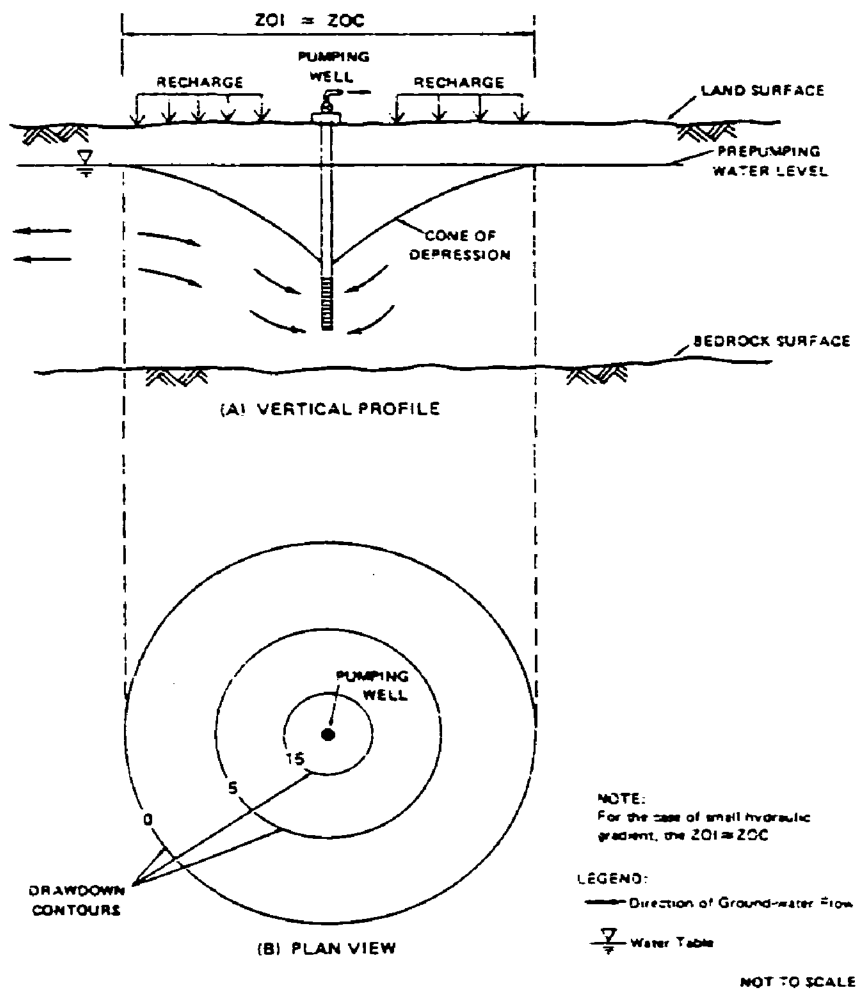


Figure 2. Aquifer with Flat Water Table and Boundaries of ZOI and ZOC
(Source: USEPA, 1987)



From Figure 2, drawdown contours can be obtained and used to delineate the WHPA. There are sometimes occasions, where the ZOC and the ZOI are approximately equal, either because of some high aquifer recharge or high pumping.

1.3.3 TOT.

This delineation criterion develops time of travel (TOT) calculations, that shows when a contaminant reaches a well. This criterion incorporates the physical aspects of advection and dispersion. Consequently, the contaminants will flow slowly or quickly towards a well, depending on how far away they are from the well activity and the aquifer hydraulic gradient. TOT is essentially a calculation obtained from groundwater flow velocities. Consequently, for a period of time, the distance of a particle can be calculated. For example, if the life of bacteria was 100 days and the groundwater flow velocity was also specified, a traveling distance of the bacteria can be calculated. Furthermore, in terms of wellhead protection, the traveling distance obtained determines if bacteria reaches and contaminates the water supply, before dying or reducing itself to harmless concentration levels.

1.3.4 Flow Boundaries.

Ridges, rivers, canals and lakes are physical/hydrologic features, which can act as a hydrologic flow boundary or groundwater divide. The zone enclosed by these physical boundaries may be considered to be the ZOC. The flow boundaries are most effective in regimes where the TOT to ZOC boundary is rather quick.

1.3.5 Assimilative Capacity.

This criterion involves the ability of the aquifer's saturated and/or unsaturated zones to hold the transport of contaminant concentrations, and reduce them below target levels before reaching the well (see Figure 3). This attenuation process involves specific knowledge of aquifer composition, conditions, and ongoing chemical reactions.

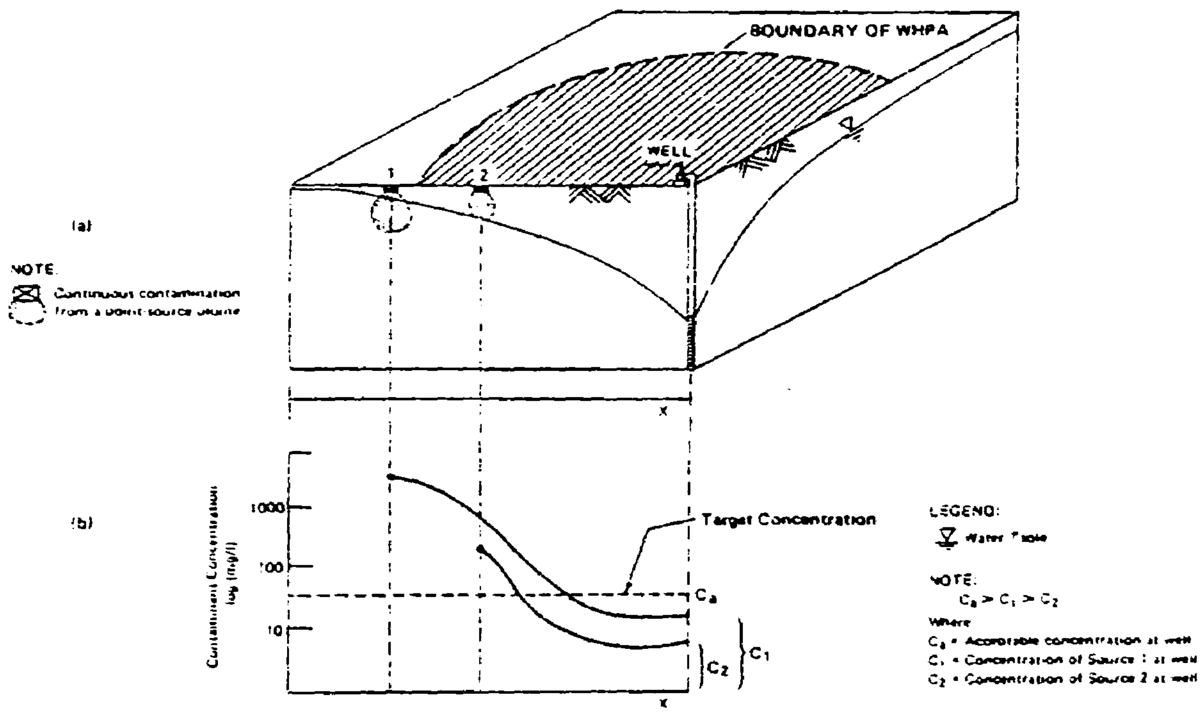
1.4 WHPA Criteria Threshold.

Once the delineation criteria has been selected. For example, say TOT is selected, then a threshold value must be determined. In the case of Florida, a 5-year TOT has been established. In Dade County, TOTs of 10, 20, 100, and 210-day travel time contours have already been established. The 210-day travel time was selected because it is the longest time of drought repeated in Miami, Florida. This means that for 210 days, Miami received rainfalls, which were less than 0.5 inches. Therefore, a drought duration of 210 days is used as a meteorological reasonable worst case condition. This, in turn, provides an approximate boundary limit for the wellhead area being protected.

1.5 WHPA Delineation Methods

In a wellhead protection program, there are six main methods which can be used to delineate a WHPA. The six methods are listed in order of increasing sophistication and increasing cost.

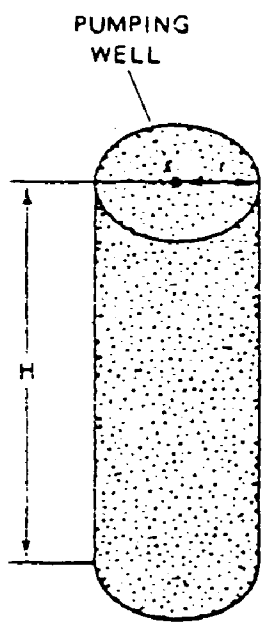
Figure 3. Assimilative Capacity Criteria
(Source: USEPA, 1987)



- Arbitrary fixed radii
- Calculated fixed radii
- Simplified variable shapes
- Analytical methods
- Hydrogeologic mapping
- Numerical flow/transport modeling

The first and least expensive is the **arbitrary fixed radii**. Accuracy of this method relies much on professional judgement and generalized hydrogeologic considerations. In a relatively short time, an arbitrary threshold distance criterion is selected, then a specified radius is drawn around the wellfield being protected. The **calculated fixed radii** uses specified TOT criterion threshold and an analytical equation to calculate the radius around the wellfield. The analytical equation is based on the volume of water drawn from a well for some period of time. The time period used should allow for groundwater remediation before reaching a well (see Figure 4). The **simplified variable shapes** method uses analytical models, where TOT and flow boundaries are the holding criteria. Calculation of the ZOC is used to develop standardized forms, which are overlayed around the well according to the direction of groundwater flow. The standardized form is calculated from hydrogeologic and pumping input parameters (see Figure 5). **Analytical methods** are also used in the delineation of a WHPA. The concept is based on the usage of the uniform flow equation, and contaminant transport.

Figure 4. WHPA Delineation Using FDER Volumetric Flow Equation for Well in Florida.
(Source: USEPA, 1987)



$$\underbrace{Q\,t}_{\text{VOLUME PUMPED}} = \underbrace{n \pi H r^2}_{\text{VOLUME OF CYLINDER}}$$

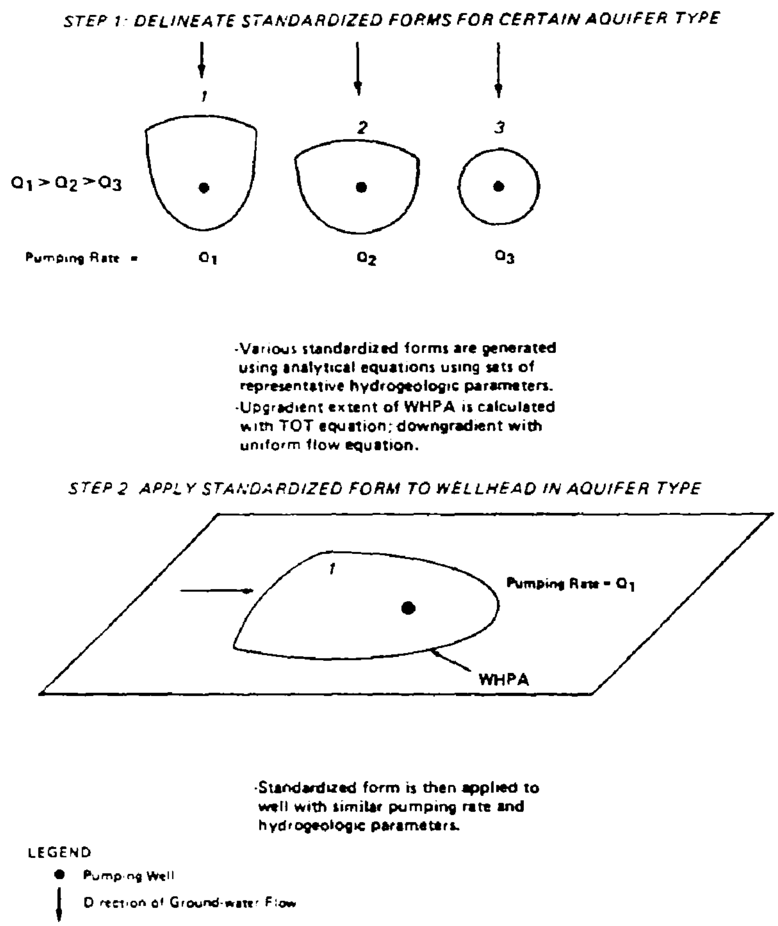
$$r = \sqrt{\frac{Q\,t}{\pi\, n\, H}} = 1138 \text{ ft}$$

WHERE

Q = Pumping Rate of Well = 694.4 gpm = 48,793,668 ft^3/yr
n = Aquifer Porosity = 0.2
H = Open Interval or Length of Well Screen = 300 ft
t = Travel Time to Well (5 Years)

(Any consistent system of units may be used.)

Figure 5. WHPA Delineation Using Simplified Variable Shapes Method. (Source: USEPA, 1987)



The analytical method uses hydrogeologic parameters to calculate the width of the ZOC to the well. Also, both upgradient, and downgradient boundaries of the WHPA can be calculated based on TOT criteria threshold values (see Figure 6). **Hydrogeologic mapping** is also used in delineating a WHPA; this method requires flow boundaries, and TOT mapping through geological, geophysical and dye tracing methods. Finally, **numerical/flow transport models** can help in delineating a WHPA, by numerically approximating groundwater flow equations and contaminant transport equations. This method fits in well with all types of hydrogeologic settings by using drawdown, flow boundaries, or TOT as criteria (USEPA, 1987).

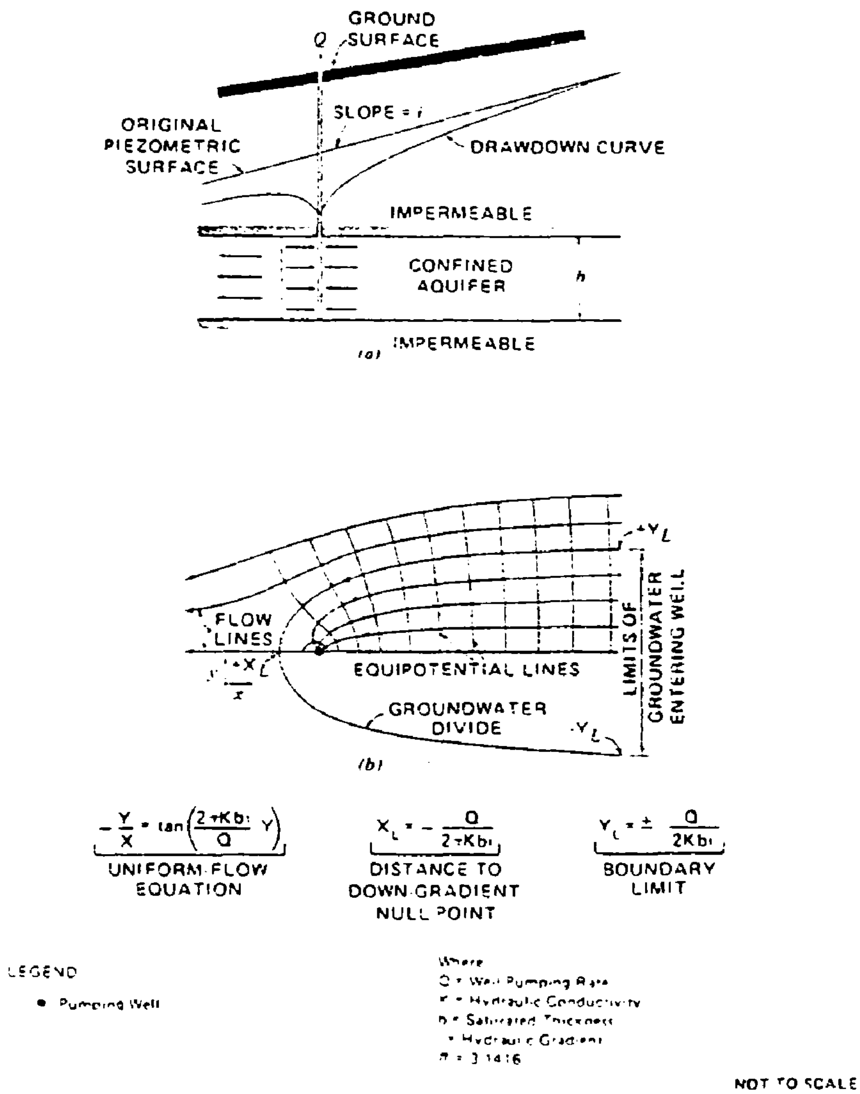
1.6 Models Used as Screening Tools for WHPA Delineation

Dade County has basically used MODFLOW, a three-dimensional numerical model to determine the characteristic groundwater flow and solute transport for delineating the WHPA of the Northwest Wellfield.

a) Numerical Modeling in WHPA Delineation.

Numerical models are expected to provide more realistic results than any other modeling approaches. However, they do require a wide range of data input. In WHPA, numerical models are helpful in describing varying hydrogeologic systems. Numerical groundwater flow models usually use an Alternating Direct Implicit algorithm to solve the finite difference approximation of the groundwater flow equation (Guiguer et al., 1991). Most of the numerical type models use a finite difference or finite element technique.

Figure 6. WHPA Delineation Using the Uniform Flow Analytical Model.
(Source: USEPA, 1987)



In the finite difference technique, a solution is obtained by approximating the derivatives of the partial differential equation in the governing equation. The finite element technique uses an integral equation, which is numerically evaluated over the transport domain (Heijde, 1988).

In general, the numerical approach requires the formulation of a grid, that represents the aquifer. At each node, data is entered, such as water table elevation, hydraulic conductivity, and others. To execute a numerical model, technical and computer expertise is required.

b) Semi-Analytical/Analytical Modeling in WHPA Delineation.

In the analytical method for delineating a WHPA, the flow boundaries are established by the time of travel. Then, the upgradient and downgradient boundary of points contributing to the well are determined. TOT is obtained by using the pore velocity which is equal to the Darcian velocity divided by the aquifer porosity. The two components that make up TOT are the regional velocity and local (near well) velocity:

$$\mathbf{TOT = Vr \times t + Vp \times t} \qquad (1)$$

where, **Vr** = regional velocity due to regional water gradient

Vp = local velocity due to local gradient near well pumping.

In semi-analytical models, analytic solutions based on space or time domain are approximated through numerical techniques (Ramanarayanan, 1992).

Most analytical models calculate travel time capture zones by forward and reverse particle tracking technique. Forward tracking is essentially used to determine whether or not a pumping well will be contaminated from some source of contamination close to the well, for example a landfill. On the other hand, reverse tracking goes in direction opposite to groundwater flow to determine the source of contamination for an already contaminated well. The basis of the calculation begins with a discharge Q equal to (Darcy's Law):

$$Q = KiA \qquad (2)$$

where, K is the hydraulic conductivity, i the hydraulic gradient, and A the cross-sectional area. Next, the Darcian Velocity is obtained by:

$$q = \frac{Q}{A} \qquad (3)$$

The seepage velocity is calculated using the effective porosity θ:

For X and Y coordinates in two-dimensional flow:

$$V_y = \frac{q_y}{\theta} \qquad (4)$$

$$V_x = \frac{q_x}{\theta} \qquad (5)$$

$$V = \frac{q}{\theta} \qquad (6)$$

With these equations, the traveling distance of a particle can be calculated with time by using the following analysis:

$$X_{i+1} = X_i + \Delta X \tag{7}$$

$$X_{i+1} = X_i + V_x \Delta t \tag{8}$$

$$Y_{i+1} = Y_i + \Delta Y \tag{9}$$

$$Y_{i+1} = Y_i + V_y \Delta t \tag{10}$$

1.6.1 WHAEM

The Wellhead Analytic Element Model (WHAEM) is used to determine TOT capture zones. WHAEM is a package developed by the USEPA in conjunction with Indiana University at Bloomington and the University of Minnesota at Minneapolis. The package includes two executables: the graphical preprocessor GAEP, Geographical Analytic Element Preprocessor, and CZAEM, Capture Zone Analytic Element Model. WHAEM uses superposition of the closed form analytical solutions to obtain a groundwater flow solution. CZAEM defines capture zone boundaries by identifying stagnation points and groundwater divides. CZAEM is based on the mathematical concept of the Dupuit-Forchheimer assumption, where vertical resistance to flow is negligible. CZAEM is a single layer model, that simulates steady flow in homogeneous aquifers. The analytic elements that WHAEM supports are river boundaries, streams, lakes, wells, uniform flow and uniform infiltration from precipitation (Kraemer et al., 1994). The analytic element

method uses superposition of analytic functions. The analytic element method does differ from the numerical technique in the following:

- The aquifer is unbounded in the horizontal plane.
- The solution is analytical. WHAEM creates contour plots and streamlines.
- There is no numerical dispersion.

Mathematical functions such as line-sinks are used as elements to model river boundaries, streams, and lakes. Line sinks simulate a constant rate of extraction or recharge along a segmented line. For example, groundwater flow along a stream is modeled by using a finer subdivision of the stream into line sink segments. The Thiem equation is used to model wells given a head and discharge rates. A pond function models areal recharge from precipitation. Finally, the uniform flow function is used to combine effects of surface water boundaries and areal recharge. The GAEP module is essentially the script file, which is created by electronically digitizing hydrologic maps. This data is entered and read by CZAEM. The WHAEM package can significantly be used as a screening tool to assist municipal water supplies in the design of a WHPA (Strack et al., 1994).

1.6.2 WHPA Model.

WHPA is a Modular Semi-Analytical Model for the Delineation of **W**ell**h**ead **P**rotection **A**reas. WHPA can be used to model pumping wells, injection wells and simulate

hydrologic boundary conditions. Unconfined, confined and leaky-confined aquifers with areal recharge can also be modeled. The WHPA model is a user-friendly PC-based computer model that was developed by the USEPA (Blandford et al., 1991). This semi-analytical groundwater flow model is composed of four modules, which are used to delineate capture zones. The WHPA model can be used based on TOT and flow boundary criteria. In the WHPA semi-analytical model there are two major assumptions:

Steady-state flow

Horizontal flow

WHPA includes the following modules:

RESSQC module delineates time related capture zones for pumping wells and contaminated fronts near injection wells. The module is based on steady-state uniform flow in homogeneous aquifers over an infinite areal extent. Well interference is accounted for.

MWCAP (Multiple Well Capture Zone) module delineates time related capture zones or hybrid capture zones for pumping wells. This module is also based on steady-state uniform flow in homogeneous aquifers. The aquifer is either of infinite areal extent or hydrologic boundaries are considered.

GPTRAC (General Particle Tracking) module contains two options: semi-analytical and numerical. The first option delineates time related capture zones for pumping wells. This module is based on steady-state uniform groundwater flow in a homogeneous aquifer. The aquifer can be of infinite areal extent or bounded by hydrologic barriers. The aquifer may be confined, leaky confined or unconfined with areal recharge. Effects of well interference is also accounted for. The numerical option delineates time related capture zones for pumping wells, under steady state groundwater flow. Various types of hydrologic boundary conditions, aquifer heterogeneities, and anisotropies can be applied through the use of the particle tracking. This is obtained from a numerical groundwater flow code.

MONTEC (Uncertainty Analysis) module conducts uncertainty analysis for the time related capture zones for single pumping wells. This is used for confined or leaky confined homogeneous aquifers.

Table 1 shows the different input parameters required for each module of the WHPA package. WHPA can delineate 3 types of capture zones: Steady-state, Time-related, and Hybrid. The steady-state and hybrid capture zones can be modeled through the MWCAP option module (see Figure 7).The Steady-state capture zone is the subsurface or surface zone that will contribute water to a pumping well, for an infinite period of time (see Figure 7).

Table 1. Required Input for WHPA Model Computational Modules
(Source: Blandford, 1991)

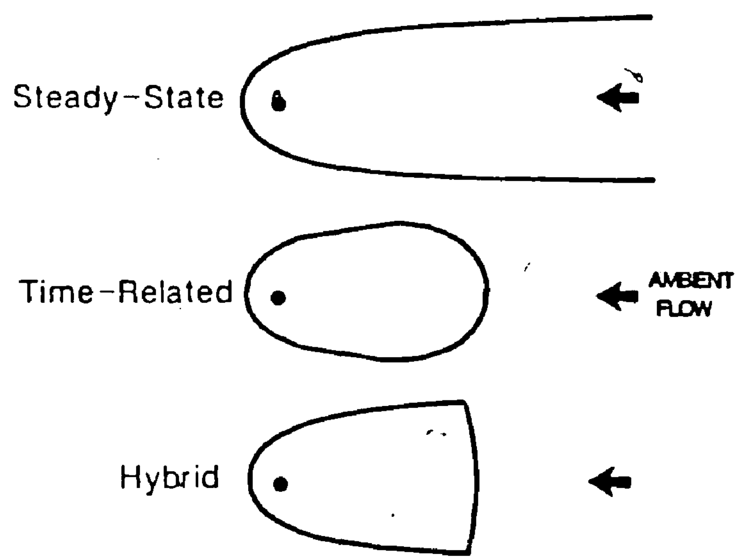
			GPTRAC	
Required Input	**RESSOC**	**MWCAP**	**Semi-analytical**	**Numerical**
Units used				
Aquifer type*	■	■	■	■
Study area limits			■	
Maximum step length	■	■	■	■
No. of pumping wells	■	■	■	
No. of recharge wells	■	■	■	■
Well locations	■		■	■
Pumping/injection rates	■	■	■	■
Aquifer transmissivity	■	■	■	■
Aquifer porosity	■	■	■	■
Aquifer thickness	■	■	■	■
Angle of ambient flow	■	■	■	■
Ambient hydraulic gradient	■	■	■	
Areal recharge rate	■	■	■	
Confining layer hydraulic conductivity			■	
Confining layer thickness			■	
Boundary condition type		■	■	
Perpendicular distance from well to boundary		■	■	
Orientation of boundary		■	■	
Capture zone type		■		
No. of pathlines used to delineate capture zones	■	■	■	■
Simulation time	■		■	■
Capture zone time	■	■	■	■
Rectangular grid parameters				■
No. of forward/reverse pathlines	■		■	■
Starting coordinates for forward/reverse pathlines	■		■	■
Nodal head values				■
No. of heterogeneous aquifer zones				■
Heterogeneous aquifer properties				■

*Confined, unconfined, or leaky confined

Note: The MONTEC module is not listed in this table. It has the same input requirements as MWCAP and semi-analytical GPTRAC, with the addition that uncertain aquifer parameters and their associated probability distributions must be specified.

Source: U.S. EPA, Office of Ground Water Protection. *WHPA—A Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas*. March 1991.

Figure 7. Capture Zone Types
(Source: Strack, 1994)



The time-related zone type may be calculated when the groundwater flow field is at steady-state. The time related capture zone is the surface or subsurface area around a pumping well, that supplies recharge to the well in a period of time. Figure 7 shows the time related capture zone for a single well. The Hybrid capture zone is a combination of the time related and steady-state. Except that it is capped at the upstream end, through physical and/or managerial restrictions (see Figure 7).

1.6.3 Calculated Fixed Radius Method

A radius for wellhead delineation of specified time period can be obtained based on an analytical equation. The equation calculates a radius from a volume of water drawn from a well in some time period. The former Florida Department of Environmental Regulation (FDER), today the Florida Department of Environmental Protection, developed the following volumetric flow equation which is used to calculate a fixed radii to delineate the Northwest Wellfield:

$$\mathbf{Qt = n\pi Hr^2} \qquad \mathbf{(11)}$$

where,

Q = Pumping rate at NW Wellfield

n = 0.2 for porosity

H = 40 ft. (interval or length of well screened obtained from Fish and Stewart, 1990)

t = Travel time in days.

r = radius

II. LITERATURE REVIEW

2.1 Legislative History.

Currently, there are 27 states with an EPA approved WHPP which was established following the 1986 Amendments to the Safe Drinking Water Act (SDWA). Now, each remaining state must prepare and submit a WHPP to EPA for approval. However, EPA has allowed flexibility in the provisions and guidelines outlined in EPA's mandate for a WHPP. Therefore, every state program can be tailored to its own needs according to their specific objectives, in order to maximize program efficiency and avoid high costs of regulation (McCormack and Trovato, 1991).

In 1980, before the 1986 Amendment to the SDWA, the passage of federal laws and ordinances regarding the protection of existing and future public water supply, compelled various state agencies to begin wellfield protection studies. For instance, the state of New Hampshire began a WHPP in the City of Dover, in order to minimize contamination threat due to anticipated population growth. The wellhead zones were determined based on analytical modeling. The city passed a groundwater protection ordinance which now restricts land use activities in the protection zone (Moore, 1993).

In some communities, high costs may come along with the implementation of a WHPP, due in part to new proposed laws and regulations. However, high costs in a well managed WHPP will ultimately result in lower costs (Caswell, 1993). Further assistance in financing approaches is offered through the USEPA for wellhead protection initiatives,

based on several case studies in funding. These case studies can be tailored to the need of every state or small community WHPP. Most costs of a WHPP are reflected upon construction of capital facilities, land acquisition, and regulation of potentially polluting commercial, residential and industrial activities (Roy and Dee, 1989).

The State of Florida, through the Department of Environmental Protection as the leading agency, have reviewed and addressed the issue of wellhead protection. Consequently, most local governments in Florida have begun developing and implementing wellhead protection programs. As a result, there are approximately 74% of municipalities and 63% of counties which are in the process of implementing a WHPP. However there is a need to develop a statewide wellhead protection program which can be flexible enough, to fit the needs and economics of every local area (Bonds, 1993).

In Dade County, Florida, there is a growing concern for the excessive application of pesticides and fertilizers. The issue is specially critical when the water table is appreciably high, because compounds such as nitrates can leach into the groundwater and contaminate recharging aquifers that are used for public water supply. The West Wellfield Interim Protection Area (WWIPA) in Dade County, Florida, is a good example of land use control. Chapter 24 of the Metropolitan Dade County Code classifies pesticides and fertilizers as hazardous substances and restricts the use of such substances in the WWIPA (DERM, 1992). In other words, the county has rezoned the area and no longer allows commercial activities such as the construction of new golf courses.

However, existing activities are allowed, but they are being heavily regulated and controlled through State regulations on the use of pesticides and fertilizers (Gadipudi, 1994).

Wellhead protection efforts usually encounter problems with land owners who claim that the value of their land has fallen due to the zoning restrictions dictated by the whole wellfield delineation results. Thus, litigation is a problem confronted quite often. Therefore, it is critical that appropriate groundwater models, pumping data, test boring, water table configurations and aquifer geology are carefully used to accurately describe the actual recharge zone for a drinking water supply. This is necessary to make sure that the methodology and results will hold true in court litigation. Once the wellhead protection zone is valid, then regulations are needed along with new zoning restrictions necessary to avoid groundwater contamination (Lennox, 1993).

2.2 Wellhead Protection Programs in the United States

Water planning is a critical task for state and county agencies, because they must look for solutions for water demand projections. Two alternatives are usually present, one is to develop potential surface-water reservoir sites or groundwater withdrawals. Therefore, optimization models are used as screening tools to determine which alternative is most acceptable. In the case of surface-water reservoirs, the model determines the yield capacity and reservoir size needed for certain demand of water consumption and in the case of groundwater development, the model determines the well capacity which would

be needed to meet the water consumption demand. This approach was applied at the Jordan River Basin in Utah (Lall, 1995). Groundwater is presently being used by the Salt Lake City for municipal water supply. The wells pump out of the confined aquifer at depths below 400 ft. A yield model was used to aid the Utah State Department in determining which water supply alternative was more cost effective and reliable in the future. However, a third possibility is also considered, by using both alternatives together, where one supplements the other, for example, increasing groundwater pumpage during some portion of the year and fixing the reservoir yield, or viceversa. Variables which go into the model formulation are: annual yield at each reservoir site, the degree for failure of the reservoir site expressed as a fraction, and total groundwater yield. Furthermore, a linked simulation-optimization is developed to determine relationships between yield (storage capacity for reservoir and aquifer yield), failure, economic and physical relationships at every site. This entire process goes through a series of iterations which finally end up with the most optimum solution. The objective of course is to minimize the total annual cost for meeting projected water demands. Final results indicated that groundwater is the most economical and optimal way out for the Utah State Department (Lall, 1995). In some cases groundwater supply is not the optimum solution because of the high demand for high quality water. Instead some communities must turn to surface water supply. This is the case for the New England town of Scituate in Massachussetts, which had an increase in residential and tourist population (Antoniello et al., 1993).

There are wellhead protection programs for complex hydrogeologic settings that have also been established in several states across the U.S. These WHPPs exist for confined, semi-confined, fractured and karst aquifer settings, where the aquifer is not open to the atmosphere and unconsolidated porous media do not control (USEPA, 1993b). Wellhead protection programs are widespread across the United States, but the concept itself is relatively new. In other regions, like Europe and Latin America, none or very little is found that is related to the Wellhead Protection Area concept (Cleary and Cleary, 1991).

A hydrologic study of a 136 square mile area in Jackson, Tennessee, was conducted in order to delineate a wellhead area for two municipal wellfields. The two wellfields, the North Wellfield and South Wellfield, supply water to Madison County. Two main aquifers, the Memphis Sand and the Fort Pillow Sand, range in thickness from 0 to 270 ft and 0 to 180 ft, respectively. Hydraulic conductivities were estimated at 80 to 202 ft/day for the Memphis Sand range. Similarly, transmissivity for the Memphis Sand ranges from 2,700 to 33,000 ft^2/day. The Fort Pillow Sand aquifer had hydraulic conductivities ranging from 68 to 167 ft/day and transmissivity values ranging from 6,700 to 10,050 ft^2/day. Several pumping scenarios were devised and simulated through the use of a finite difference groundwater flow model. The model calibration represented existing hydrologic conditions which indicated that 25% of the steady-state water budget is discharged to pumping wells. The model was later adjusted to simulate the effects of planned pumping scenarios. The first scenario would simulate effects of the groundwater system due to an increase in pumping rate to 20 MGD for the North Wellfield and 15

MGD for the South Wellfield. The increase in pumping rate had reached maximum drawdown of up to 38 ft. The increase in pumping rate had determined a 9% increase of water discharging to pumping wells. Travel time capture zones for the wellfields were determined by using a particle-tracking post-processor program, MODPATH. A 5-year time of travel capture zone for the North & South wellfields was approximately 1.6 by 2.2 miles (Bailey, 1992).

The St. Peter-Prarie du Chien-Jordan aquifer in Rochester, southern Minnesota, is representative of a karstic aquifer, where the zone of contribution (ZOC) was calculated for two municipal wells. The ZOC obtained from the hydrogeologic mapping method was 4,100 acres, and that obtained using the numerical model MODFLOW was 2,180 acres. Generally, numerical models compute larger zones of contaminant transport than analytical models. However, the numerical model used in this study was not designed for delineation of recharge areas to wells. Results indicate that the factors affecting a recharge area are the pumping rate, well location, and proximity of discharging wells to rivers and streams or impervious boundaries (Delin and Almendinger, 1993).

The Verona Wellfield in Battle Creek, Michigan, is another example of how wellhead protection can prevent groundwater contamination. This site was declared a superfund site by the EPA after VOCs were found. The wellfield consisted of 30 wells, where 17 of them were removed due to existing contamination. Instead, eight wells were used as purging wells to cause redirection of contaminated groundwater and protect the remaining

13 production wells. This was done in order to stop the spread of contamination. Eventually with the help of other state agencies, the city managed to put together a WHPP with time of travel and flow boundaries criteria, and established land use controls. With the implementation of this program, nine new production wells were constructed (O'Brien, 1993).

The North Cheshire Wellfield located in Cheshire, Connecticut, is the town's public drinking water supply which serves approximately 82% of its population. In past years, the wellfield has shown traces of health hazardous chemicals, such as SOC, including trichloroethylenes. Groundwater modeling was done for the South Central Connecticut Regional Water Authority's North Cheshire Wellfields (Lennox et al., 1990). Numerical models were developed and sensitivity analysis was conducted in supporting an aquifer protection plan for this wellfield. The wellfield was delineated, and results showed industrial and commercial sites which represented the greatest risk to groundwater contamination. The development and implementation of the aquifer protection program faced opposition from property owners who believed that the land value would depreciate when rezoning for wellfield areas occurred. Therefore, it is of primary importance, that a WHPP be developed to meet the needs of a community, taking into consideration also economic growth.

It is important for Wellhead Protection programs to take into consideration future withdrawal scenarios and look ahead for potential future sources of water supply (Navoy,

1994). In Camden, New Jersey, the Potomac-Raritan-Magothy aquifer is the major source for the Delaware Bay area. However due to its increased withdrawal and potential danger of saltwater intrusion, the New Jersey Department of Environmental Protection reduced its 1983 withdrawals by 35 percent. In view of this restriction, the City of Camden had to find an alternate potential source of water supply. The solution in part was the Wenonah-Mount Laurel aquifer. The aquifer would need to uptake the remaining 35 percent withdrawal, which would mean approximately 7 million gallons per day (MGD). However, projected withdrawal rates indicated that by the year 2020 the withdrawal rate would increase to more than 14 MGD. Simulation of projections indicated that there would be a cone of depression in the Camden area by the year 2020, that would range from 10 feet above sea level to 60 feet below sea level. Thus, adjacent aquifers and hydrologic features such as stream infiltration will be influenced by this wide cone of depression. One conclusion of the study was that a comprehensive study for future management plan for increased water demand needs to be developed. This is done in order to determine how critical this new induced cone of depression will be, or specifically, will it have enough recharge, will it generate to much interference with other aquifers such that the cone of depression is increased, will it generate large infiltration rates, or in worst cases will there be saltwater intrusion ? (Navoy, 1994)

Preliminary studies for developing wellhead protection programs must include aquifer assessment plans, to determine whether or not the aquifer is suited for drinking water supply. For instance, an aquifer study was done on the regional aquifers of Tennessee,

one known as a basal sandstone and described as poorly sorted, with low porosity and permeability (Brahana et al., 1982). It extends throughout most of Tennessee, west of the Valley and Ridge Province. The aquifer has very little recharge because the sandstone is overlain by a thick layer of Paleozic carbonates and shales with low porosity. The basal sandstone was also found to be at depths greater than 5,500 feet below land surface. In terms of water quality, concentrations of dissolved solids in water were found to be less than 40,000 mg/L to 200,000 mg/L and more. The Safe Drinking Water Act indicates that underground sources of drinking water must not have concentrations greater than 10,000 mg/L of dissolved solids. After further evaluation the aquifer was not used as a source for drinking water, because of high dissolved solids concentrations, low porosity and permeability, and deep depth. Instead the aquifer is being investigated for gas, oil or minerals for exploitation (Brahana et al., 1982).

Wellhead protection areas can be determined from travel time of groundwater flowlines. These flowlines are estimated from computed average linear velocities in the flow field. In the southeastern region of Salt Lake Valley, Utah, a 48-square mile area was studied in order to determine an average linear velocity (Freethey et al., 1994). Geologic maps, water table maps and soil borings were used to estimate conductivity, porosity and slope of the potentiometric surface. These three hydraulic properties are needed to estimate average linear velocity. Hydraulic conductivity was estimated from a thickness weighted average of values. Hydraulic conductivities were found from 98 different control points, with values ranging from 20 to 250 ft/day. The porosity of the aquifer ranges from 15

to 35 percent, obtained from geologic maps. Water levels were measured during dry and wet seasons to obtain potentiometric contour maps. Linear velocity was computed and ranged from 0.06 to 144 ft/day with a mean of 3 ft/day. The Utah State Department has defined their protection zones to be at 250 days, minimum time necessary to decrease risk of organic chemical and pathogen contamination. The second zone is 15 years, minimum time to decrease risk of inorganic contamination to acceptable levels. With the availability of hydrologic and geologic data, the hydraulic properties can be determined and used to compute the average linear velocity by dividing the hydraulic conductivity and the effective porosity, and later multiplying by the hydraulic gradient. Consequently, travel time can be calculated by dividing the length of a flowline or pathline by the average linear velocity along that same flowline. Final results, for the principal aquifer in the Salt Lake Valley Region, revealed that along a 2-mile flowline the travel time was about 11 years (Freethey et al., 1994).

2.3 Wellhead Protection Programs in Florida

In Florida there are several wellhead protection programs which have been compared to each other, in an effort to provide guidance to other local governments that plan to adopt a wellhead protection program. In Dade county, legislature has strengthened its groundwater protection policy plan by adding new local plan requirements for water recharge areas, water wells and wellfield protection. In certain counties, such as Alachua, Volusia, and St. Lucie, the simplified radius method is used to protect, mostly, specific wells. However, in most counties, such as West Palm Beach, Broward, Dade and Lee,

the travel time and drawdown contours are used to determine protection zones for larger wellfields. The overall protection zone for these counties is subdivided and regulated through the use of four regulation zones of influence (Blain et al., 1992).

In 1985, before the 1986 Amendment to the SDWA, a WHPP was established in Lee County, Florida. The intent of the program is to regulate potential contaminants near the public supply wellfields which pump more than 1 MGD. Lee County estimates that the WHPP costs less than $200,000 per year. Their wellfields were modeled based on a time of travel (TOT) concept (USEPA, 1987). The WHPP of Lee County WHPP is designed to protect near surface aquifers from contamination related to land use activity and ground surface aquifers from damaged wells (Dickenson and Banks, 1992).

Broward County, as well as Dade County have established several wellfield protection programs. Important elements in these programs can serve as clear examples of what a WHPP must have, for instance: identifying wellfield pollutants and their sources, map zones of influence around wellfield, and finally develop and implement strategies to minimize interaction between land uses and potable water wellfields (Shair, 1992).

2.4 Modeling Efforts in Developing WHPPs

The U.S. Geological Survey in conjunction with the South Carolina Department of Health and Environmental Control performed a study on the effectiveness of the capture zone delineation methods for subsurface drinking water supplies. A 15-square mile area is

located in the southern region of Hilton Head Island along the southeastern coast of South Carolina (Landmeyer, 1994). Most of the potable water is pumped from 10 production wells, from the semi-permeable upper Floridan aquifer lying beneath Hilton Head Island. Several modeling approaches were used to determine capture zones for the confined aquifer. Initially, the Arbitrary Fixed Radius Method was used to delineate the travel-time capture zone for the study area. However, further investigations and the usage of other delineating methods, such as the Calculated Fixed Radius and two numerical (semi-analytical) models, RESSQC and MWCAP, disagreed with the initial 100-foot radius determined from the Arbitrary Fixed Radius Method. The use of these two models provided a more realistic representation of the area contributing to the wellfield. Perhaps, the major differences were found to be that the initial Arbitrary Fixed Radius Method underestimated the upgradient portion of groundwater flow and over estimated the downgradient recharge portion of the well, thus the location of a stagnation point was not accurate enough (Landmeyer, 1994).

TOT is a program developed by the Oklahoma Water Resources Board. TOT uses groundwater flow equations and time of travel calculations in order to delineate wellhead protection zones. The ZOC is expected to increase if pumping periods and pumping rates are higher. However, other important factors affect the size of the ZOC, this being the use of average or maximum pumping rates, use of screen length, and the length of up gradient TOT boundary Y_L shown in Figure 6 (Fabian et al., 1992).

For multiple well systems, the drawdown at any point in the wellfield is the sum of all drawdowns from every well. Several wells closely spaced can be connected to one supply line to meet large demands. Therefore, in 1898 Forchheimer developed an equation for unconfined aquifers which calculates the drawdown at any point for wells parallel to a line source (Raghunath, 1982).

Several cities around the U.S also make use of Geographic Information System (GIS) modeling to interface with several groundwater models to delineate wellhead protection zones. The end result is that changes in public water supply or land use control can be quickly assessed. The degree of accuracy is also well accounted for. GIS basically stores, manipulates analyzes and maps out large amounts of data (Rifai et al., 1993).

Safe yield for aquifers is usually determined through a water balance. New methods for determining safe yield of aquifers have been developed, which includes aquifer dimensions, hydraulic parameters, and the duration of the worst drought. The method is essentially based on establishing a level to where discharging from an aquifer can be allowed. This level is then related to the worst drought so that a sustainable pumping rate is obtained (Miles and Chambet, 1995).

Analytical element models are used to determine capture zones for pumping systems or wellhead protection. The models will calculate stagnation points, upgradient divides and dividing streamlines, all based on steady-state equations. Equations are available for both

confined and unconfined aquifers. Generally, capture zones are used to determine contaminant spreads from leaking underground storage tanks. In doing so the x-axis of the capture zone is aligned with the direction of groundwater flow (Grubb, 1993).

For simple aquifers, capture zone curves can be described by three analytical equations, the uniform flow equation, distance to the downgradient null point (stagnation point) and the boundary limit equation. These equations calculate the specific discharge at some pumping rate Q. However, some assumptions must prevail: (1) aquifer with constant regional hydraulic conductivity; (2) isotropic and homogeneous aquifer of constant thickness; and, (3) constant effective porosity. Computer codes for some simple aquifers can be used for aquifer remediation and wellhead protection with acceptable results (McElwee, 1991).

Analytical, semi-analytical, and numerical flow models in conjunction with particle tracking methods, were used for the capture zone simulation of the municipal wellfield at Wooster, Ohio (Springer and Bair, 1992). Travel-time capture zones were delineated for a stratified-drift buried valley aquifer. The delineation results were later compared to determine differences and accuracy among all three.

Stratified-drift aquifers found in glaciated parts of the Midwest, Pennsylvania, New York, and New England are high in infiltration, yield, and overlain by well drained valley floors. The comparison of these three models are based on visual comparison of

simulated and observed heads, calculation of mean absolute error and root mean square error, and lastly the distribution of pathlines used for delineating the travel-time capture zone. The study from Springer and Bair (1992) also shows that the analytical flow model used was CAPZONE, which takes into account recharge, and uses the Theis equation to calculate drawdown in a confined aquifer for the municipal wellfield. The semi-analytical model DREAM was also used to calculate drawdowns by using the Theis equation. The third model was MODFLOW, a three dimensional finite difference model, which simulates all the major components of groundwater flow. After 13 model runs for simulated heads, CAPZONE had a mean absolute error (deviation from true mean value) of 3.44, DREAM had 3.86, and MODFLOW 2.04. From the comparison of conceptual errors and goodness of calibration between simulated and measured heads, results indicated that CAPZONE and MODFLOW were within a reasonable range. In other words, MODFLOW predicts more accurately than any of the other two. The major differences between the models was that the semi-analytical and analytical ones could not account for spatial variations in aquifer thickness and conductivity for the stratified drift aquifer. All three models were later used to delineate the North Wellfield in Wooster, Ohio, and compare results for one year travel-time capture zones. Comparison of areas had shown that the capture zone for the wellfield using CAPZONE had an area of 356 acres, DREAM an area of 318, and MODFLOW 476 acres. The main difference is due to the distribution and orientation of pathlines obtained from particle tracking (Springer and Bair, 1992).

Delineating techniques must also consider available budget resources for analysis and the degree of accuracy. A numerical and analytical model were used to determine the contributing area for six municipal groundwater supplies in Northern New York. The main aquifer is the Tug Hill aquifer. For purposes of comparison, the contributing area of the Lacona-Sandy Creek wellfield was computed first by using a finite difference groundwater flow model and post-processing particle tracking program, and secondly, by using a Dupuit Uniform Flow method. The Dupuit Method computed a contributing area of 0.04 mi^2 at a pumping rate of 200 gpm and hydraulic conductivity of 1,200 ft/day. The numerical method computed a contributing area of 0.13 mi^2 for the same hydraulic conditions. Contributing areas were computed for five other municipal wellfields, which totalled an area of groundwater contribution of 17 mi^2 (Zarriello, 1990).

Groundwater modeling is very useful in predicting hydraulic head distribution for a production well near a contaminated site (Hudak, 1994). For instance along the Miami River in southwest Ohio, there are four wellfields with capacities ranging from 17,000 to 87,000 m^3/day. A solid waste landfill is located near the site, which poses a potential threat for groundwater source contamination. The glacial aquifer at the site consists of unconsolidated sand and gravel, ranging from a few meters to about 76 meters . The river at the site is hydraulicly connected to the groundwater. Model simulation results were illustrated through contour maps for different pumping scenarios. Hydraulic head configuration, cone of depression and flow pathlines were analyzed to determine if they would run through the landfill and converge at the different wellfields. It was determined

that two of the four wellfields were prone to contamination from the landfill (Hudak, 1994).

Groundwater travel time criteria are used to delineate wellhead zones at Brooklyn Park, Minnesota, by using the Analytical Element Model. The model is also used extensively in parts of Europe. This method is representative of a closed form analytical function known as an analytical element. For example, streams, lakes, wells, and rainfall infiltration are analytical elements (Wuolo, 1995). Presently, the City of Brooklyn Park receives its water supply from 15 wells, but at peak demand the wellfield has difficulty meeting the demand. Therefore, the city needs to establish new wellfield sites that will suffice projected water demands.

The Minnesota Department of Health Rules relating to Wellhead Protection has used the water-time-of-travel criteria to define a minimum threshold value of 10 years for wellhead protection zone in confined aquifers, and 20 years for unconfined aquifers. Beneath the study area is an unconfined aquifer with varying zones of outwash sand and gravel. This unconfined aquifer overlies the bedrock aquifer. Municipal wells from the Brooklyn Park obtain their water supply from the unconfined aquifer, and two aquifers in the bedrock, Mt. Simon Hinckley and the Franconia-Ironton-Galesville bedrock aquifer. The water table aquifer ranges from 50 to 400 ft thick, and the other two aquifers are approximately 150 ft thick. The Analytical Element Modeling approach took into account natural recharge and discharge boundaries which would be linked to the groundwater flow. The

model was used to model the first two aquifers mentioned. The AEM model proved to be useful over finite difference and finite element models in this particular case. The city used the model to locate new wells for water demands through the year 2012 (Wuolo, 1995).

Calibration studies are usually done by comparing measured heads to computed model heads. Some of the hydraulic parameters (conductivity, aquifer thickness, porosity, and hydraulic gradient) used for the models are average estimates. The average estimates have upper and lower boundary values. Therefore the probability of uncertainty in these values exists. Consequently, when an analytical model is used to delineate travel-time capture zones with such values, it is possible sometimes that the resulting travel-time capture zone is overly conservative or sometimes the resultant travel-time capture zone is not sized enough for sufficient protection. It is herein when Monte Carlo simulation can be used to determine the parameters which are most sensitive and again determine travel-time capture zones which take into account the uncertainty of hydraulic parameters.

The Monte Carlo based approach was used in a study done for the City of North Canton, Ohio. The uncertainty at this site was due to limited well log information, spatial parameter variations in hydraulics, and heterogeneous geology. The objective of the study was to determine a one-year capture zone for one of three municipal wells operated. The varying parameters chosen for the Monte Carlo simulation study were hydraulic conductivity and porosity (Bair et al., 1991).

The Monte Carlo simulation for one-year capture zones of the municipal well was performed by CAPZONE and GWPATH, analytical flow and groundwater flow-travel time models, respectively. The CAPZONE model was used to calculate drawdowns at the site and incorporate results into GWPATH to determine the one-year capture zone. Both CAPZONE and GWPATH delineate capture zones through reverse particle tracking pathline. The end coordinates of a pathline for a given period determines one endpoint representing the perimeter of the travel-time capture zone. For this specific study, 36 pathlines were selected to represent the capture zone. The Monte Carlo statistics were later carried on with 100 random paired values of porosity and hydraulic conductivity. A 75th and 90th percentile confidence level were used to produce a confidence region of a one-year capture zone. For example, if you have 36 endpoint distribution for 100 simulations then the total endpoint distribution would be 3600 endpoints. In order to obtain 75 percent confidence level, 25 percent of the endpoints must be deleted and the remaining is called the convex hull set of endpoints. The final result illustrates where the majority of pathlines are located, thus it is prudent placing monitoring wells outside the perimeter of this area for wellhead protection (Bair et al., 1991).

2.5 Groundwater Monitoring and Remediation Efforts.

Groundwater monitoring is a key element in the ongoing success of a Wellhead Protection Program. Monitoring programs also assist in management of land use. This is essentially done by evaluating groundwater quality, thus indicating what kinds of activities must be excluded or limited from the Wellhead Area. Part of the success of a monitoring program

is based on best management practices, such as having good sampling schedules, and placing monitoring wells at sites with heavy commercial or industrial activity.

The use of capture zones in remediation plans is a common method. A contaminant plume can be redirected to an extraction well through the control of the hydraulic gradient. The magnitude of pumping and location of wells plays a major role in determining a remediation strategy and minimizing cost. The cost usually includes the number of wells and their construction, the types of pumps, piping, etc. This indicates that the cost is proportional to the pumping rate. With the use of a contaminant transport model and a two-dimensional groundwater flow model, several scenarios are tested to determine the best pumping rate and the best location of an extraction well or wells. In some remediation plans, the more simplistic models assume that the driving force for contaminant movement is purely advective with little dispersion and retardation occurring (Ahlfeld and Sawyer, 1990).

Improvement can be made to wellhead protection programs by adding risk management programs which will consider contaminant sources. A study for risk analysis of wellhead projection divides contaminant sources into two categories: chronic sources and spills. Chronic sources include, for example septic tanks, while spills include accidental releases from commercial or industrial facilities handling hazardous waste. Risk defines the probability of an event occurring. A well managed wellhead protection program is one that can demonstrate that even if a chronic source is present within the wellhead area, that

the pumped water still has acceptable quality. The same applies for spills occurring within the wellhead protection area. Therefore, a risk-analysis procedure is the best way to demonstrate these events. Some programs have been developed which perform this risk-analysis. RISK is a modular computer program designed for this purpose. RISK estimates the probability density function of travel time for each contaminant source within the recharge zone, and calculates the probability distribution function of contaminant in pumped water. The overall result is a risk assessment for adverse health effects on the population being served by the wellfield (Chin and Chittaluru, 1994).

Contributing recharge areas may sometimes not include possible sources of contamination. However, this does not mean that the groundwater quality is not threatened by such sources. The possibility of contamination still remains due to its closeness and any varying conditions in the hydrogeology which may alter the contributing recharge area (Reilly et al., 1993).

III. STUDY AREA

3.1 Location

The focus of this study is on the recently constructed Northwest Wellfield, located in an undeveloped area of Dade County, Florida (see Figure 8). The Northwest Wellfield lies along a north-south stretch, 1.8 miles west of the Homestead Extension of the Florida Turnpike (HEFT), between NW 90th Street and NW 58th Street (see Figure 9). Undeveloped land exists West of the HEFT. The Northwest Wellfield is one of the largest wellfields in the United States. Indeed, each well pumps as much as 50 million liters per day. The outermost protective zone of the Northwest Wellfield has a 1 ft drawdown (Hoffer, 1989). These wells were constructed in order to meet the projected increase in water demand. Most of the groundwater in South Florida comes from the Biscayne Aquifer, which is composed mainly of highly permeable limestones, sandstones, and overlying deposits of sand. The Biscayne Aquifer thickness is approximately 300 ft thick going in a direction south of the county and approximately 150 ft north of the county. Groundwater recharge of the Biscayne Aquifer occurs mainly through rainfall, which averages about 60 inches per year (Camp Dresser & McKee, Inc., 1982). Groundwater moves generally in the south-east direction from the Conservation Areas to the Atlantic Ocean. However, local groundwater flow can be influenced by drainage canals, rainfall, or water withdrawals. Most of Dade County's water supply for public consumption, industrial use and irrigation is pumped from the Biscayne Aquifer.

Figure 8. Areal Extent of the Biscayne Aquifer
(Source: DERM, 1985)

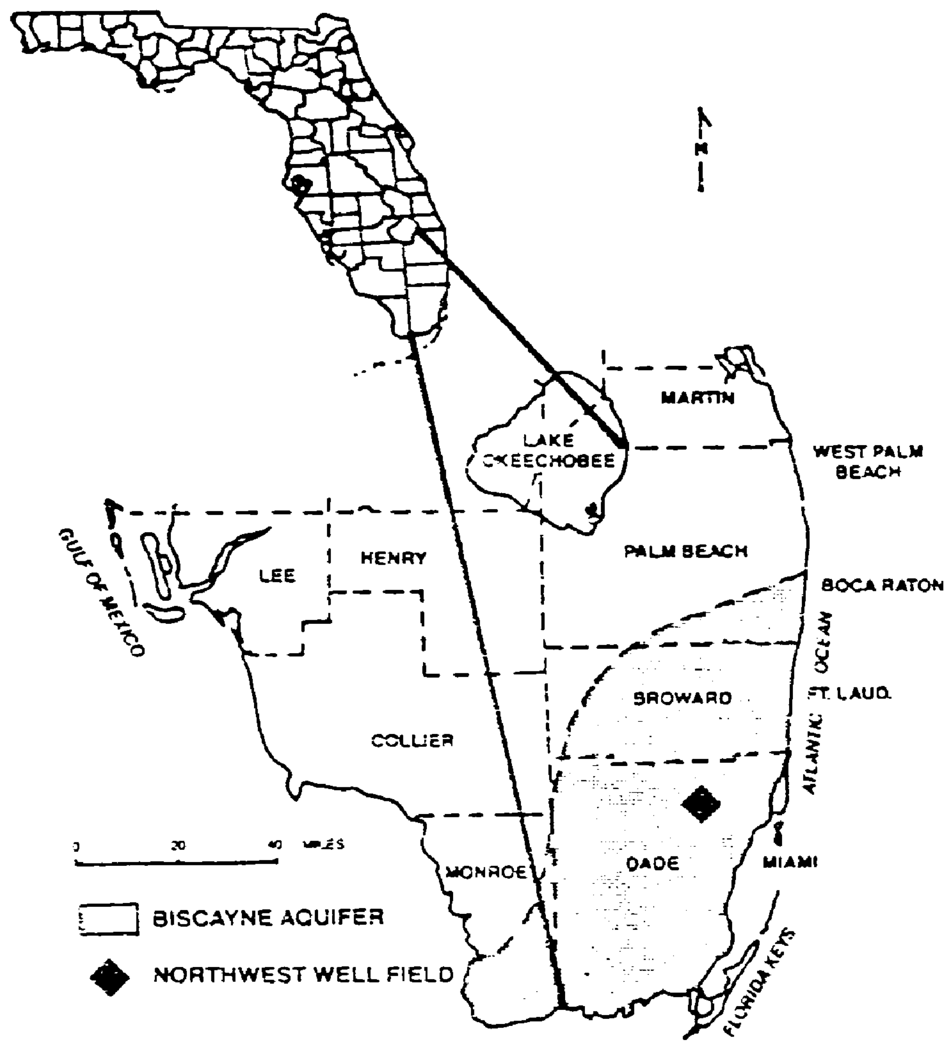
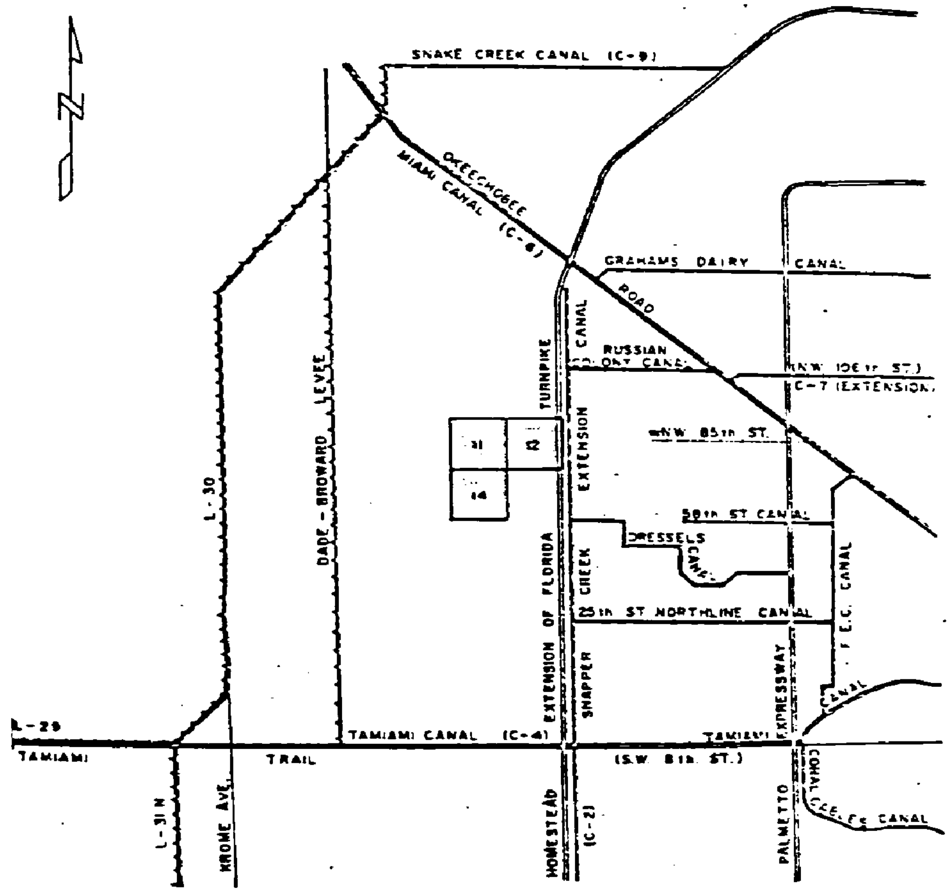


Figure 9. Site of the Northwest Wellfield and Surrounding Canal Network.
(Source: DERM, 1984)



NOT TO SCALE

3.2 Northwest Wellfield Protection Plan According to Dade County Study.

The Northwest Wellfield production wells provide good quality water to North Dade County. The eastern periphery of the existing cone of influence is located east of the HEFT and Snapper Creek Extension Canal. The county is concerned with existing sources of contamination located in this eastern part. Therefore, the main objective of the county was to reduce or retract the eastern boundary of the cone of influence, by way of canal modification for better aquifer recharge, and reducing wellfield pumpage. In result, the county has developed a three phased wellfield protection plan for the Northwest Wellfield. The contamination threat originates from the 58th Street landfill and resource recovery facility shown in Figure 10. In 1985, water withdrawals showed traces of contamination in pumped waters. Computer modeling done by the county supported the previous statement, thus indicating that withdrawal rates are so high that the wellfield is withdrawing water from contaminated areas, such as the landfill area and other nearby industrial areas. The WHPP has been implemented in three phases, as follows:

Phase 1 in the WHPP defines the area which needs protection, by finding out what contaminants may be closely in contact with the groundwater. The drawdown caused by the Hialeah, Preston and Miami Springs Wellfields interfaces with the drawdown caused by the Northwest Wellfield. Due to relatively low water quality, the county has reduced the use of the water withdrawn from the Hialeah, Preston, and Miami Springs Wellfields; this, in turn, resulted in an increase in the withdrawal rate of the Northwest Wellfield, therefore increasing the cone of influence. Therefore, in Phase 1 all secondary canals

extending east from the Snapper Creek Extension (SCE) Canal as shown in Figure 11, have been plugged in order to prohibit runoff coming from industrialized areas into the SCE Canal. The Phase 1 protection boundary was placed west of the 58th Street Landfill in order to avoid the presence of contaminated areas.

Phase 2 attempts to reduce high pumping at the Northwest Wellfield by using advanced treatment technologies, such as air stripping at the Hialeah/Preston Water Treatment Plants to improve water quality coming from production wells at these plants. This will help to reduce the already extended cone of influence of the Northwest Wellfield from contaminated areas. With this implementation, the Phase 2 boundary would shift farther west as shown in Figure 10.

Phase 3 is, of course, the permanent definition of the final protection area. The Phase 3 boundary was first based on groundwater computer modeling to obtain results on pollutant travel time and, secondly, on canal construction and modification. The latter was done in order to produce a hydrologic boundary along the SCE Canal, prohibiting the entrance of contaminants along the eastern periphery and also increase water recharge to the wellfield obtained from newly constructed canals, thus reducing the cone of influence further west; refer to Figure 10 (DERM, 1985).

3.3 Contaminants of Concern

Dade County's water supply seems most threatened by SOCs. For example,

Figure 10. Three Phased Wellfield Protection Program Boundaries
(Source: DERM, 1985)

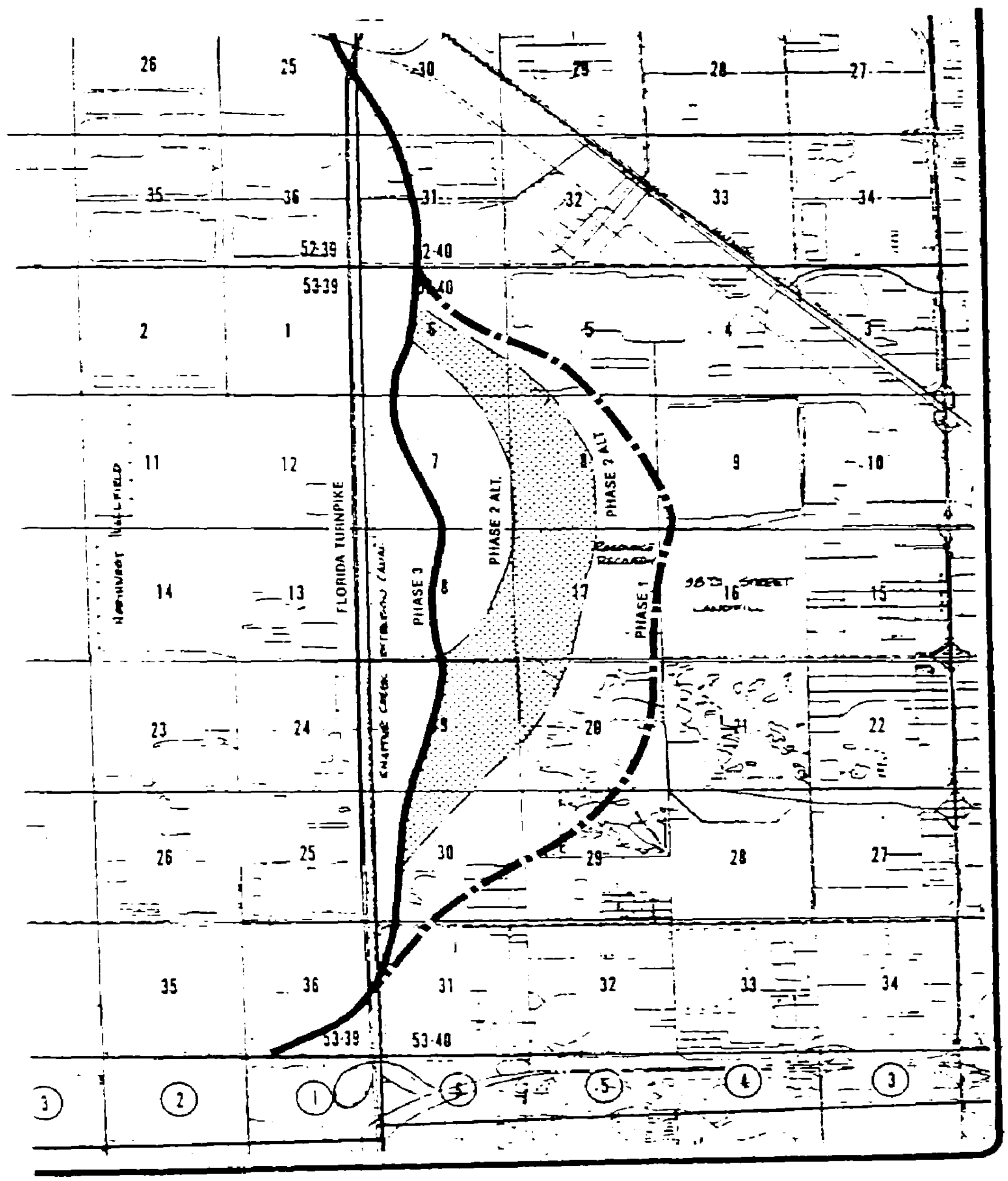
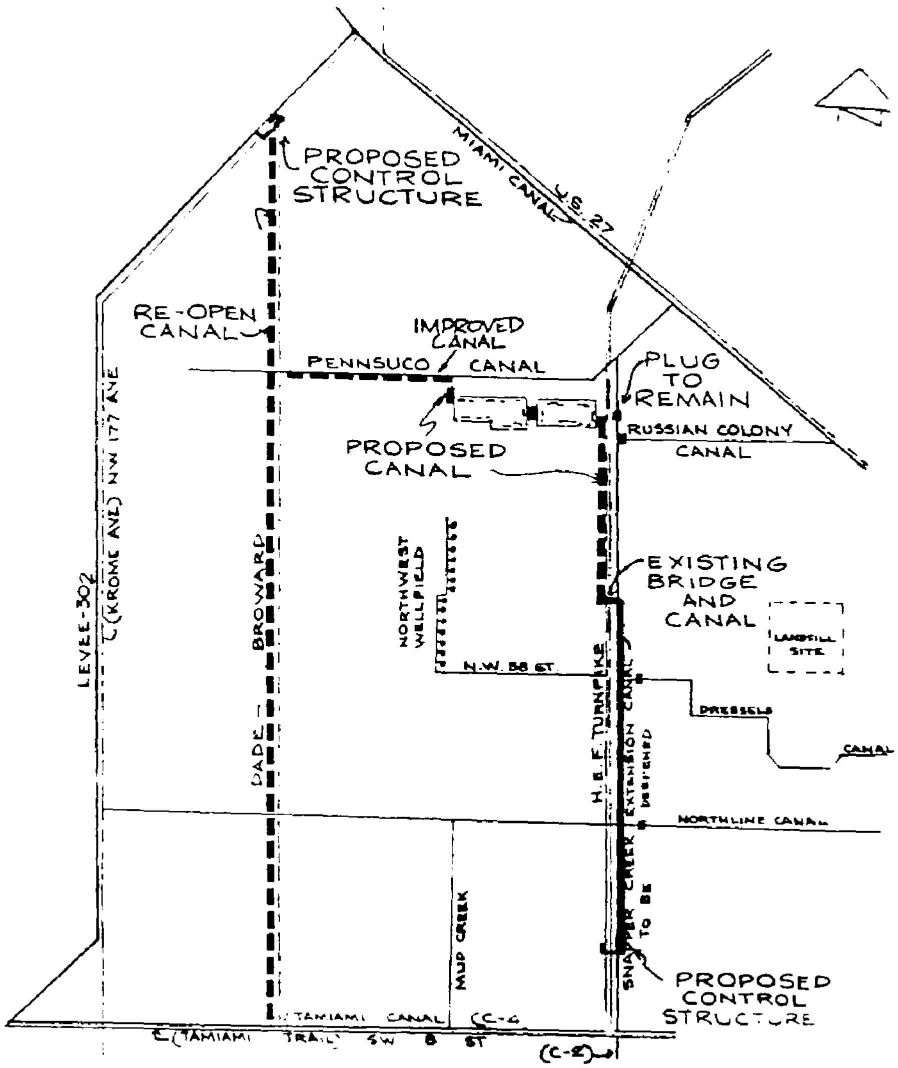


Figure 11. Recommended Canal Modifications
(Source: DERM, 1985)



tetrachloroethylene and trichloroethylene are solvents which biodegrade into vinyl chloride, which is a human carcinogen. Unacceptable levels of this life threatening compound have been found in the Hialeah, Preston and Miami Springs water supply. Table 2 illustrates the comparison of water quality for both Preston and Northwest Wellfields. From Table 1 the Hialeah/Preston and Miami Springs sites show the presence of vinyl chloride in concentrations of 3.79 ppb over 1 ppb (drinking water standard by the Department of Environmental Regulations), a human carcinogen, whose parents are tetrachloroethylene and trichloroethylene. The concentrations present at these sites after treatment represent 257 cancer incidents per 1 million persons in terms of a carcinogenic health risk. The only way of course to effectively remove these contaminants is through investments in advanced treatment technologies. Granular active carbon (GAC) and air stripping are presently being used as treatment to remove most of the VOCs and SOCs (DERM, 1985).

3.3.1 Contaminated Sites in the Vicinity of the Northwest Wellfield.

The Northwest 58th Street Landfill, Miami Drum Site, Miami International Airport and Unsewered Industrial Areas are sites where contaminated groundwater was found.

a) NW 58th Street Landfill

Contaminants leaching into the groundwater had a potential threat to nearby water supplies including the Miami Springs and Preston Wellfields.

Table 2. Comparison of Water Quality Between the Northwest Wellfield and the Preston Wellfield for VOCs and THMs.
(Source: DERM, 1985)

Parameter	Preston Wellfield after current treatment Concentration (ppb)	Preston Wellfield after current treatment Predicted Cancer Risk per 10^6 pop.	Removal (percent)	Preston Wellfield after air stripping Concentration (ppb)	Preston Wellfield after air stripping Predicted Cancer Risk per 10^6 pop.	DER Drinking Water Standards (ppb)	Blending 70% Northwest Wellfield with 30% Preston Wellfield & Air Stripping Concentration (ppb)	Blending 70% Northwest Wellfield with 30% Preston Wellfield & Air Stripping Predicted Cancer Risk per 10^6 pop.
Vinyl Chloride	3.79	252.7	99.92	.003**	2.000	1	.001**	.667
Vinylidene Chloride	.51	2.1	98.9*	.006**	.088		.002**	.030
Trans-1,2-Dichloroethene	8.71		78*	1.92			.58	
1,1-Dichloroethane	3.06		98.9*				.01**	
Cis-1,2-Dichloroethene	12.12		78	2.67			.80	
1,1,1-Trichloroethane	.00		98.9*			200		
1,2-Dichloroethane	.00		78*			3		
Tetrachloromethane	.00					3		
Trichloroethylene	2.97	1.7	98.9	.03	.017	3		
Tetrachloroethylene	.00		98.9*			3		
Chlorobenzene	.99		98.9	.01**			.02**	
O,M,P chlorotoluene	1.12		98.9	.01**			.01**	
M,P-dichlorobenzene	.99		99.92	.001**			.01**	
0-dichlorobenzene	.76		98.4	.01**			.003**	
Benzene	--					1		
Ethylene Dibromide	.00					.02		
THMs	22.5	76.5***	99%	.23	.810***	100	.25	.850***
TOTALS	57.32	333		4.92	2.915		1.69	1.547

* Presumed % removal determined by comparing Henry's Coefficient of each compound to Henry's Coefficient of compounds evaluated during EPA air stripping demonstration in February, 1984.

** Below analytical detection limit for that compound.

***Risk calculated assuming 100% of THM analysis is chloroform.

Note: Probabilistic risk estimations are based on data published in the June 12 Federal Register and presume consumption of 2 liters of drinking water over a 70 year lifespan.

b) Miami Drum Site

Originally a drum recycling company and now a Metrorail Maintenance Facility is located east of the 58th Street Landfill. The drum recycling company was inactive since 1982, after having reported high concentrations of chemical waste. Cleanup programs were completed in 1982.

c) Miami International Airport

Leaks from underground storage tanks and accidental oil spills and other industrial chemicals have been reported for the last 15 years.

d) Unsewered Industrial Areas

This area contains over 1,000 potentially polluting industries. One industry location is the Pepper Steel & Alloy, which does pollute groundwater.

3.3.2 Characterization of Source Contaminants Near the Northwest Wellfield.

The Biscayne aquifer is mainly composed of permeable limestones and sandstones. The groundwater flow in the aquifer is primarily horizontal and eastward to the ocean. The Northwest Wellfield occupies a three-square mile site. The most important formations underlying the soil surface are the Fort Thompson Formation and the Key Largo Limestone. The hydraulic conductivities of these soil formations range from 1000 ft per day and above. In 1984, the U.S. Congress Office of Technology Assessment has grouped groundwater contamination sources into 6 major categories. Therefore according

to the Office of Technology Assessment, the sources of groundwater contamination near the Northwest Wellfield would fall under categories 1 and 2. The first category defines sources designed to discharge substances, which includes septic tanks and cesspools. The second category defines sources of contamination designed to store, treat, and/or dispose of substances, which include landfills for hazardous and non-hazardous waste, and underground storage tanks for hazardous and nonhazardous materials (Barcelona et al., 1988).

Dade County tries to maintain and improve the quality of water so that the cancer risk does not go over one in a million persons, assuming that a person consumes 2 liters of water per day over their entire life. The existing contamination at the Hialeah, Preston and Miami Springs wellfield is an example of what can happen to the newest drinking water supply, the Northwest Wellfield, if regulations and adequate zoning are not implemented. If there is no preventive control for the groundwater quality, then it can easily occur that SOCs, which are mostly found in Dade County can enter the aquifer supplying water to the Northwest Wellfield and contaminate it; the risk is high because the Biscayne Aquifer is highly permeable, with limited capacity for degradation or retardation of contaminants. The Northwest Wellfield shows no signs of high levels of synthetic chemical concentrations, however, there are trihalomethanes (THMs) present. THMs are organic compounds formed in water treatment processes due to chlorine (a disinfectant) reactions with naturally occurring organics.

Unfortunately in Dade County, vinyl chloride, THMs (eg.,chloroform), trichloroethylene and tetrachloroethylene are life threatening chemical compounds which are commonly found in parts of the Biscayne Aquifer. The physical and chemical properties along with the type of existing soil structure in the Biscayne Aquifer, indicates that the contaminants are highly mobile due to small Koc's, Kow's less than 500, water solubilities greater than 1000 ppm, and vapor pressures less than 0.01 mm Hg; thus limited adsorption and volatilization take place. Such high mobility supports estimating a conservative retardation factor of approximately one. Tables 3 and 4 contain information for the contaminants of concern in the vicinity of the Northwest Wellfield.

Table 3. **Physical and Chemical Characteristics of Possible Contaminants for the Northwest Wellfield**

Category	Vinyl Chloride	Trichloroethylene	Tetrachloroethylene	THM: Chloroform
Chemical Family		Chlorinated Hydrocarb.	Chlorinated Hydrocarb.	Chlorinated Hydrocarb.
Formula	CH_2CHCl	C_2HCl_3	Cl_2CCCl_2	$CHCl_3$
Health Risk	carcinogenic	carcinogenic	carcinogenic	carcinogenic
Flash Point	50°F	Slight	None	None
Koc (mg compound/g carbon)	N/A	18.2	34.5	1.6
Boiling Pt.(@ 760 mm Hg)	65° C	87° C	121° C	61° C
Melting Pt. (@ 760 mm Hg)	-98° C	-73° C	-22° C	-64° C
Solubility (mg/L)	Slightly, 2.67×10^3	Slightly, 1.1×10^3	Insoluble 1.5×10^2	Slightly, 8.2×10^3
Biodegradation	Moderate	Moderate	Moderate	Moderate
Kow	2.4×10^1	2.4×10^2	3.9×10^2	9.3×10^1
Vapor Press. (mm Hg @ 20°C)	100	58	13	159
Mobility	yes	yes	yes	yes
Volatilization	yes	yes	yes	yes
Adsorption	low	low	low	low

Table 4. Possible Contaminants and Their Sources

(Sources: DERM, 1984)

Source	Contaminants
Septic Tanks	*SOC's, Chlorides, Nitrates, Coliform & Noncoliform Bacteria
Landfills	Chlorides, Heavy Metals
Spills	Chlorides, Hydrocarbons, Heavy Metals
Sewage Lines	Pathogens, Nitrates, Hydrocarbons, Heavy Metals
Mining Activities	Heavy Metals
Underground Storage Tanks	Nitrates, Hydrocarbons
Gas Station/Repairs	Gasoline, oils, solvents
Dry Cleaning	Perc, Petroleum Solvents
Medical Office, Clinic	Biological Wastes, Formaldehyde
Beauty Parlor	Dyes, contaminated rinse solutions
Car Wash	Detergents
Swimming Pools	Maintenance Chemicals
Photo Developing	Cyanides, Silver
Junkyards	PCB's, Hydrocarbons
Lumber Yards	Wood Preservatives: Pentachlorophenol, Chromated Copper, solvents
Electroplating	Chromic Acid, Spent Solvents, Metallic Salts
Food Processing	Chlorine, ammonia, Ethylene Glycol, Formaldehyde
Veterinarians	Peroxides, Solvents, drugs

*SOCs: Trichloroethylene, Tetrachloroethylene

IV. METHODOLOGY

4.1 Controlling Hydrological Characteristics in Modeling the Northwest Wellfield Cone of Influence.

EPA has put out a 5 step process in WHPA delineation: (1) Form a community planning team; (2) Define the land area for protection; (3) Identify and locate potential contaminants; (4) Management of a WHPA; (5) Future planning. For the purposes of this study, emphasis will begin on step 2. This will be done through the use of three of EPA's methods for delineating the WHPA.

Physical hydrologic characteristics of the site and aquifer are needed for use of the model and delineation of the area. Table 5 is a checklist of data information that will aid in delineating the WHPA (USEPA, 1993a). Several controlling hydrologic site characteristics are considered for the preliminary analysis of the Northwest Wellfield modeling scheme (DERM, 1984):

- local flow conditions depend on regional flow patterns;
- chemical contaminants become diluted and may react with aquifer material;
- bacteria have limited time of existence;
- hydraulic gradients near wells depend on pumping rates, transmissivity, canals and regional gradients;
- The Snapper Creek Extension Canal acts as a hydrologic boundary; and
- a water divide exists along HEFT

Table 5. Information Available from Existing Mapping on the Northwest Wellfield
(Source: USEPA, 1993a)

	Groundwater Resources			Hydrogeologic Information					
	GW Quality	GW Availability	Location of Wells	Trans-missivity	Storativity	Hydraulic Conductivity	Surface Water Resources	Zoning Districts	Location of Possible Contami-nant Sources
Topographic Maps			x				x		x
Geologic Maps		x		x			x		
Soils Maps						x	x		
USGS Hydrologic Atlases		x		x			x		
Well Logs	x		x	x	x	x			
Test Boring Logs	x								
Water Table Maps		x							
Land Use Maps			x				x		
Zoning Maps			x				x	x	x
Roadway and Utility Maps									x

4.1.1 Boundary Conditions.

Similarly, the delineation process must take into account several important steps when utilizing the computer code (DERM, 1985):

- determine initial conditions from average potentiometric heads from average pumping rates and average recharge rates, for a specific period of time;
- determine regional 210-day drought potentiometric heads; this is done by having zero recharge from precipitation, while pumping is still going on at an optimum rate;
- use of a constant elevation aquifer condition; this may be represented by canals, conservation areas, or the Atlantic Ocean.

4.2 Selection of Criteria and Methods for Wellhead Delineation.

Tables 6 and 7 suggest TOT as a preferred approach along with the method of analytical modeling. It is important to note that TOT was established by the county to be 30, 210 and 500 day travel time zones. The analytical model chosen gives the opportunity to use data with some simplicity under the TOT concept. The TOT criterion can help accommodate future changes in pumping patterns due to increase in water demand population. Thus TOTs can be adjusted. The analytical method is at hand and its fine level of expertise and accuracy makes it feasible and useful for wellhead protection programs. Because, the Calculated Fixed Radius is relatively simple and easy to do, therefore it was also used and compared with the WHPA Model and WHAEM.

Table 6. Technical Consideration versus Criteria

(Source: Modified from USEPA, 1987)

Technical Consideration / Criteria	Ease of Application	Ease of Quantification	Variability Under Actual Conditions	RANK 1 to 5
Distance	H	H	L	3
Drawdown	M	H	H	4
Time of Travel	M	M	H	5
Flow Boundaries	L	N/A	H	1
Assimilative Capacity	L	L	L	2

L = LOW
M = MEDIUM
H = HIGH
N/A = NOT APPLICABLE
5 = Most desirable
1 = Less desirable

Table 7. Criteria versus Method

(Source: Modified from USEPA, 1987)

CRITERIA / METHOD	Availability of Tools	Simplicity of Data Requirements	Suitability for Hydrogeologic Settings	Accuracy	Feasibility
Arbitrary Fixed Radii	H	H	N/A	L	H
Calculated Fixed Radii	H	H	N/A	L-M	H
Simplified Variable Shapes	L-M	H	H	M	M
Analytical Methods	H	M	H	M-H	H
Hydrogeologic Mapping	L-M	L-M	H	M-H	M
Numerical Flow/ Transport Models	L	L	H	H	L

N/A = NOT APPLICABLE
L = LOW
M = MEDIUM
H = HIGH

4.3 Estimated Population and Water Demand Study

In conducting a water demand study it is important to define some key definitions. Water demand is defined as the total amount of water required to meet the public consumption. The average water demand is defined as the total water consumed in one year divided by 365 days. The average gpcd (gallons per capita per day) is obtained by dividing the average water demand by the population being served. Also, the Miami population growth projection for the year 2000 is 2,129,000 (Miami Business Profile, 1992-1993). In order to obtain a water demand projection for the Northwest Wellfield, it was important to obtain the population number being served by the Hialeah/Preston Water Treatment Plants for some initial point in time. Information based on a 1990 census data, documented by the Miami Dade Water and Sewer Authority Department (MDWASAD) and Metropolitan Dade.

The Dade County Planning Department in their "Water Facilities Master Plan" (MDWASAD, 1992) estimated that in the years 1993 and 1994 a population number of 1,010,000 and 1,025,000, respectively, was being served. An approximate current annual growth rate was estimated by this study to be 1.5% from the following:

$$\frac{Populat.\ 1994\ -\ Populat.\ 1993}{Populat.\ 1994}\ x\ 100\%\ =\ Annual\ Growth\ Rate$$

The plan predicts that the water demand population projection follows a linear projection for years 1985 through 2010. It should be understood that population growth in Dade County will be subject to a number of important factors, including high international and national migration, age distribution, land limitations, and socio-economic characteristics, among others. For the purposes of this study, a compromising exponential growth (Rogers, 1985) at the previously calculated rate was selected, considering that it provided a prediction comparable to others (MDWASAD, 1992; also see Figure 13), but yet slightly conservative. Therefore, the following equation (Rogers, 1985) was used to obtain population estimates for years after:

$$\mathbf{P(t) = P(0)\ exp(rt)} \qquad \textbf{(12)}$$

where, P(t) = future population at some time t.

P(0) = initial population served for 1995 equals 1,030,000

r = annual growth rate, 1.5%

t = period of time in years, 5, 10, 15, 20, and 25.

With Equation (12), water demand populations were estimated for the years 1995, 2000, 2005, 2010, and 2025. These values were the basis to estimate future water demands. Table 8 contains projected population growth for years 1995 to 2025.

Table 8. Estimated Population Growth Served by Hialeah/Preston Water Plant.

YEAR	POPULATION
1995	1,030,000
2000	1,110,221
2005	1,196,689
2010	1,289,892
2015	1,390,355
2025	1,615,362

4.3.1 Estimated Population and Water Demand Study for the Northwest Wellfield.

The Hialeah/Preston Water Treatment Plants are supplied by the Hialeah/Miami Springs, Preston, and Northwest Wellfields. Currently, the Northwest Wellfield has 15 wells which pump a total of approximately 115 MGD. The Hialeah/Miami Springs has 23 wells which pump approximately 60 MGD. The Preston has 7 wells which pump approximately 50 MGD. Table 9 gives a summary of location, pumping rates and wells for each wellfield. Obviously, the Northwest Wellfield seems to be used entirely as a water supplier and not as a supplement to the other wellfields, which was intended to be at first. The estimates from water demand population numbers are multiplied by the average consumption rate of 182 gallons per capita per day (gpcd), which is an estimated value for the year 1990 from MDWASAD. MGD values are finally listed in Table 10 which represent present and future water demand projections for the Hialeah/Preston Water Treatment Plant. Assuming that the rated pumping capacities for the Hialeah/Miami Springs and Preston are fixed at 60 and 50 MGD, respectively, which is expected because of high contamination level, an estimate for what the required Northwest wellfield demand can be obtained. Required demand can later be compared with current capacity. For example:

$$\frac{\textit{Ave Consumption x Projected Population}}{1{,}000{,}000} = \textit{DEMAND (MGD)}$$

Now,

DEMAND(MGD) - Hialeah/Miami Sprgs.(MGD capacity) - Preston (MGD capacity)

= Required Northwest Wellfield demand (MGD)

Table 9. Summary Table of Each Water Supplier.
(Source: MDWASAD, 1992)

Location	**Pumping Rate (MGD)**	**Number of Wells**
Hialeah/Miami Springs	60	23
Preston	50	7
Northwest Wellfield	115	15
TOTAL	**225**	**45**

The population served or needed to be served by this demand is calculated by dividing the required Northwest Wellfield by the average consumption rate of 182 gpcd. Results are shown in Table 10.

Finally in Table 11, a comparison of average and maximum day water demands for the entire Hialeah/Preston water treatment system are compared to the estimated average demands (MDWASAD, 1992). The estimated results for the demands are slightly higher; however, they remain within the range of the average and maximum demands. This estimate serves as a rough value for a good worst case scenario. Graphical results are also plotted for estimated water demand and population projections. Figure 12 shows estimates of population projections from 1995 to 2025. This prediction closely relates to the population projection study shown in the "Water Facilities Master Plan" (MDWASAD, 1992). It is important to note that this population projection is only the population demand pertaining to the Hialeah/Preston Water Treatment Plant and not Dade County entirely. Figure 13 compares predictions for 1995 to 2010 of estimated water demand with average and maximum water demands obtained from the "Water Facilities Master Plan". Thus, predicted water demands for 1995 to 2010 lie well between maximum and average demands indicated from the "Water Facilities Master Plan" study. Figure 14 indicates the population demand served exclusively by the Northwest Wellfield. In Figure 15, the estimated demand for the Northwest Wellfield is shown. The figure also illustrates the operating capacity of the wellfield at 115 MGD.

Table 10. Estimated Demand and Estimated Population Served for Northwest Wellfield

YEAR	DEMAND (MGD)	POP. SERVED	CURRENT STATUS (MGD)
2000	92	505,500	115
2005	108	593,400	115
2010	125	686,813	115
2015	143	785,700	115
2025	184	1,010,989	115

Table 11. Comparison of Estimated, Maximum and Average Demand for Hialeah/Preston Water Treatment Plant.
(Source: MDWASAD, 1992)

YEAR	Hialeah/Preston Average (MGD)	Hialeah/Preston Maximum (MGD)	Estimated Average Demand (MGD)*
1995	166	199	187
2000	192	230	202
2005	204	244	217
2010	214	245	234

*Calculated estimate in current study

Figure 12. Population Demand for Hialeah/Preston Water Treatment Plant

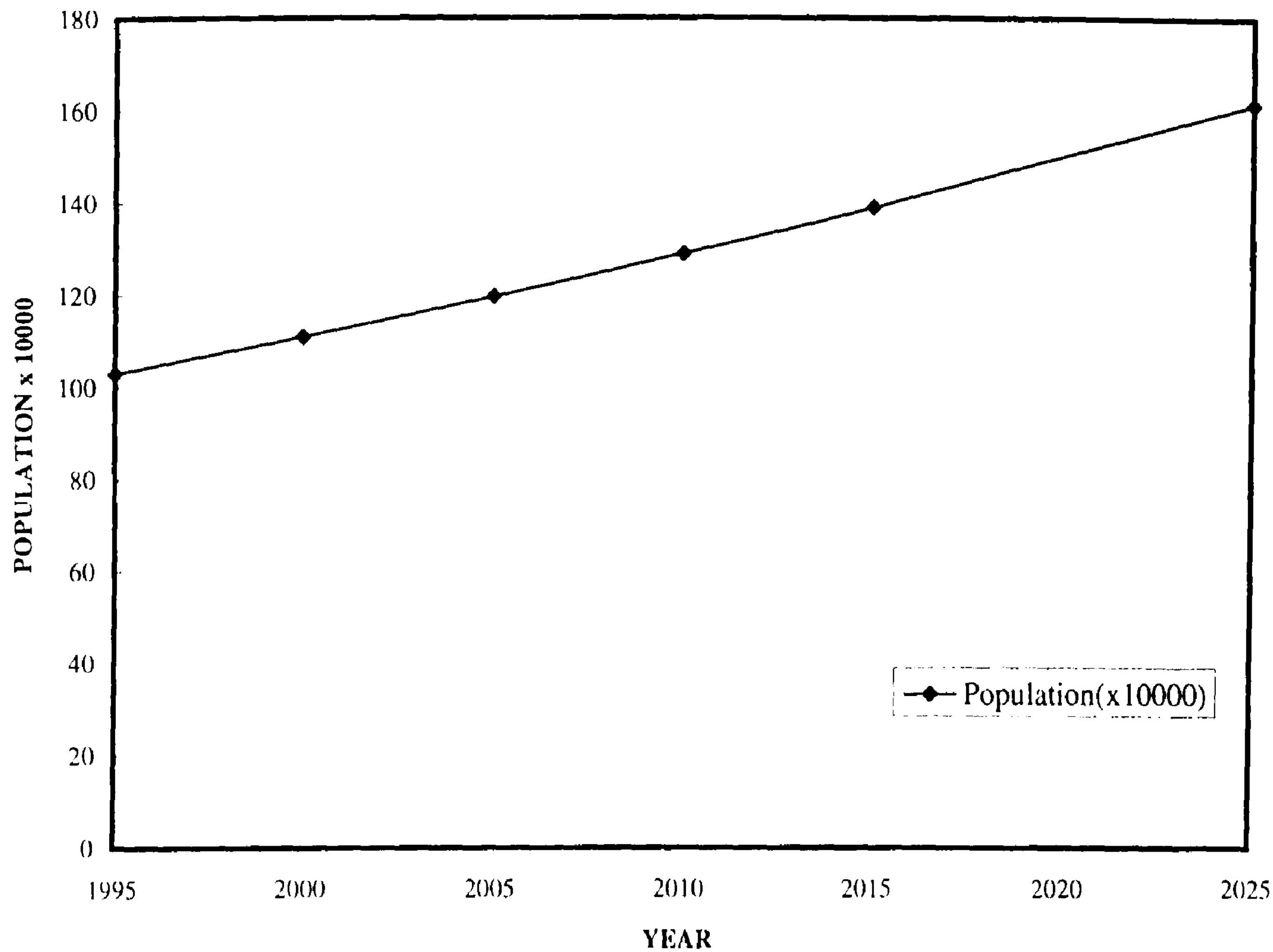


Figure 13. Comparing Estimated Water Demand with Dade County's Ave. and Max. Demands for Hialeah/ Preston Plant

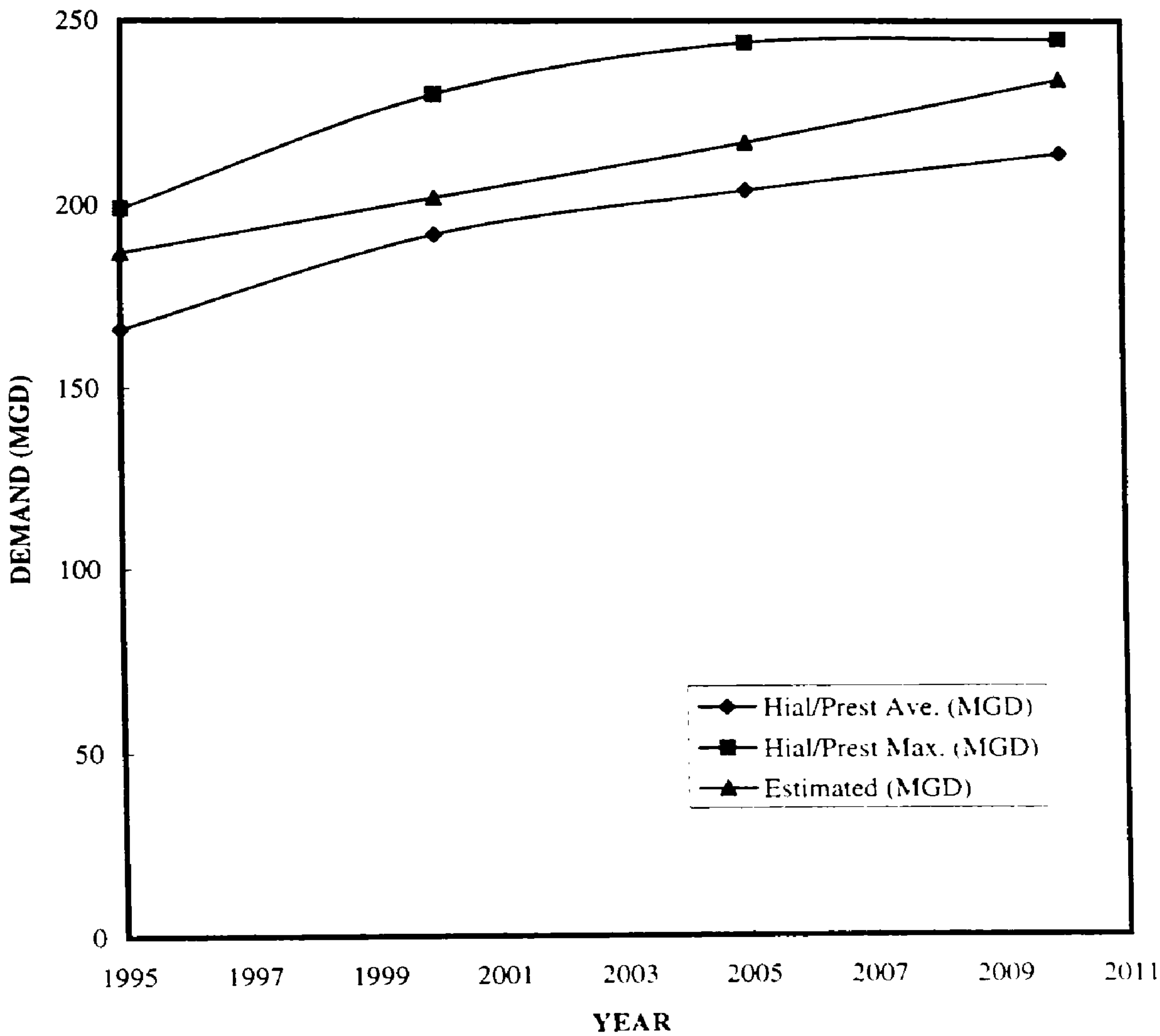


Figure 14. Estimated Population Served by Northwest Wellfield

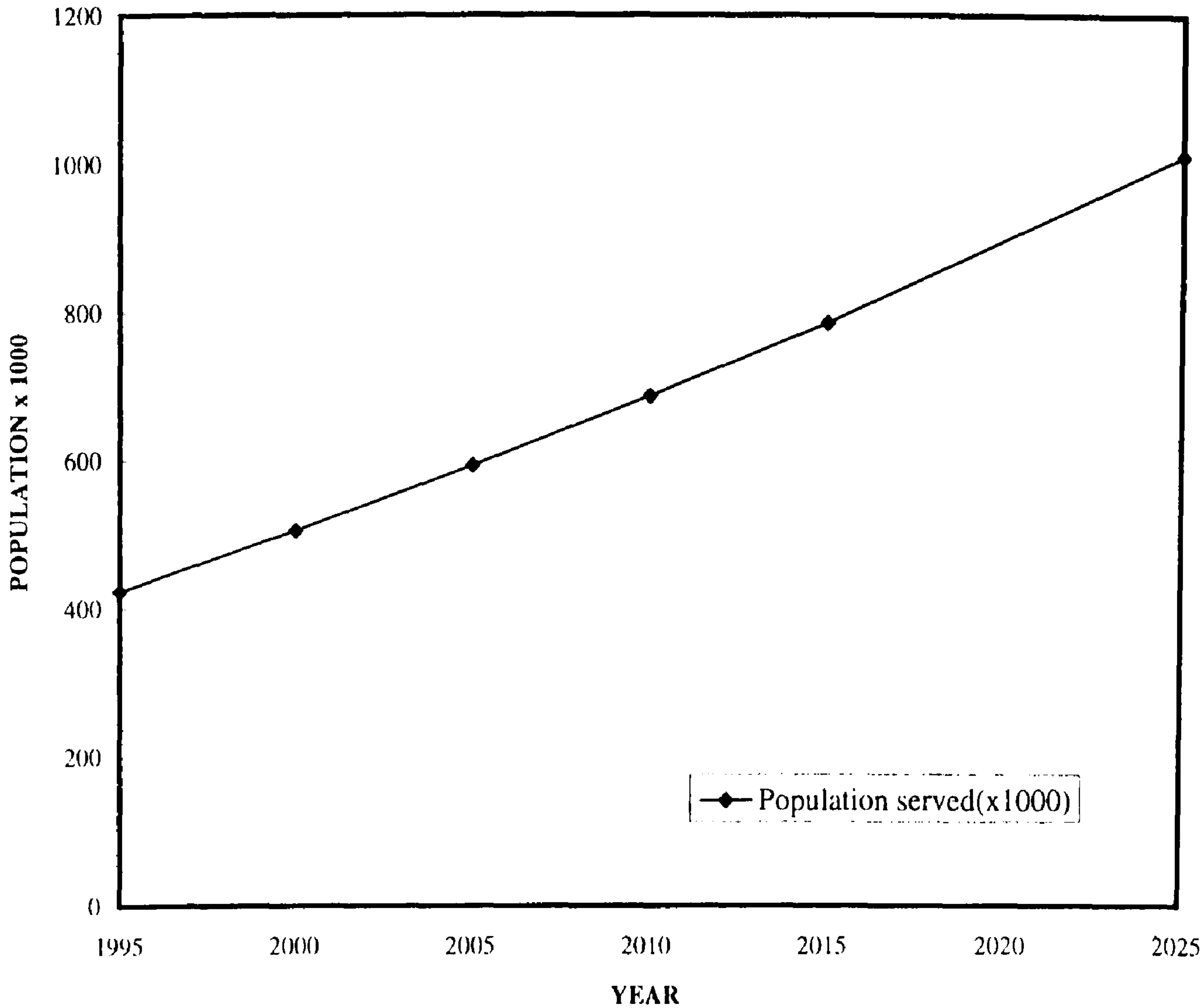
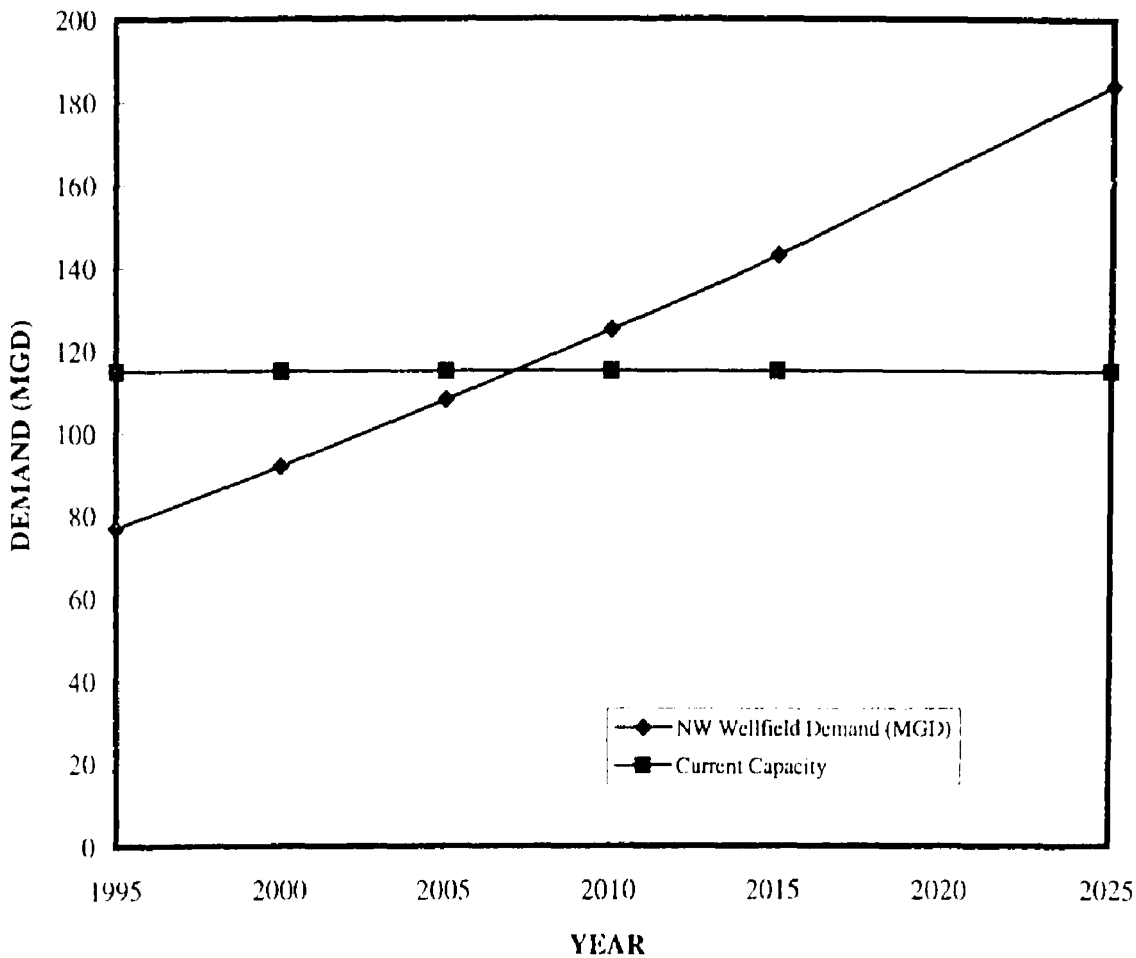


Figure 15. Estimated Northwest Wellfield Demand and Current Status



Consequently, the intersection of these two representative lines indicates that the wellfield capacity will be surpassed approximately by the year 2007. Figure 16 illustrates the estimated demand and population for the Hialeah/Preston Water Treatment Plant, as well as the Hialeah/Preston average and maximum demands obtained by MDWASAD. Figure 17 shows again the operating capacity of the wellfield along with the estimated projected demand for the Northwest Wellfield. In this case, the projected demand population served by the Northwest Wellfield is also shown. Consequently, Figure 17 shows that a maximum demand of 620,000 will be served by the Northwest Wellfield, by the time the estimated water demand surpasses the wellfield's operating capacity.

4.4 Description of General Data for the Northwest Wellfield.

The ambient groundwater flow was found from the United States Geological Survey (USGS) Map showing the prevailing groundwater flow directions for the study area. The ambient groundwater flow was obtained from a Fish and Stewart (1990) report entitled "Hydrogeology of the Surficial Aquifer System Dade County, Florida." Other related information was obtained from the Dade County Department of Environmental Regulation and Management. A regional hydraulic gradient for the Northwest Wellfield was determined from a groundwater level map which represented the dry season period for the month of April (Fish and Stewart, 1990). Therefore, the hydraulic gradient was computed at 0.004 ft/ft. Modeling scenarios were built around dry season information, because this represents a worst case scenario, where water availability is in less quantity and pumping is still fixed at the operating rate.

Figure 16. Estimated Population-Water Demand forHialeah/Preston Plant and Dade County Ave., Max. Demand

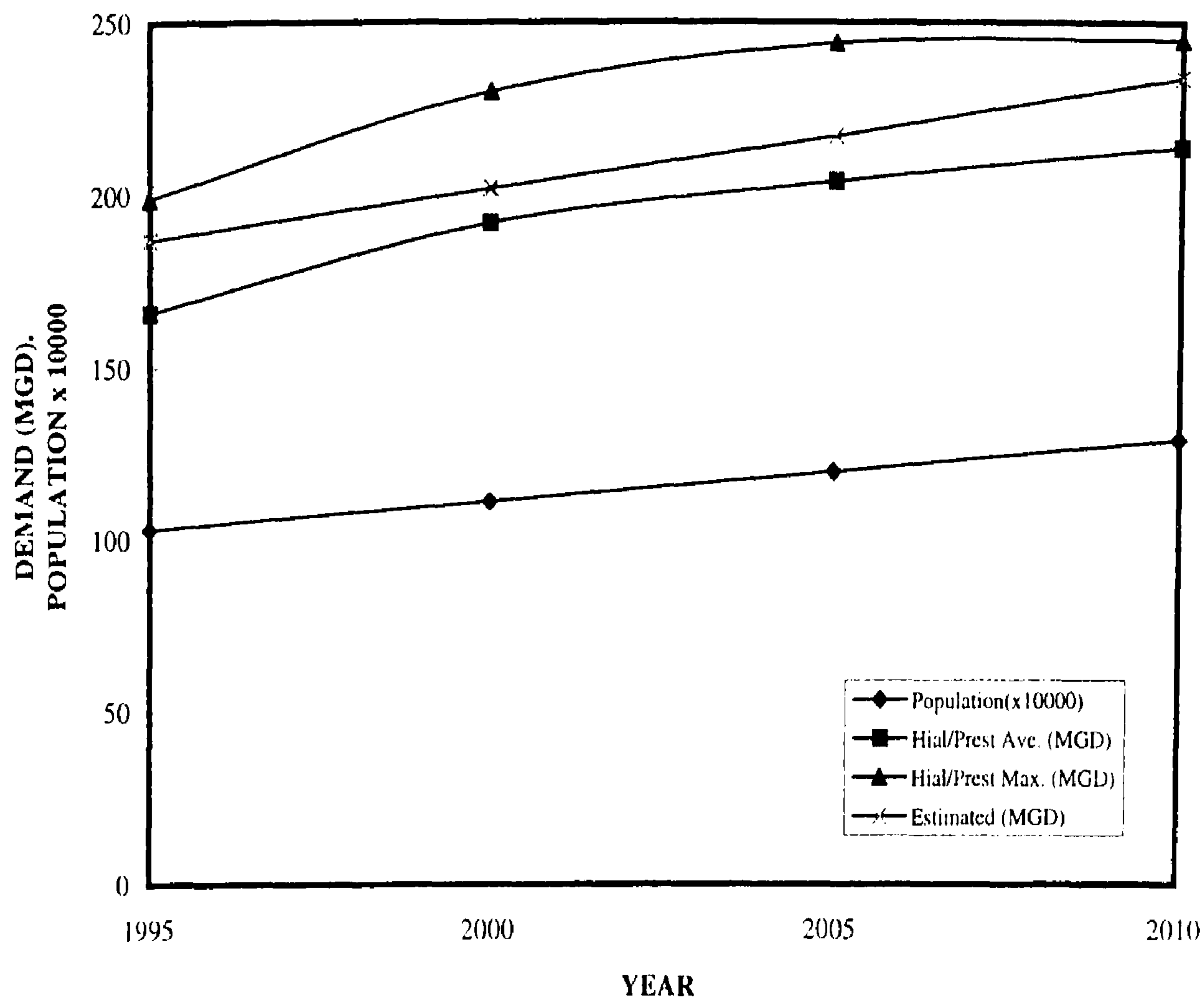
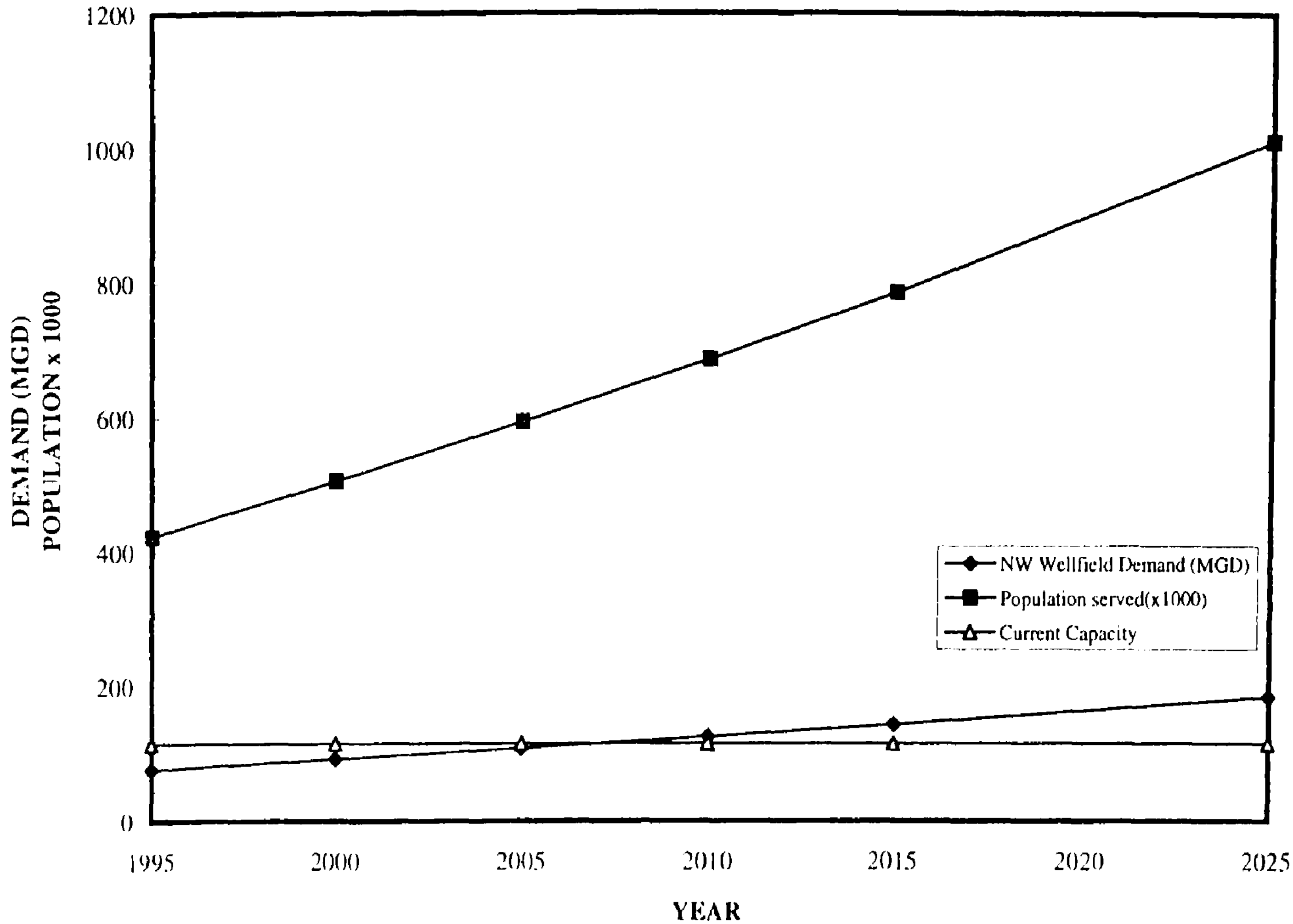


Figure 17. Estimated Water Demand, Population Served and Current Status for Northwest Wellfield



This causes the aquifer to become more sensitive to contaminants in small concentrations, because dilution effects have decreased, thus some contaminants can measure up to larger concentrations than the drinking water standard.

Some assumptions which must hold true for these models are the following: homogeneous aquifer, and steady-state uniform ambient groundwater flow. Table 12 contains general data used for all three modeling methods. Table 13 contains x and y plane coordinates for locations of each well.

Table 12. General Data for Modeling Protection Zones of the Northwest Wellfield.
(Source: DERM-GIS database system, 1994)

MIN. X-COORD (FT)*	815580
MAX. X-COORD (FT)*	885762
MIN. Y-COORD (FT)*	518027
MAX. Y-COORD (FT)*	594368

* *Florida State System*

Table 13. Well Coordinates
(Source: DERM-GIS database system, 1994)

Well No.	X-COORD (FT)	Y-COORD (FT)
1	848923	553032
2	848946	552256
3	848967	551457
4	848967	550658
5	849014	549996
6	849037	549288
7	849060	548512
8	847736	548444
9	847736	547713
10	847759	546937
11	847804	546183
12	847782	545430
13	847827	544677
14	847873	544015
15	847782	543011

4.5 Description of General Scenarios

The 15 production wells which make up the Northwest Wellfield are the study area on which three capture zone modeling methods are used, in order to estimate travel-time capture zones for the entire wellfield. One present (1995) and three future case scenarios for increasing water demands in years 2010, 2015 and 2025 are analyzed. From a study on population demand for the Hialeah/Preston Water Treatment Plant, it was estimated that the Northwest Wellfield demands for the years 2010, 2015, and 2025 are 125, 143, and 184 MGDs, respectively. These values are previously shown in Table 10. The modeling methods used were WHPA, WHAEM and the Calculated Fixed Radius Method. The different input parameters for each modeling method is shown in Table 14. The corresponding computer input files for WHPA and WHAEM are shown in Appendices A1 and A3, respectively. These three methods were used based on the time of travel criteria established by the Dade County Ordinance on wellhead protection zones. Captures zones for each model are developed according to the following time of travel criteria (shown in Table 15).

4.5.1 Modeling Scenario

Modeling of a conservative substance is assumed in order to obtain results describing a worst case scenario. The entire wellfield production rate is represented and replaced by one equivalent production well, with pumping rate equal to total demand (Q at 115, 125, 143, and 184 MGD).

Table 14. Input Parameters

Input Parameter	WHPA	WHAEM	Calculated Fixed Radius
Transmissivity	1300000 ft^2/day	N/A	N/A
Pumping Rate (Q)	115, 125, 143, and 184 MGD	115, 125, 143, and 184 MGD	115, 125, 143,and 184 MGD
Hydraulic Gradient	0.00036	0.00036	N/A
Porosity	0.2	0.2	0.2
Angle of Ambient flow	-5.0^0	-5.0°	N/A
Aquifer Thickness	150 ft	45.7 m	N/A
Boundary Type	No Boundary	No Boundary	N/A
Capture Zone	Time Related (days)	Time Related (days)	Time Related (days)
Aquifer Type	Unconfined	Unconfined	Unconfined
Length of Well Screened	N/A	N/A	40 ft
Permeability	N/A	2,641 m/day	N/A

*N/A: Not Applicable

Table 15. Time of Travel Criteria for Developing Capture Zones

CAPTURE ZONE NO.	TIME OF TRAVEL (DAYS)
1	10
2	30
3	100
4	210
5	500

An equivalent well pumping at a rate Q is superimposed upon the regional system. In using the three modeling methods, described previously, a single well analysis is preferred, since superposition of capture zones for each well individually tend to show deviation from actual results due to overlap of capture zones. The Northwest Wellfield has 15 wells spaced close together, thus causing capture zone overlap. Consequently, all 15 wells were represented by a single well. A similar study done by McElwee (1991) demonstrates the actual case of capture zone overlapping. In the Northwest Wellfield, the location of an equivalent well representing the entire wellfield is assumed to be midway along the existing wellfield distribution. The x-coordinate is 848398 ft and y-coordinate 548478 ft. The single well comparison of all three methods was chosen due to the fact that two of the three methods cannot account for well interference, these being WHAEM and the Calculated Fixed Radius Method. This modeling scenario also takes into consideration that the capture zones are determined based on the travel time of groundwater flow and the pumping rate, which is a more realistic and conservative approach. If the drawdown criterion was considered, the location of the well would not seem reasonable, instead drawdown superposition would be used in order to find a location x and y for a well representing the entire system of wells. Table 16 shows the case scenario for each model run.

4.6 Land Use at the Northwest Wellfield

The Northwest wellfield land use area is dictated by the Comprehensive Development Master Plan (CDMP) Land Use Plan Map of the Dade County Zoning Code, Chapter 33

Table 16. Modeling Scenario for an Equivalent Well

CASE SCENARIO	YEAR	Q (DEMAND) (MGD)
1	1995	115
2	2010	125
3	2015	143
4	2025	184

and the Dade County Environmental Regulations, Chapter 24-12.1 Potable Water Supply Wellfield Protection Ordinance (DERM, 1984). The zoning area of the Northwest Wellfield can be divided into two areas, east and west of the HEFT. The area to the west of HEFT is zoned as open space, as specified by the CDMP land use Plan Map. This is important because most of the groundwater flow comes from the western part of the cone of influence of the wellfield. The area east of the wellfield is zoned as commercial and industrial, as follows (refer to Figure 18):

IU-1	Industrial, light manufacturing district (e.g., warehouses).
BU-1	Neighborhood business district (e.g., restaurants).
BU-2	Special business or regional shopping center (e.g., drug store).
BU-3	Liberal business district (e.g., paint store).
OPD	Office park district (e.g., office buildings).

Table 17 illustrates the different existing land uses east of HEFT, and Table 18 shows the 1983 Ordinance on Wellfield Protection Zones. It is important to note that these commercial/industrialized areas keep growing westerly, which could pose a potential threat to the wellfield. Future urban type development in the Northwest wellfield could bring in several types of contaminating sources such as sewer lines, septic tanks and stormwater runoff. Nearby areas in the Northwest Wellfield are presently being used for quarrying of limestone which is used as fill material in Florida and for cement manufacturing (Page, 1987).

Figure 18. Dade County Land Use Map
(Source: Metro-Dade Planning, 1994)

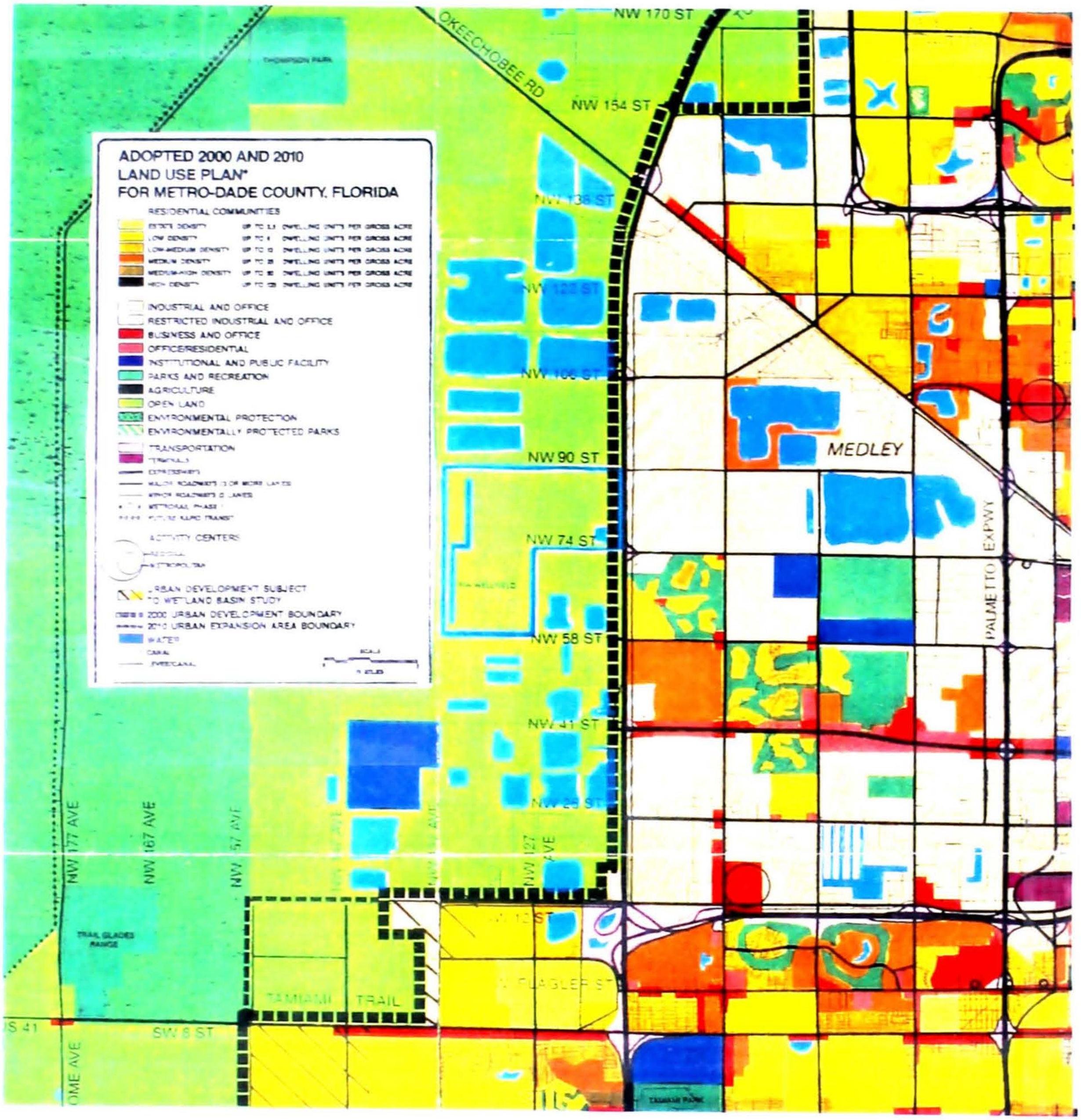


Table 17. Land Uses in the Northwest Wellfield (East of HEFT)
(Source: Chapter 33, Metropolitan Dade County & Zoning Manual.)

USE	ZONING DISTRICT				
	OPD	BU-1	BU-2	BU-3	IU-1
Office Buildings	x	x	x	x	x
Medical Office, Clinic	x	x	x	x	x
Restaurant		x	x	x	x
Beauty Parlor		x	x	x	
Drug Store		x	x	x	
Dry Cleaning		x	x	x	
Paint Store		x	x	x	
Car Wash			x	x	
Gas Station/repairs			x	x	
Liquor Store			x	x	
Pool Supplies			x	x	
Veterinarians/Medical Labs			x	x	
Photo Developing			x	x	x
Major Shopping Stores			x	x	
Contractors Storage Yards				x	x
Exterminators/Insecticides				x	x
Lumber Yards				x	x
Electroplating					x
Food Processing					x
Storage Warehouses					x

Table 18. 1983 Ordinance on Wellfield Protection Zones

(Source: DERM, 1984)

Regulated Activity	**< 100 ft**	**100ft-10d**	**10 - 30d**	**30 - 100d**	**100 - 210d**	**> 210d**
New uses involving handling of hazardous material	Prohibited	Prohibited	Prohibited	Prohibited	Prohibited	Permitted
Res./septic tanks	Prohibited	1 DU/2.5ac.	1 DU/ac.	1.7 DU/ac.	2.4 DU/ac.	2.9 DU/ac.
Non-res. use/septic tanks	Prohibited	1400 ft^2/ acre	3500 ft^2/acre	6000 ft^2/acre	8500 ft^2/acre	15000 ft^2/acre
Res./sewers	Prohibited	2.4 DU/ac.	4.6 DU/ac.	No Limit	No Limit	No Limit
Non-res. use/sewers	Prohibited	8500 ft^2/acre	16000 ft^2/acre	No Limit	No Limit	No Limit

DU = dwelling unit

V. RESULTS AND DISCUSSION OF CAPTURE ZONE MODELING FOR THE NORTHWEST WELLFIELD

5.1 Modeling Results for the Calculated Fixed Radius Method

For years 1995, 2010, 2015, and 2025, the estimated water demands are 115 MGD, 125 MGD, 143 MGD and 184 MGD, respectively. The calculated radius for each case scenario are shown in Table 19. These results were calculated using Equation 11, the volumetric flow equation. Curves are plotted which illustrate the relationship between pumping rate and the calculated radii for the different times of travel. From these curves any pumping rate can be depicted and matched with the corresponding radius. Figures 19 through 23, illustrate graphs for predicted pumping rates versus radius for all 4 demands and respective travel time.

Figures 24 through 27 show plots which represent each case scenario illustrated previously in Table 16. Plotted results indicate that protection zones for 210-day and 500-day travel time capture zones are well beyond the Florida Turnpike groundwater divide, thus resulting in a high possibility for contamination of the wellfield. Figure 28, shows a sizable comparison of 500-day capture zones for 115 MGD (1995) and 184 MGD (2025).

5.2 Modeling Results for WHPA

Time related capture zones for the Northwest Wellfield are delineated using the Multiple Well Capture Zone Module (MWCAP) from the WHPA model. A time related capture

Table 19. Calculated Fixed Radius for Modeling Scenario

Travel Time / Q (MGD)	10 days	30 days	100 days	210 days	500 days
115	2,473	4,284	7,821	11,333	17,487
125	2,578	4,466	8,154	11,816	18,232
143	2,758	4,777	8,721	12,638	19,501
184	3,128	5,418	9,893	14,336	22,120

*Radius in ft.

Figure 19. Predicted Radius as Function of Pumping Rate for a 10-Day Traveling Time Scenario

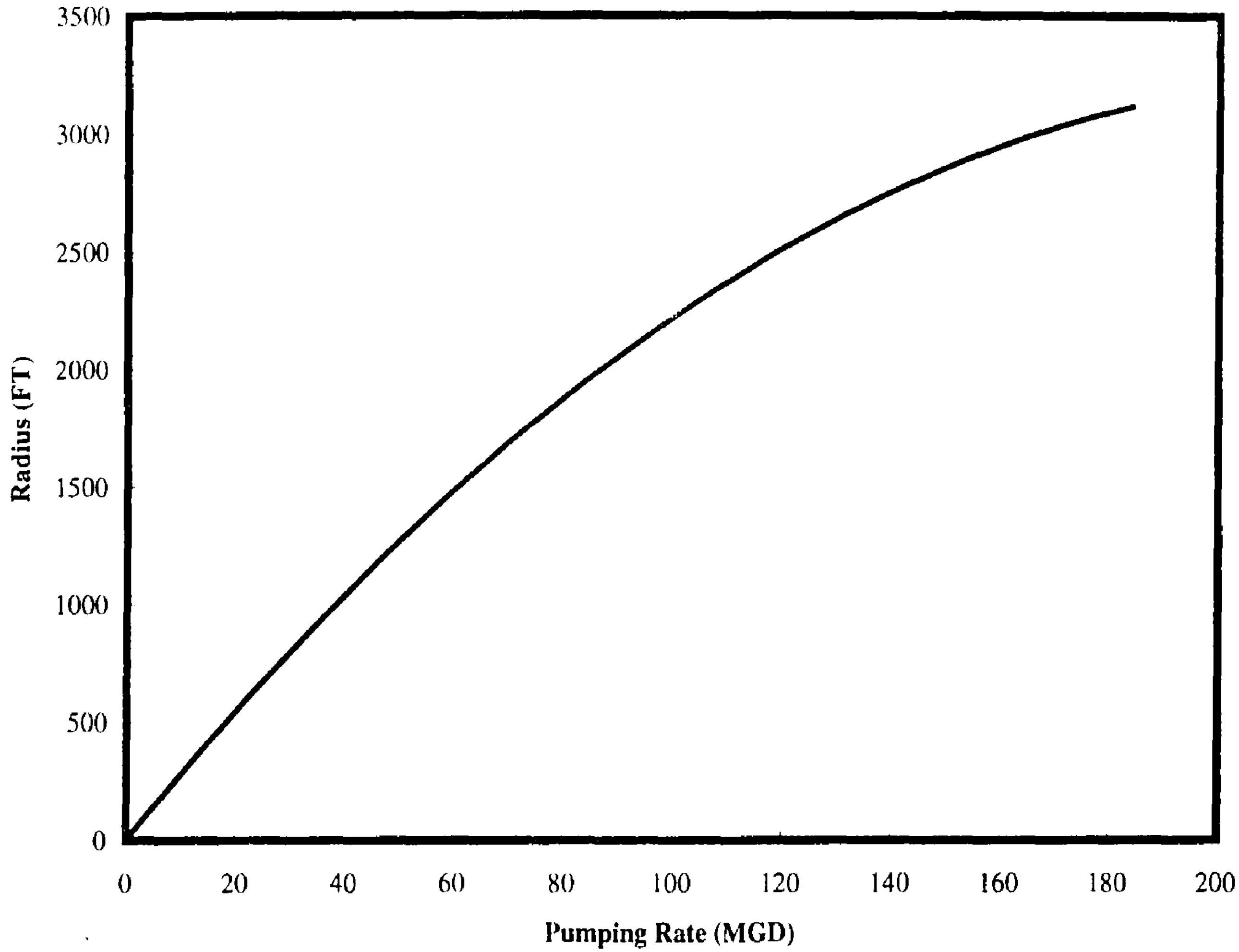


Figure 20. Predicted Radius as Function of Pumping Rate for a 30-Day Traveling Time Scenario

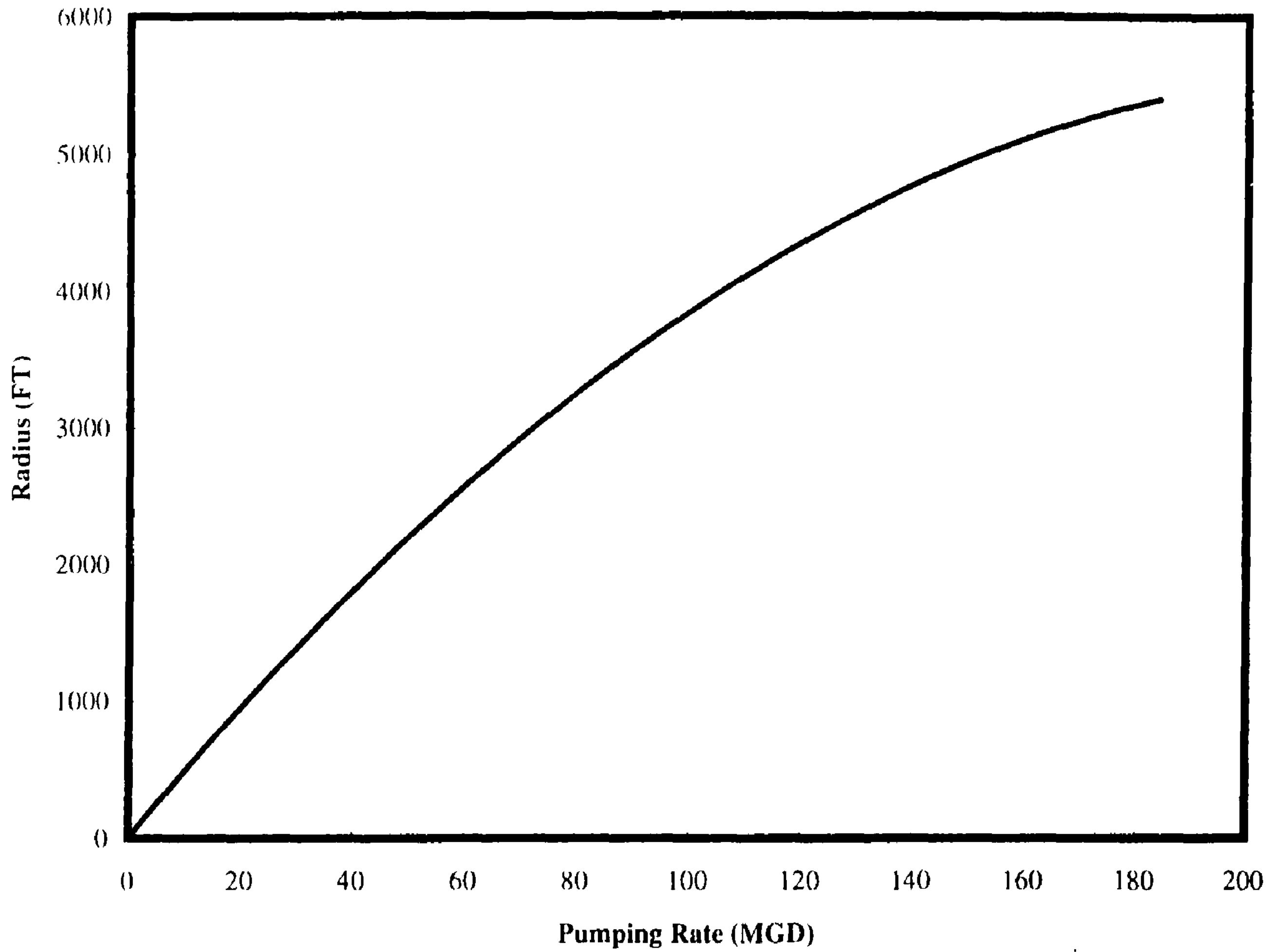


Figure 21. Predicted Radius as Function of Rate for a 100-Day Traveling Time Scenario

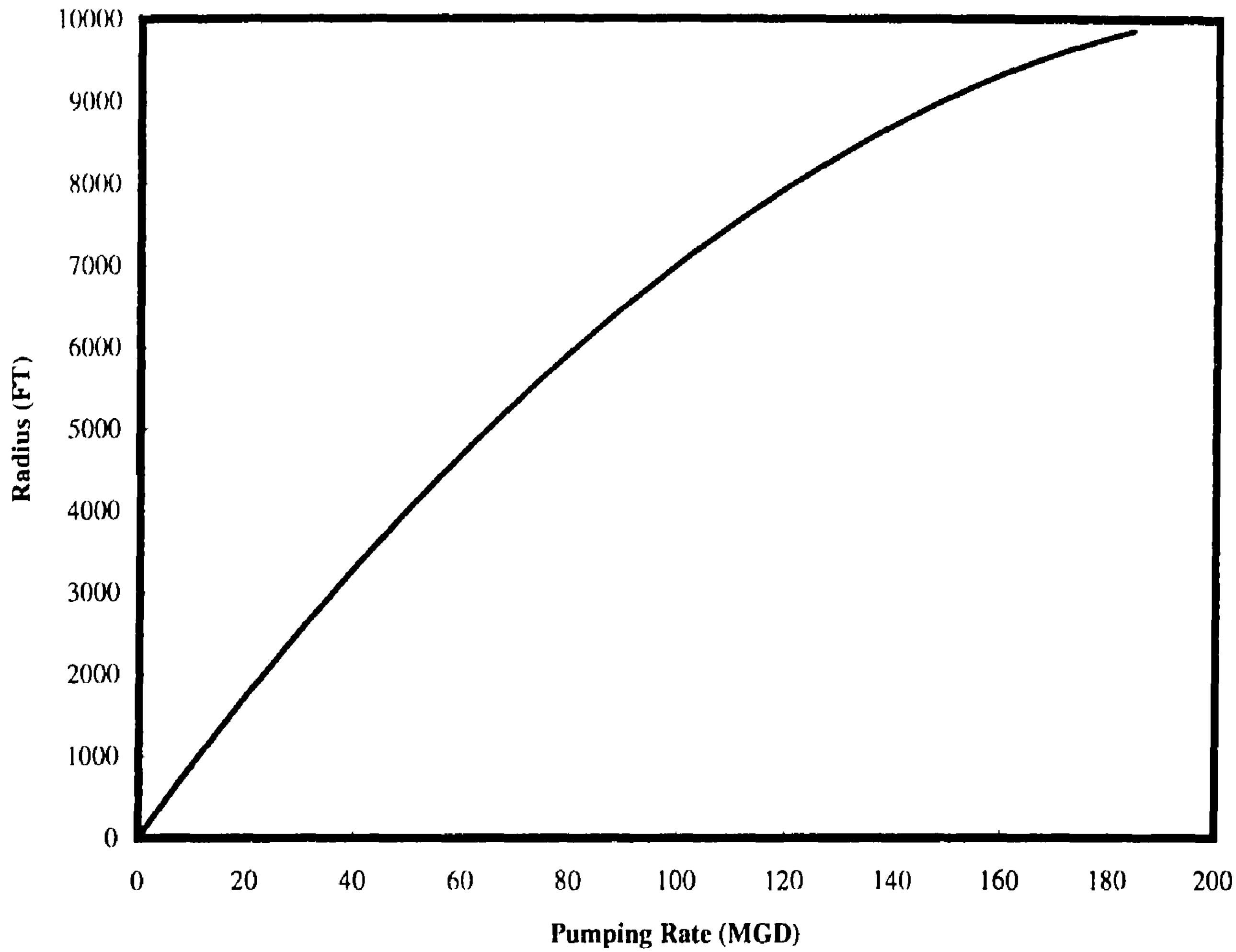


Figure 22. Predicted Radius as Function of Pumping Rate for a 210-Day Traveling Time Scenario

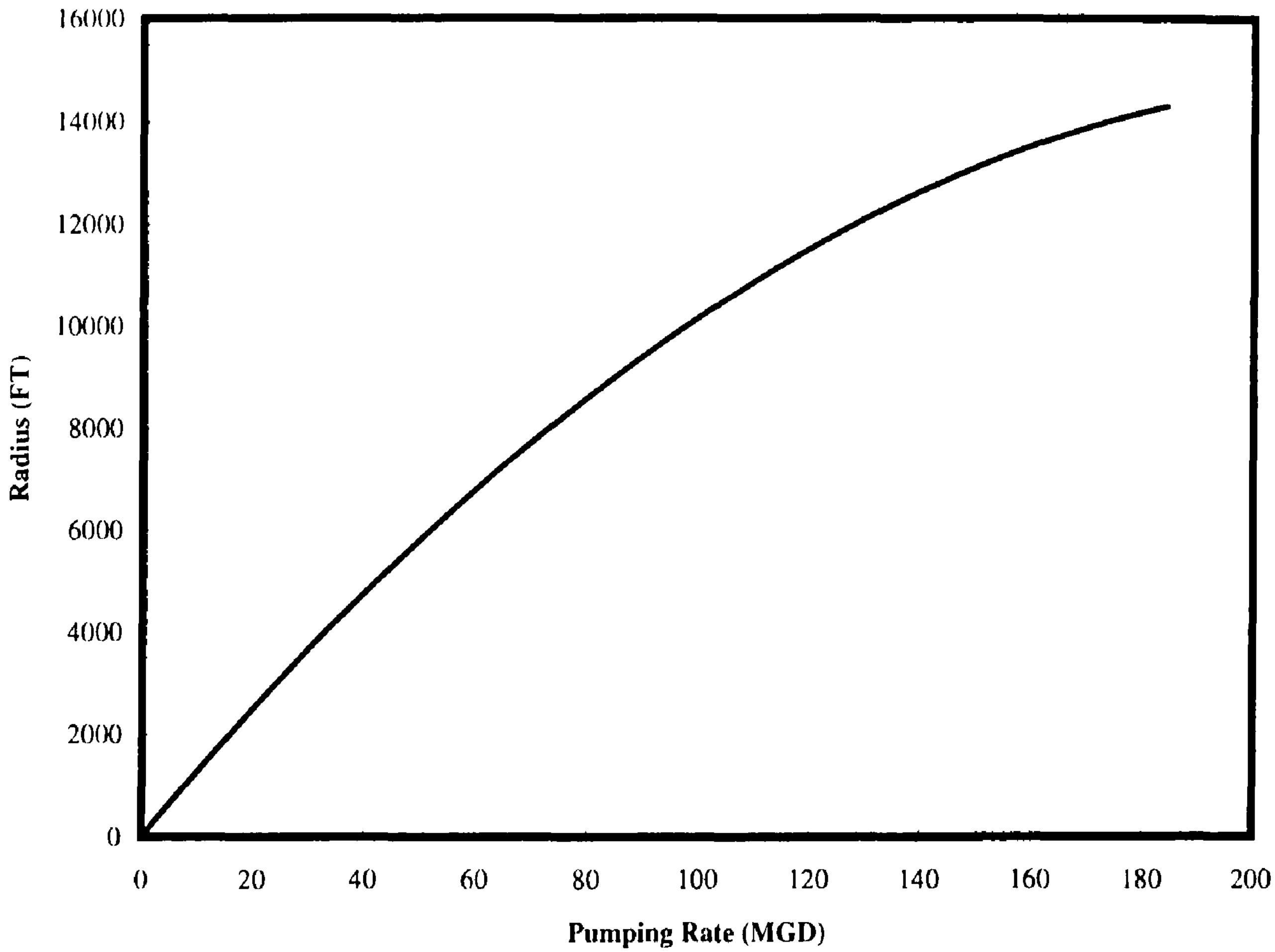


Figure 23. Predicted Radius as Function of Pumping Rate for a 500-Day Traveling Time Scenario

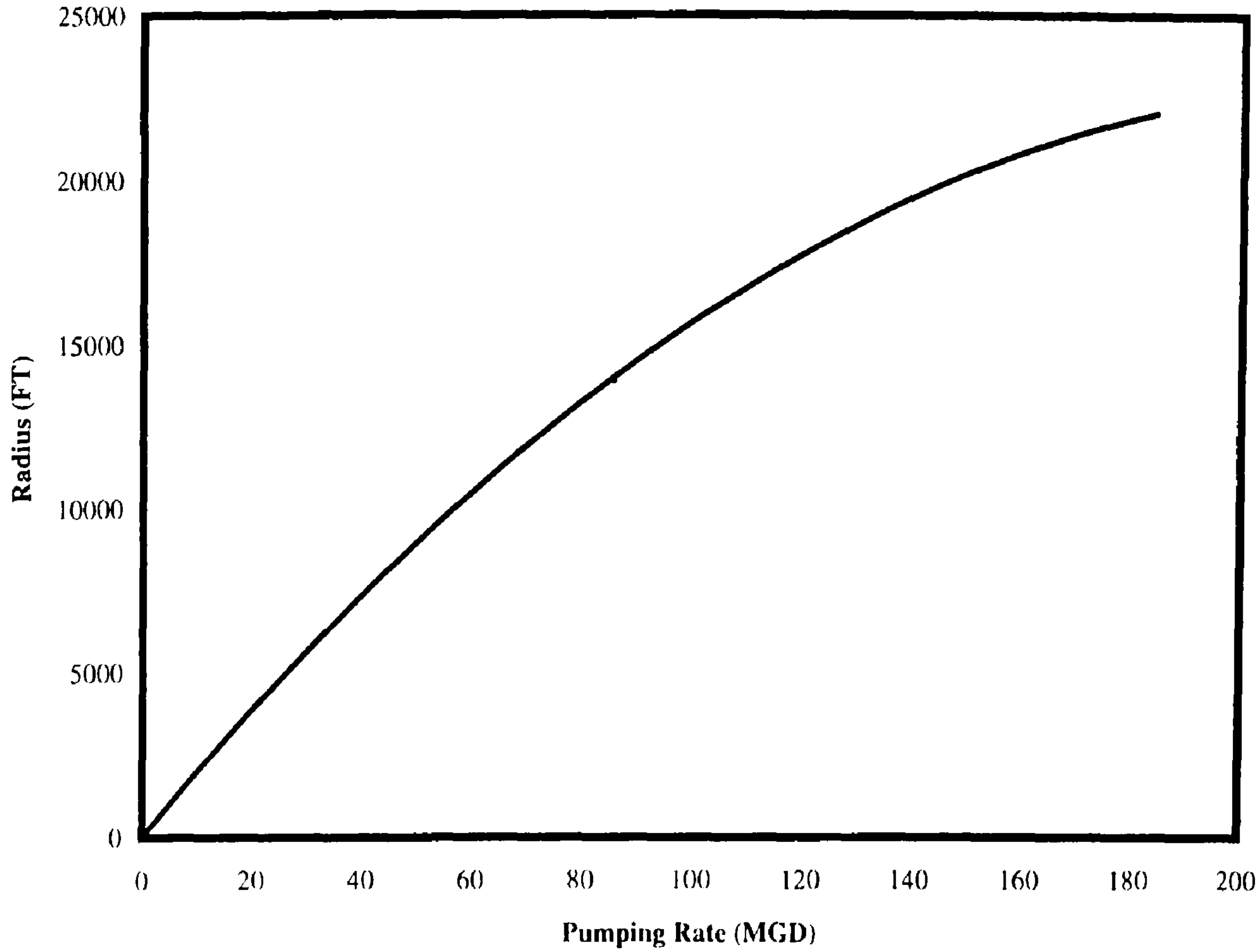


FIGURE 24 OVERLAY OF DADE COUNTY ZONING ACTIVITIES AND THE NW WELLFIELD TRAVEL TIME CAPTURE ZONES USING THE CALCULATED FIXED RADIUS METHOD AT 115 MGD FOR 1995.

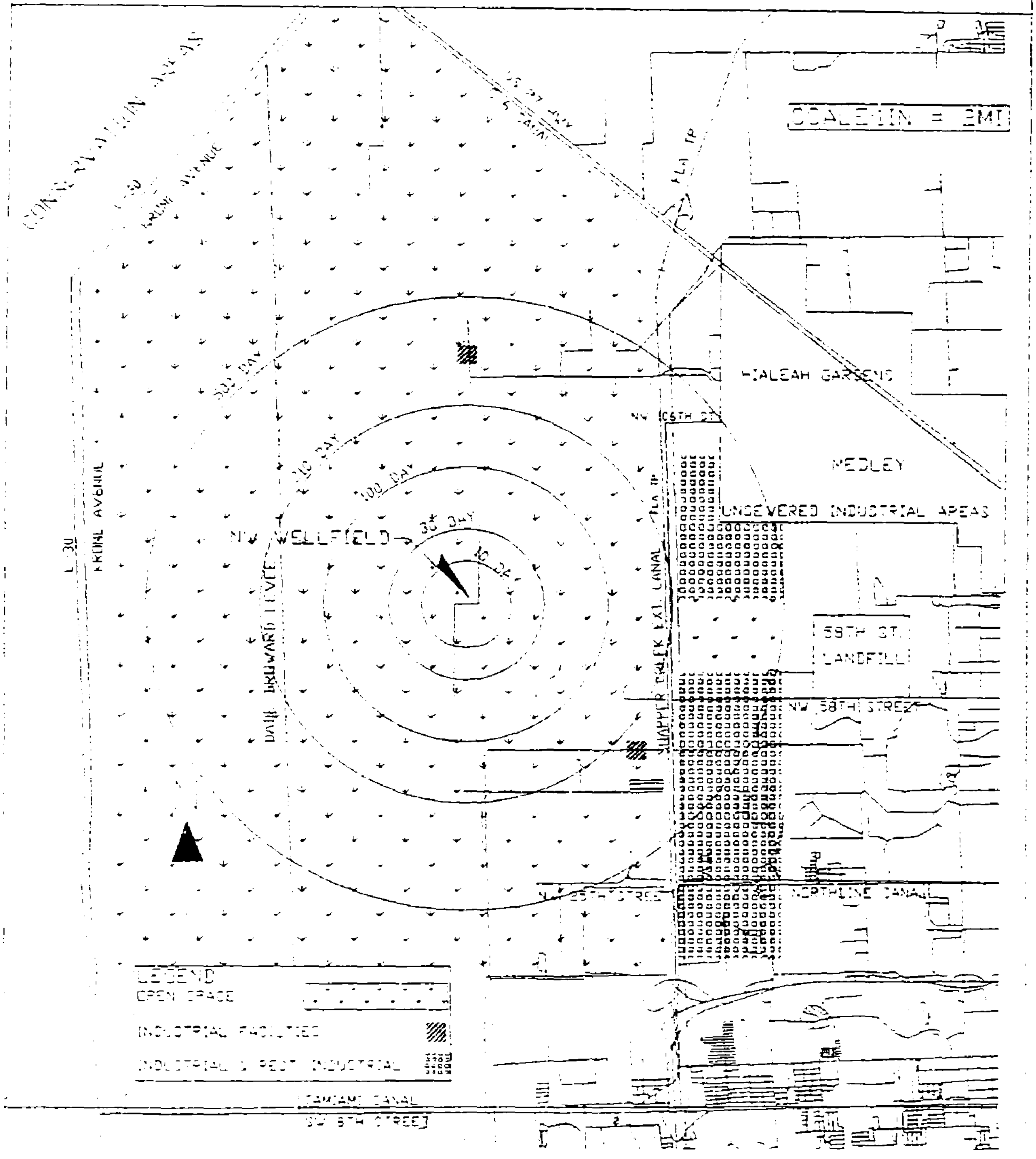


FIGURE 25. OVERLAY OF DADE COUNTY ZONING ACTIVITES AND THE NW WELLFIELD TRAVEL TIME CAPTURE ZONES USING THE CALCULATED FIXED RADIUS METHOD AT 125 MGD FOR 2010

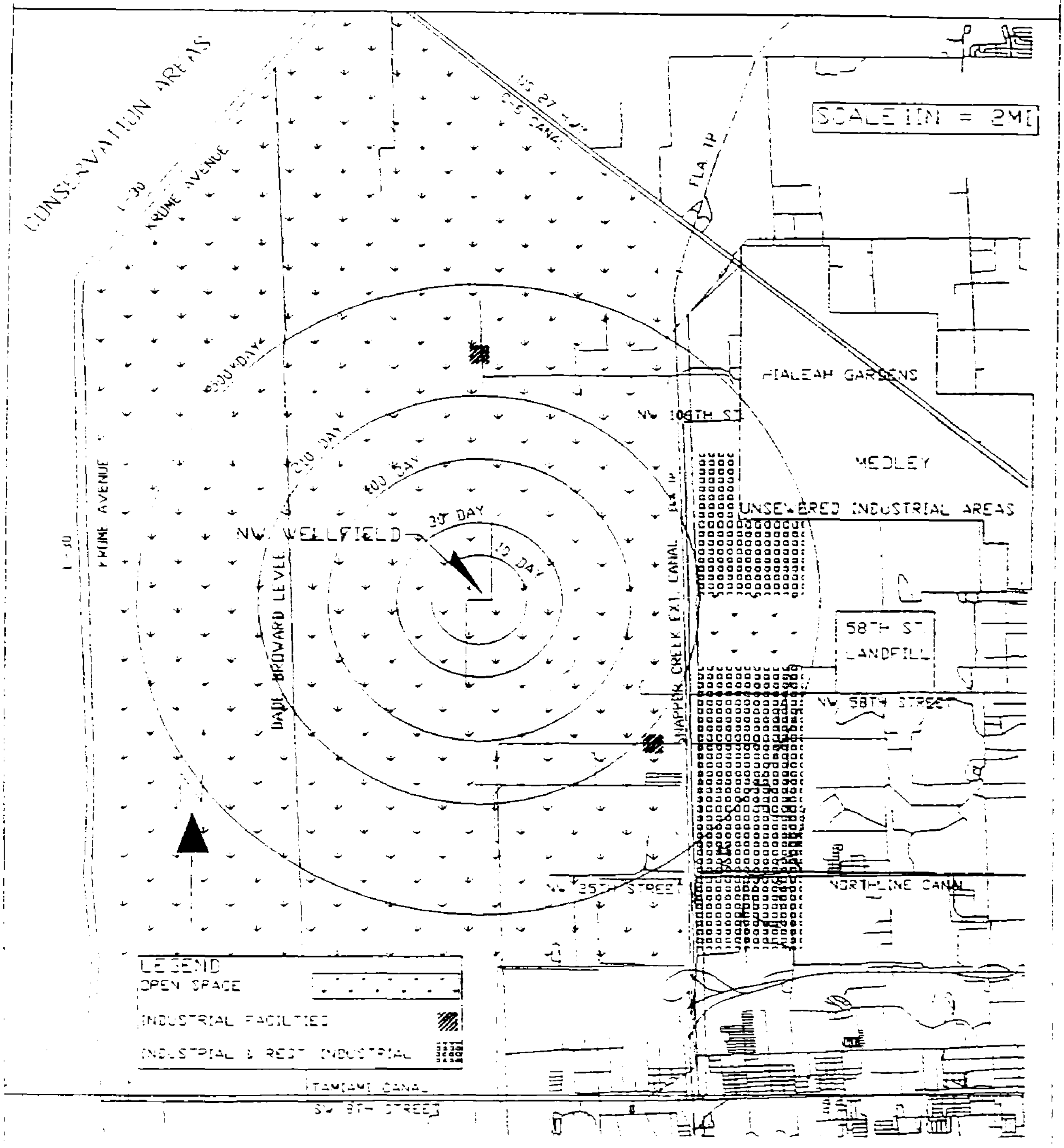


FIGURE 26. OVERLAY OF DADE COUNTY ZONING ACTIVITES AND THE NW WELLFIELD TRAVEL TIME CAPTURE ZONES USING THE CALCULATED FIXED RADIUS METHOD AT 143 MGD FOR 2015

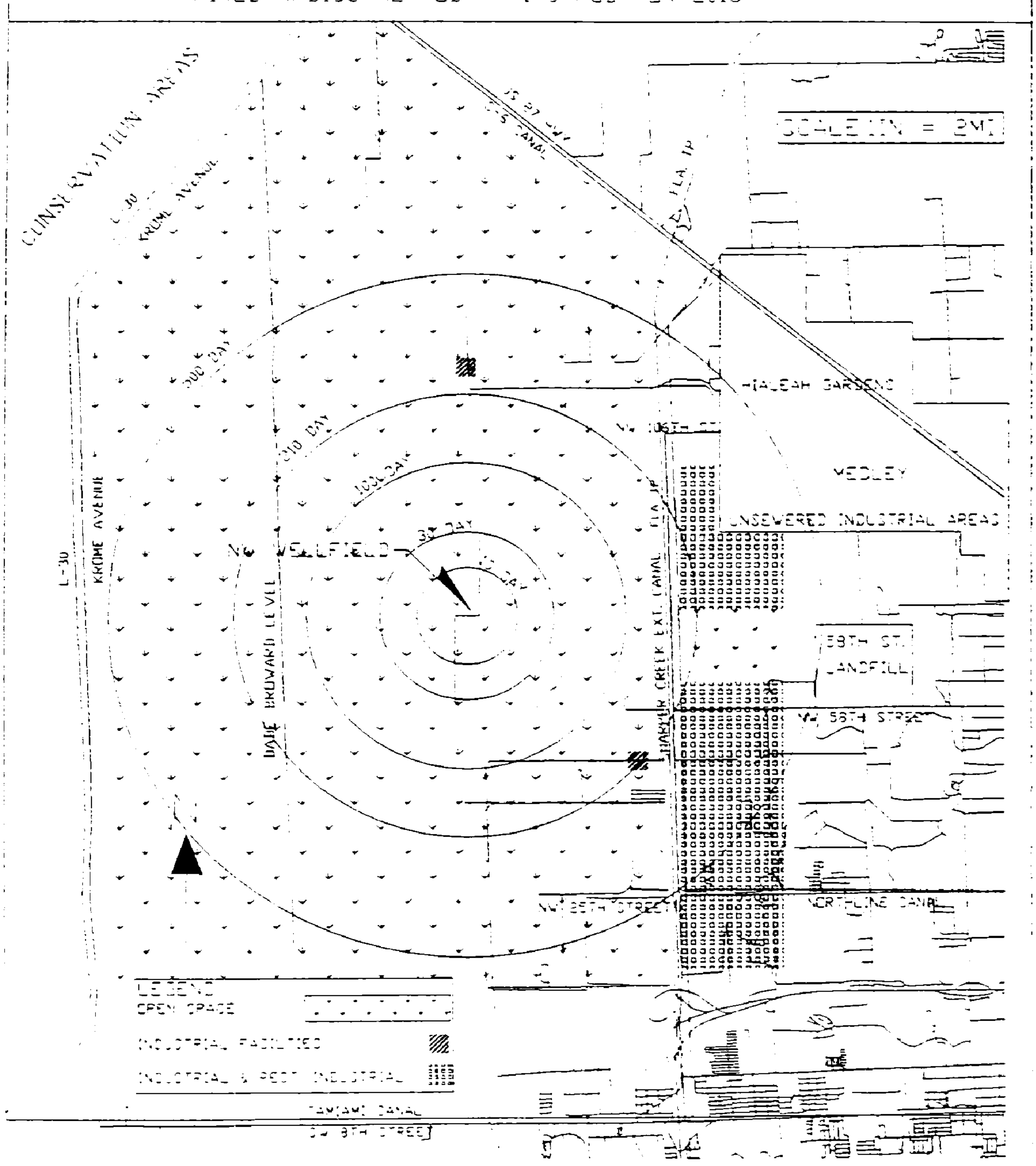


FIGURE 27 OVERLAY OF DADE COUNTY ZONING ACTIVITIES AND THE NW WELLFIELD TRAVEL TIME CAPTURE ZONES USING THE CALCULATED FIXED RADIUS METHOD AT 184 MGD FOR 2025

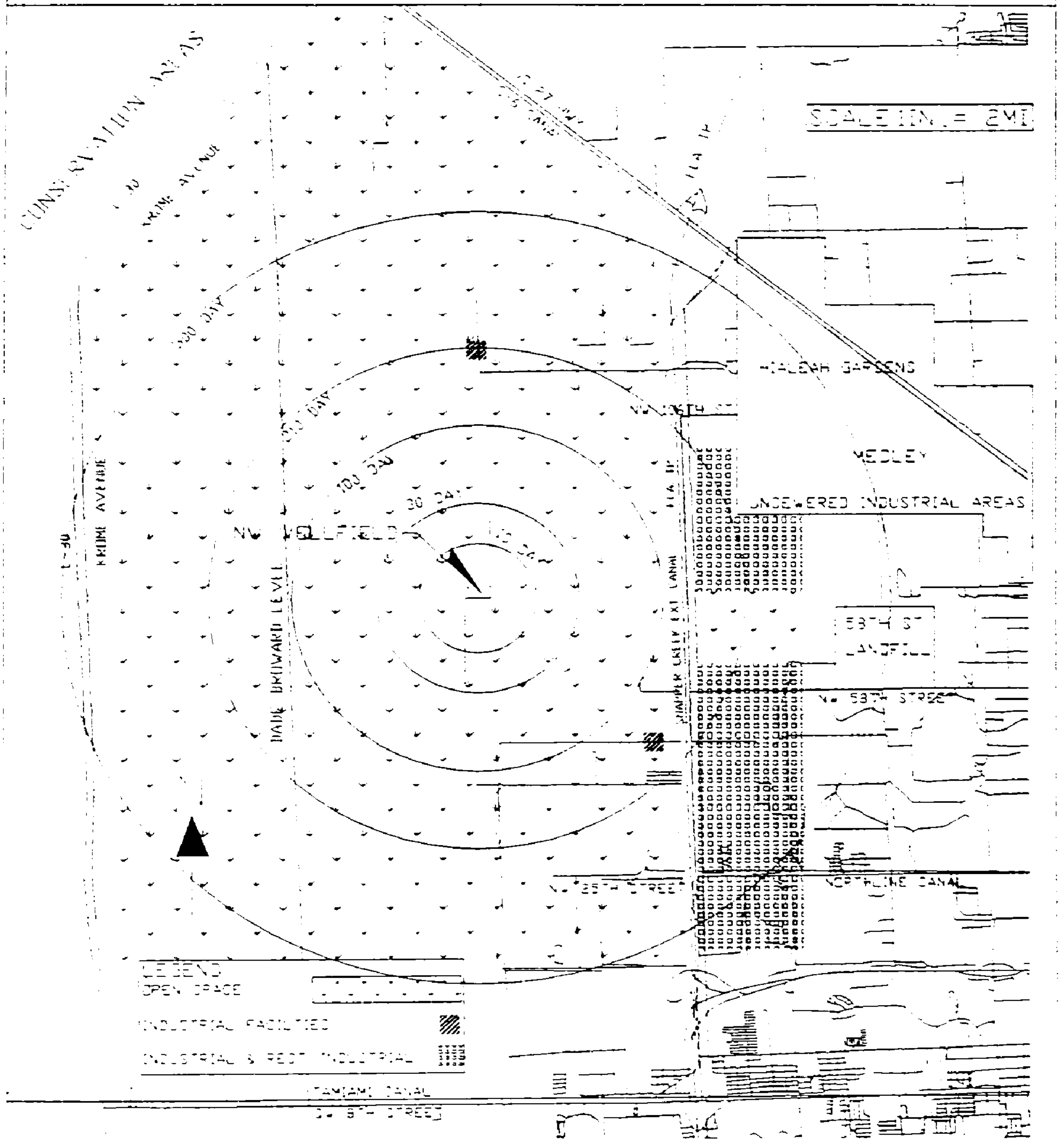
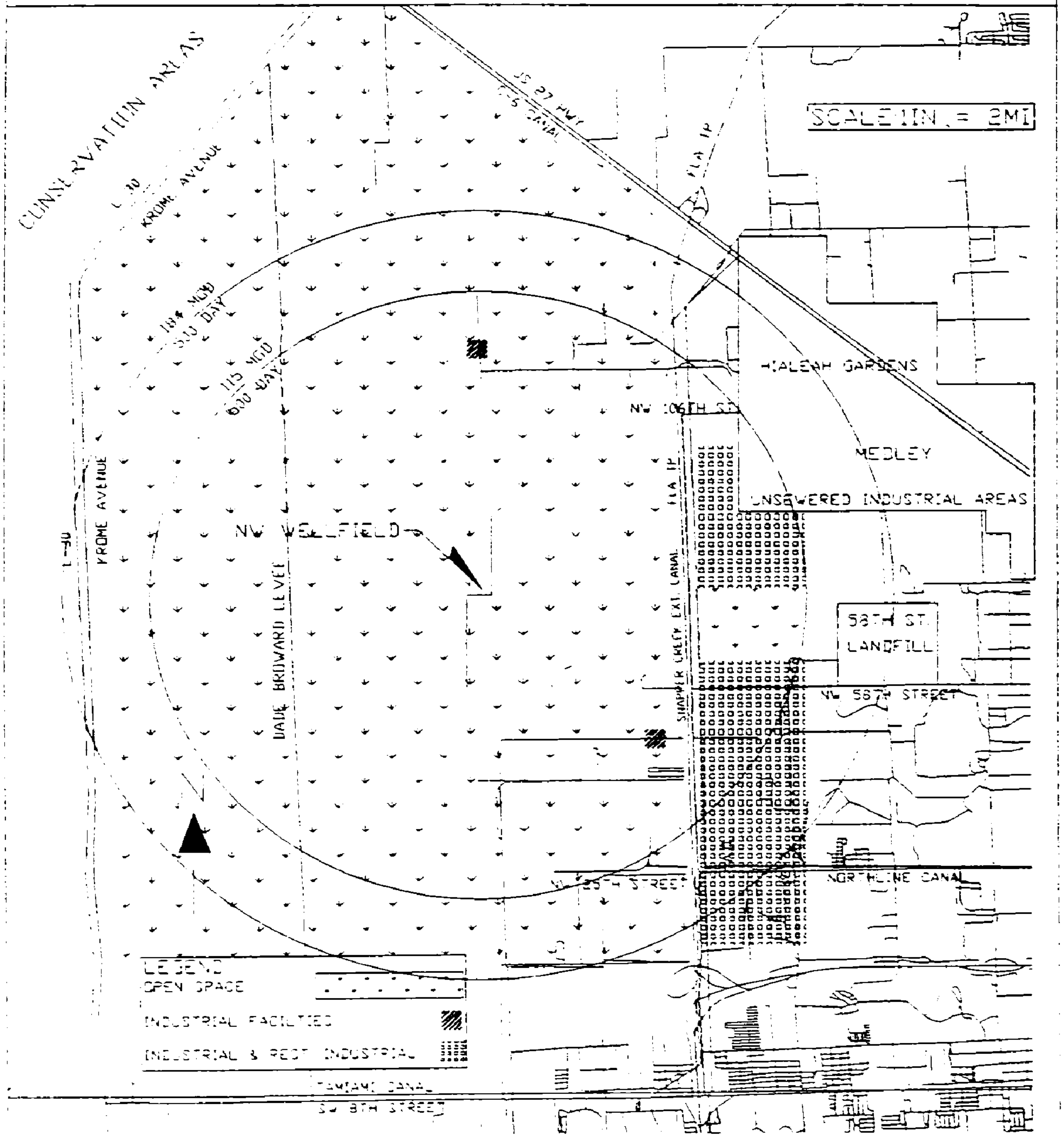


FIGURE 28. 500 DAY TRAVEL TIME CAPTURE ZONES FOR NW WELLFIELD AT 115 MGD FOR 1995 AND 184 MGD FOR 2025



zone is essentially the area surrounding the pumping well which is contributing groundwater to a well for some specific time period. MWCAP delineates steady-state and time related capture zones. Well interference is ignored. A steady-state solution can also be obtained which illustrates the delineated surrounding area for a well with pumping time period equal to infinity.

Figures 29, 30, 31, and 32 illustrate the delineated capture zones for each case scenario illustrated previously in Table 16. Each capture zone shows pathlines which indicate the direction of groundwater flow to the well. The steady state solution is also shown which comprises the ZOC. The overlay of these plots on the existing land use base map shows that for demands of 115 and 125 MGDs there is no potential threat of any contamination on site. However, at a demand of 184 MGD (Figure 32), the 500-day protection zone and the steady state solution are near to two industrial facilities present. Thus, there is potential threat to the water supply. The industrial facilities lie close to the ZOC. Figure 33 shows a comparison of 500-day protection zones for demands at 115 MGD and 184 MGD. This indicates that by the year 2025 the 500-day protection zone will increase in size due to increase in wellfield pumpage.

5.3 Modeling Results for WHAEM.

WHAEM is used to delineate time related capture zones which define stagnation points. Also the ZOC for the wellfield is determined. The executable CZAEM from the WHAEM model uses a superposition of the closed form analytical solution to obtain a

FIGURE 29 OVERLAY OF DADE COUNTY ZONING ACTIVITES AND THE NW WELLFIELD TRAVEL TIME CAPTURES ZONES USING THE WHPA MODELING METHOD AT 115 MGD FOR 1995

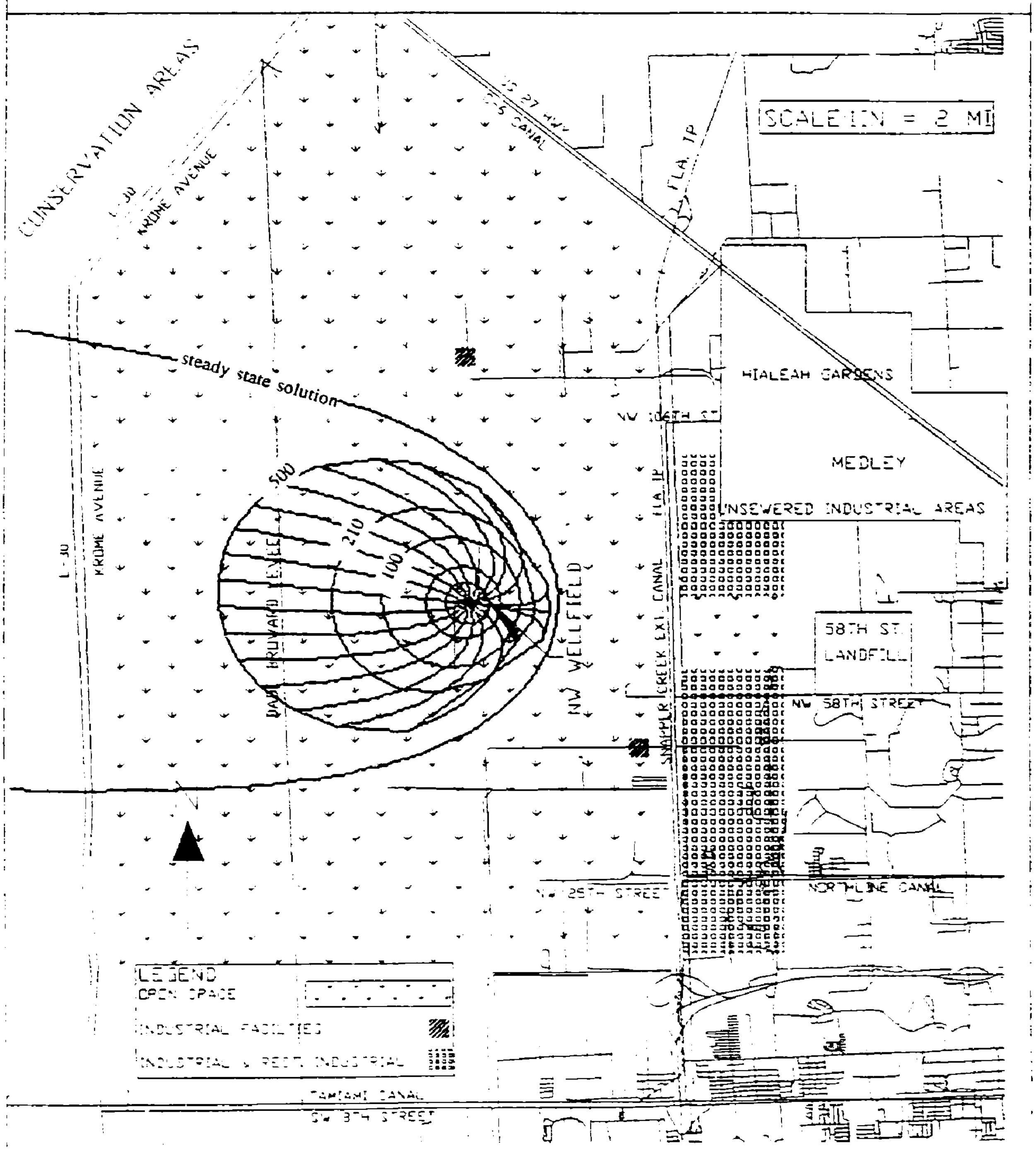


FIGURE 30 OVERLAY OF DADE COUNTY ZONING ACTIVITIES AND THE NW WELLFIELD TRAVEL TIME CAPTURED ZONES USING THE WHPA MODELING METHOD AT 125 MGD FOR 2010

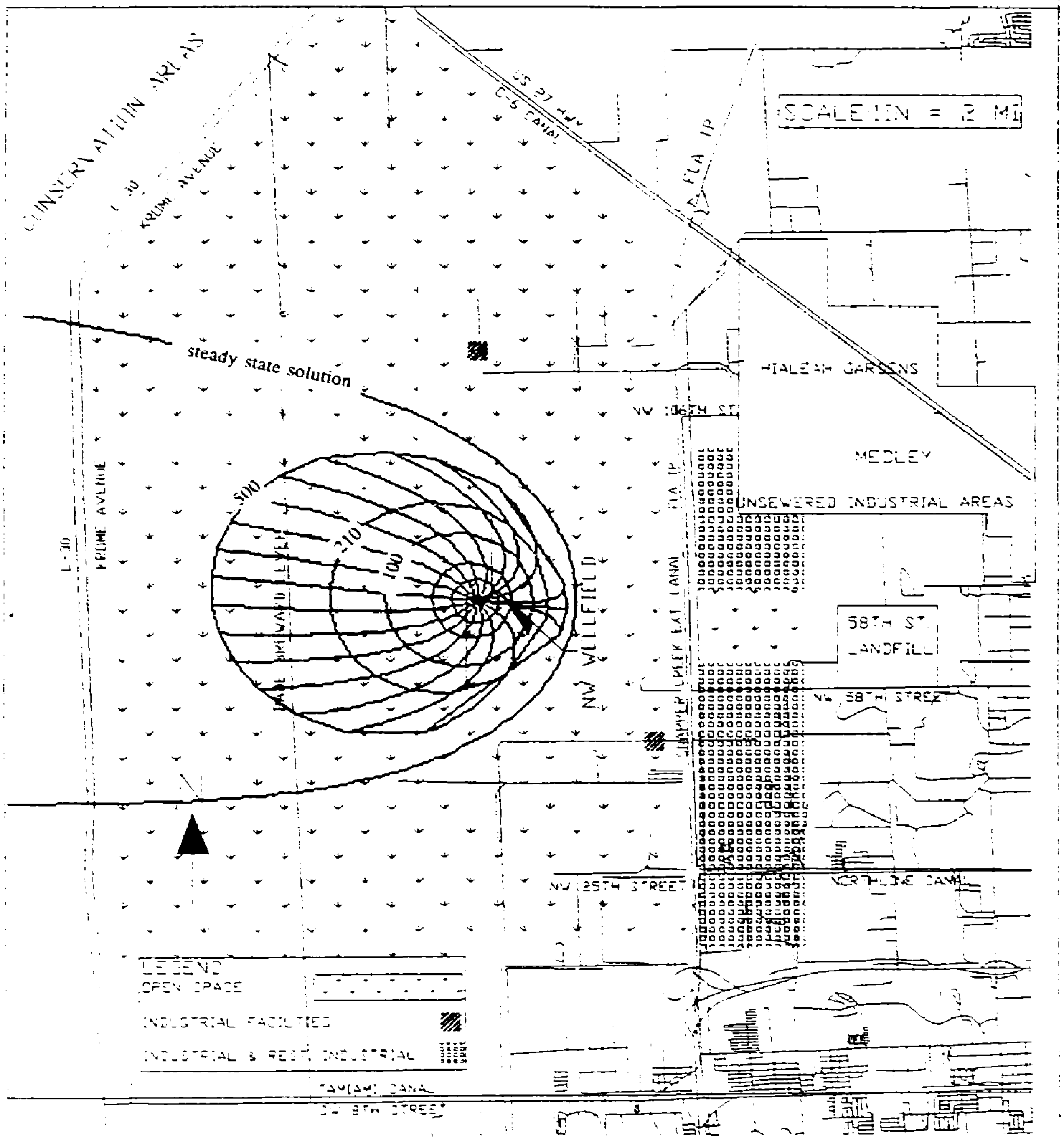


FIGURE 31. OVERLAY OF DADE COUNTY ZONING ACTIVITES AND THE NW WELLFIELD TRAVEL TIME CAPTURES ZONES USING THE WHPA MODELING METHOD AT 143 MGD FOR 2015

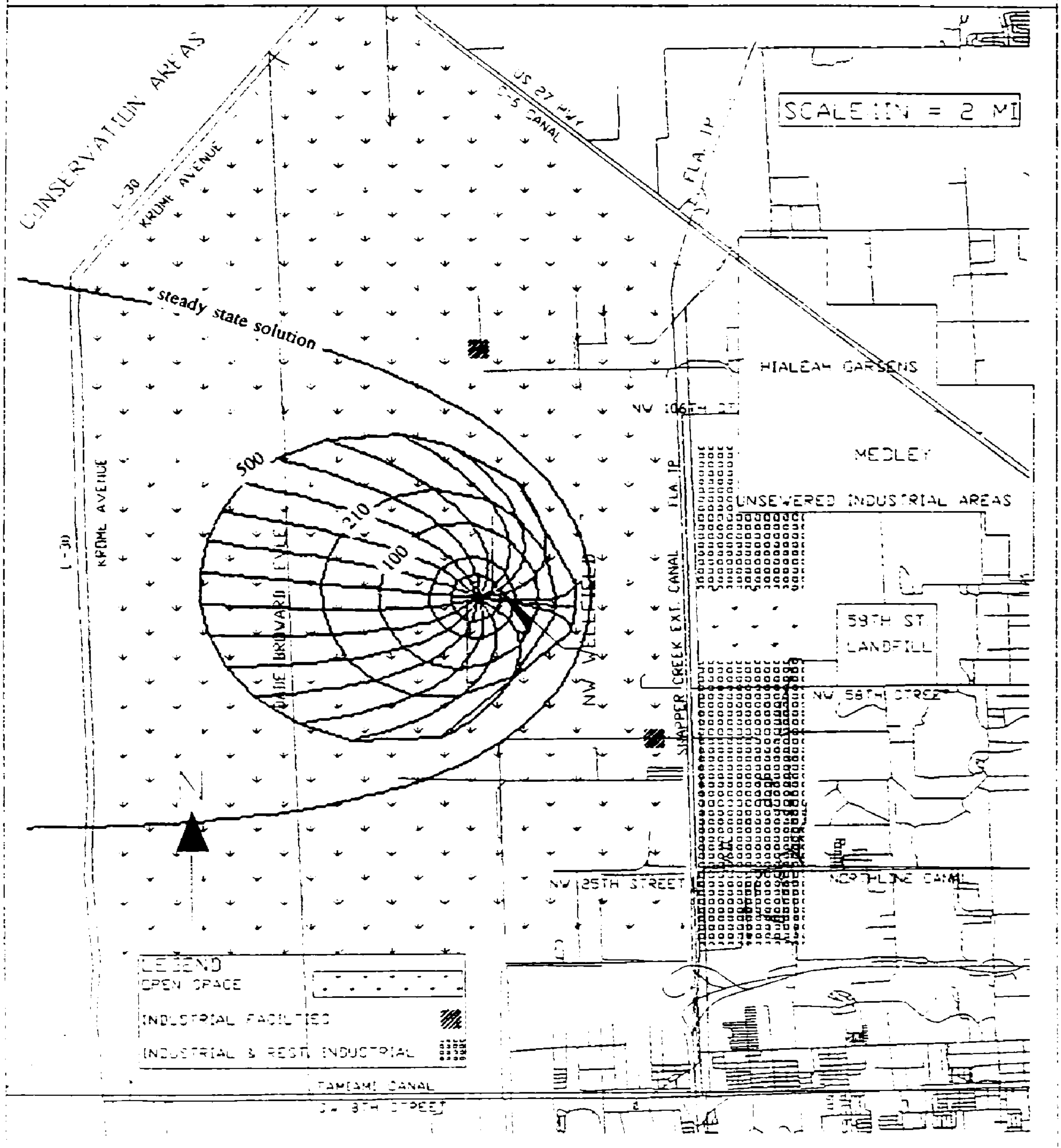


FIGURE 32 OVERLAY OF DADE COUNTY ZONING ACTIVITES AND THE NW WELLFIELD TRAVEL TIME CAPTURES ZONES USING THE WHPA MODELING METHOD AT 184 MGD FOR 2025

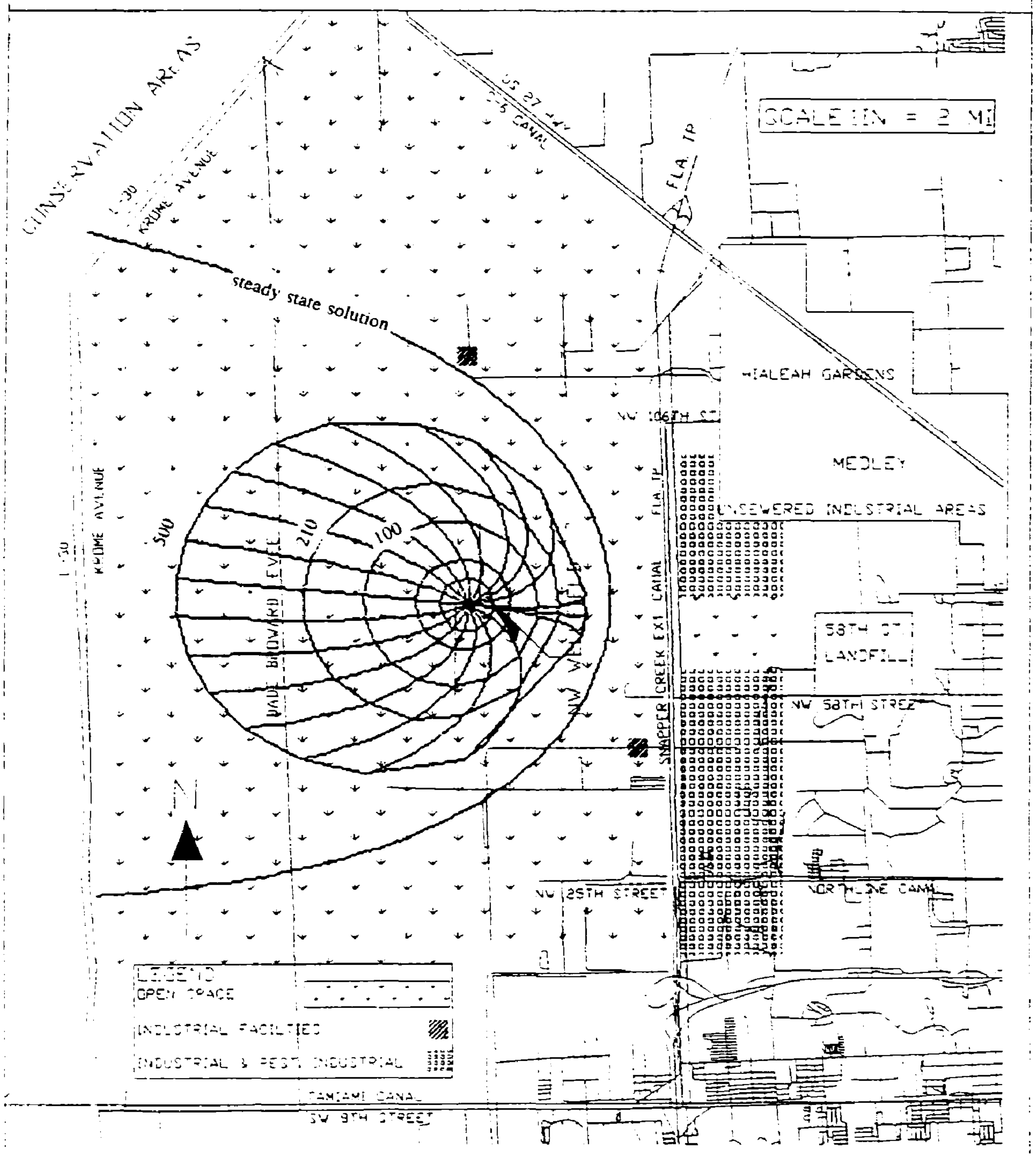
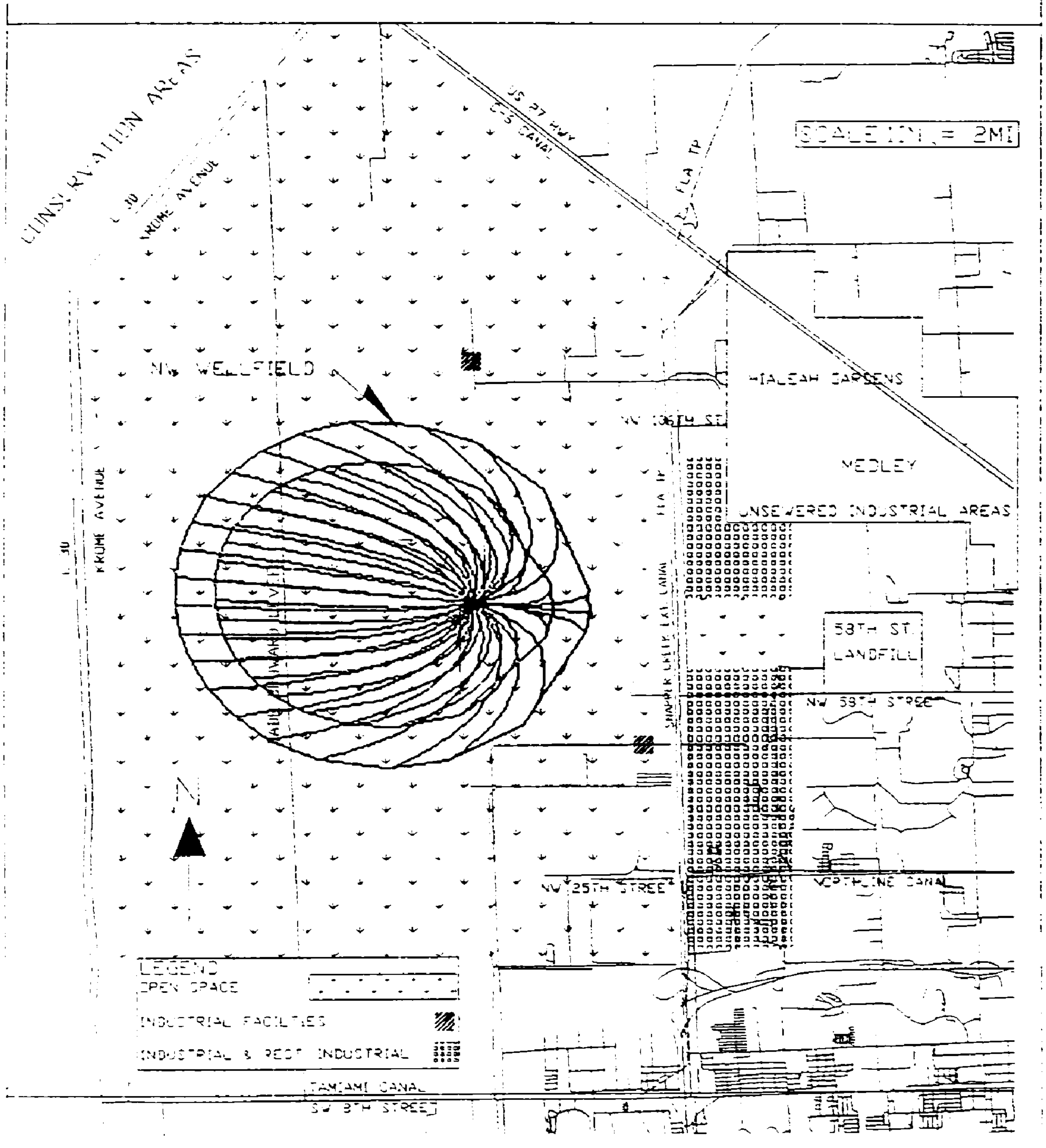


FIGURE 33 500 DAY TRAVEL TIME CAPTURE ZONES FOR NW WELLFIELD AT 115 MGD FOR 1995 AND 184 MGD FOR 2025



groundwater flow solution. CZAEM also, simulates steady-state flow in homogeneous aquifers. CZAEM basically uses the same hydraulic parameters as does WHPA. The only exception is that uniform flow is calculated for the model as the amount of groundwater flowing per unit length of aquifer. In other words the uniform flow is the constant discharge per unit width of aquifer. This was calculated as follows:

$$\mathbf{q = h \times K \times dh/dx} \qquad \mathbf{(13)}$$

where, $h = 45.7$ m (150 ft.)

$K = 2641$ m/d

$dh/dx = 0.0004$

$q = 43.5$ m/day

WHAEM was run 20 times in order to satisfy each case scenario defined previously in Table 16. Figures 34, 35, 36, and 37 illustrate the capture zones for all four case scenarios (see Table 16). Figure 34 shows that the 500-day protection zone boundary is not in contact with any possible source of contamination. However, the steady state solution comes closer to being in contact with industrial facilities. Protection zones of Figure 35 at 125 MGD increase in size, thus coming closer in contact with industrial facilities on site. At 143 MGD, the 500-day protection zone does come in clear contact with the industrial facilities. Also important is that the capture zone for the 500-day time

FIGURE 34 OVERLAY OF DADE COUNTY ZONING ACTIVITES AND THE NW WELLFIELD TRAVEL TIME CAPTURE ZONES USING WHAEM MODELING METHOD AT 115 MGD FOR 1995.

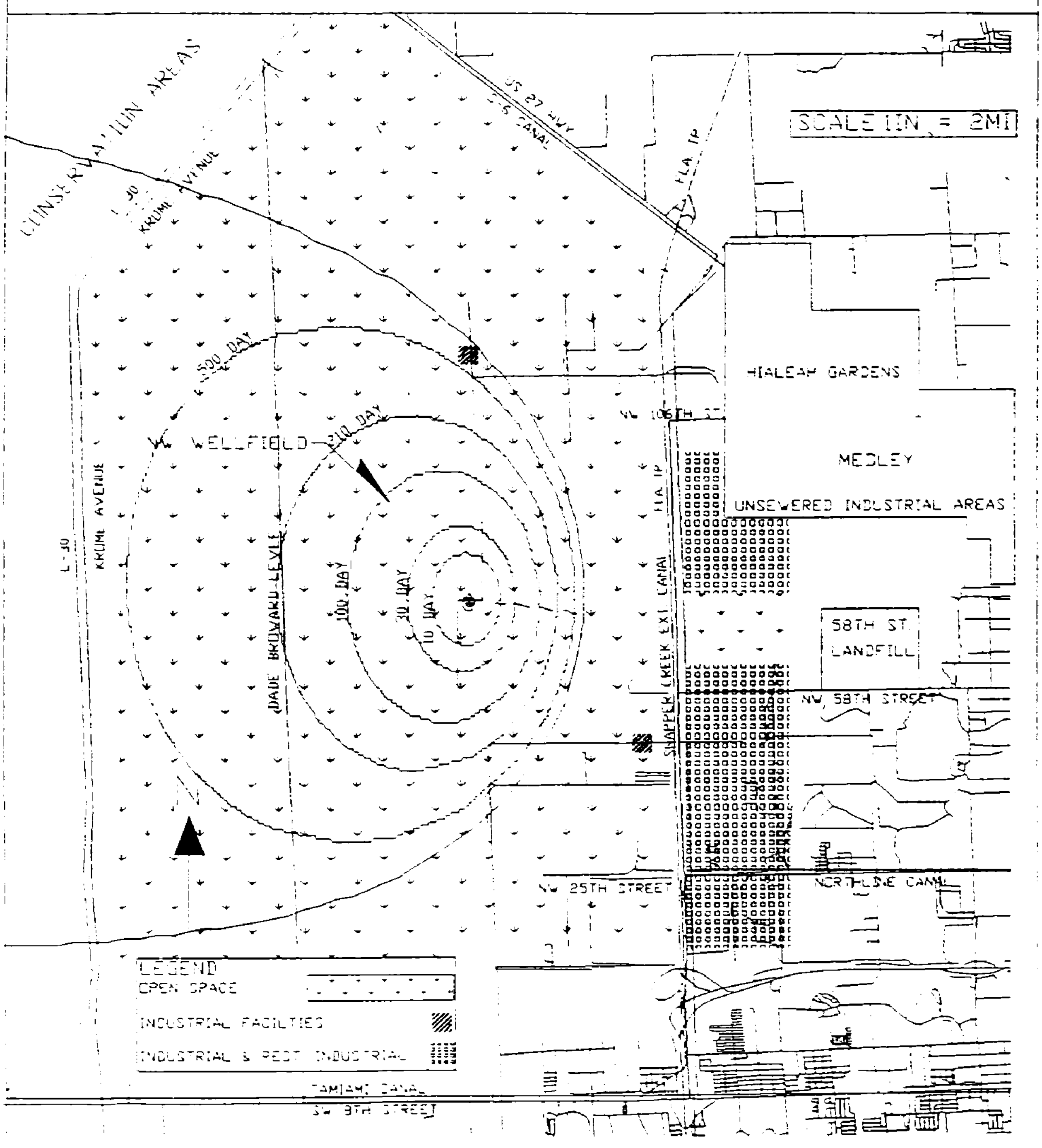


FIGURE 35 OVERLAY OF DADE COUNTY ZONING ACTIVITES AND THE NW WELLFIELD TRAVEL TIME CAPTURE ZONES USING WHAEM MODELING METHOD AT 125 FOR 2010

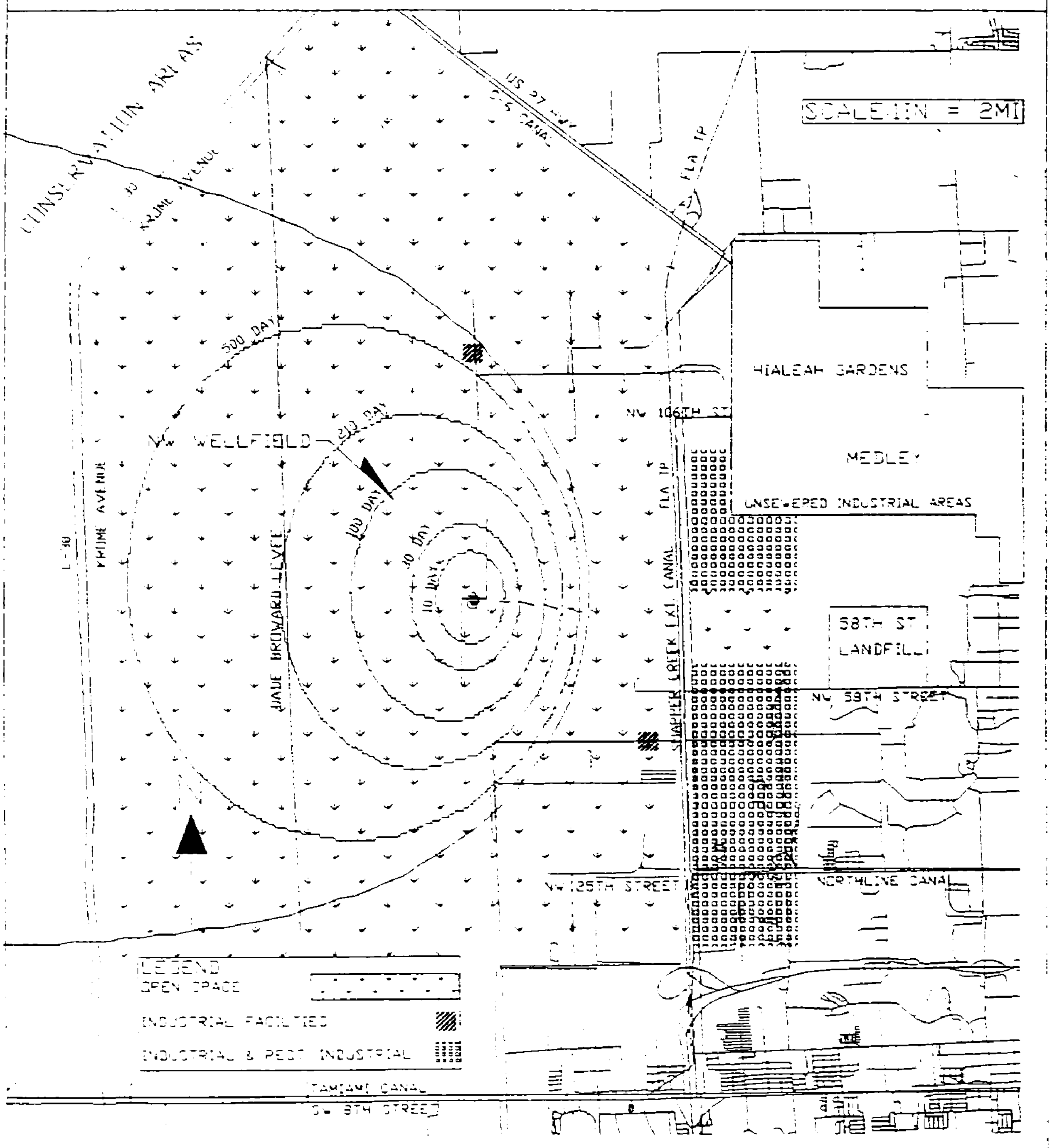


FIGURE 36. OVERLAY OF DADE COUNTY ZONING ACTIVITES AND THE NW WELLFIELD TRAVEL TIME CAPTURE ZONES USING WHAEM MODELING METHOD AT 143 MGD FOR 2015.

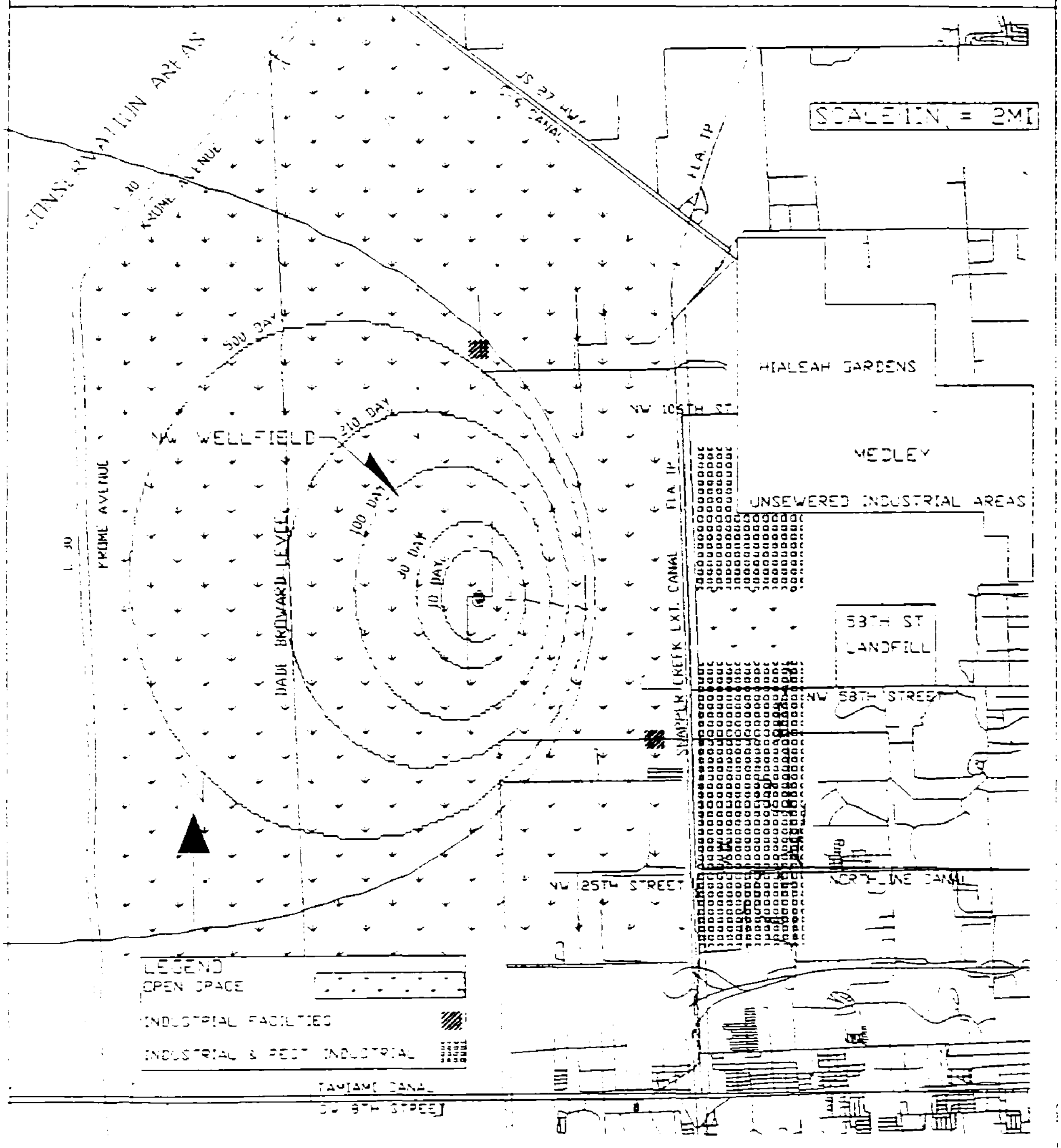
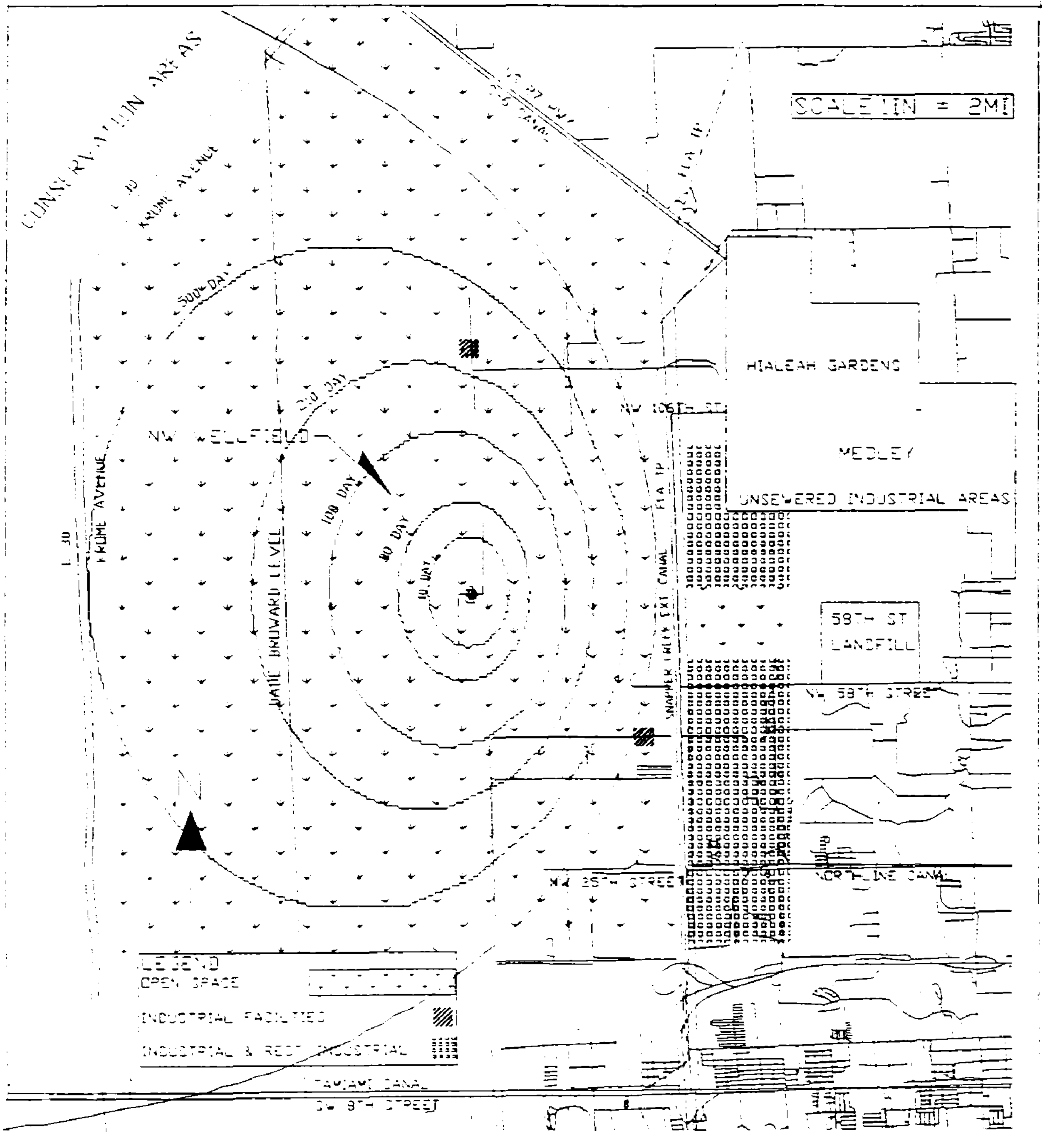


FIGURE 37 OVERLAY OF DADE COUNTY ZONING ACTIVITES AND THE NW WELLFIELD TRAVEL TIME CAPTURE ZONES USING WHAEM MODELING METHOD AT 184 FOR 2025



of travel has shifted further east, closer to the existing groundwater divide along the Florida Turnpike. Figure 37 at 184 MGD shows that its steady-state solution and 500-day capture zone are close within the established groundwater divide. This appears as the most critical case scenario because the protection zones have reached heavily industrialized areas, where the hazardousness and risk of contamination are evidently higher.

5.3.1 Subcase Modeling Scenario for WHAEM

The executable file CZAEM is used to determine the entire zone of contribution for the entire wellfield. The ZOC calculated by the model is done for two case scenarios at 115 MGD and 184 MGD. These two cases (see Table 20) were chosen in order to illustrate the difference between two extreme case scenarios as far as predicted water demands are concerned. The entire pumping rate is divided amongst the 15 wells to obtain a pumping rate per well. Table 20 presents the WHAEM subcase for two case scenarios, which is done in order to observe the critical difference in ZOC at demands of 115 and 184 MGDs.

Figures 38 and 39 illustrate the zones of contribution for 115 and 184 MGD, respectively. Flow lines are represented by dashed lines. The majority of flowlines (pathlines) fall into the wellfield while others continue unaffected by the pumping rate. In Figure 38 for 115 MGD, the ZOC is clearly defined and shows no significant possibility of running into any possible source of contamination. However the ZOC of Figure 39 at 184 MGD comes

Table 20. WHAEM Modeling Subcase: 15 Individual Wells

CASE SCENARIO	YEAR	Q(DEMAND) (MGD)	PUMPING RATE (MGD/well)
1	1995	115	7.66
4	2025	184	12.3

FIGURE 38 ZONE OF CONTRIBUTION FOR NW WELLFIELD USING WHAEM AT 115 MGD FOR 1995

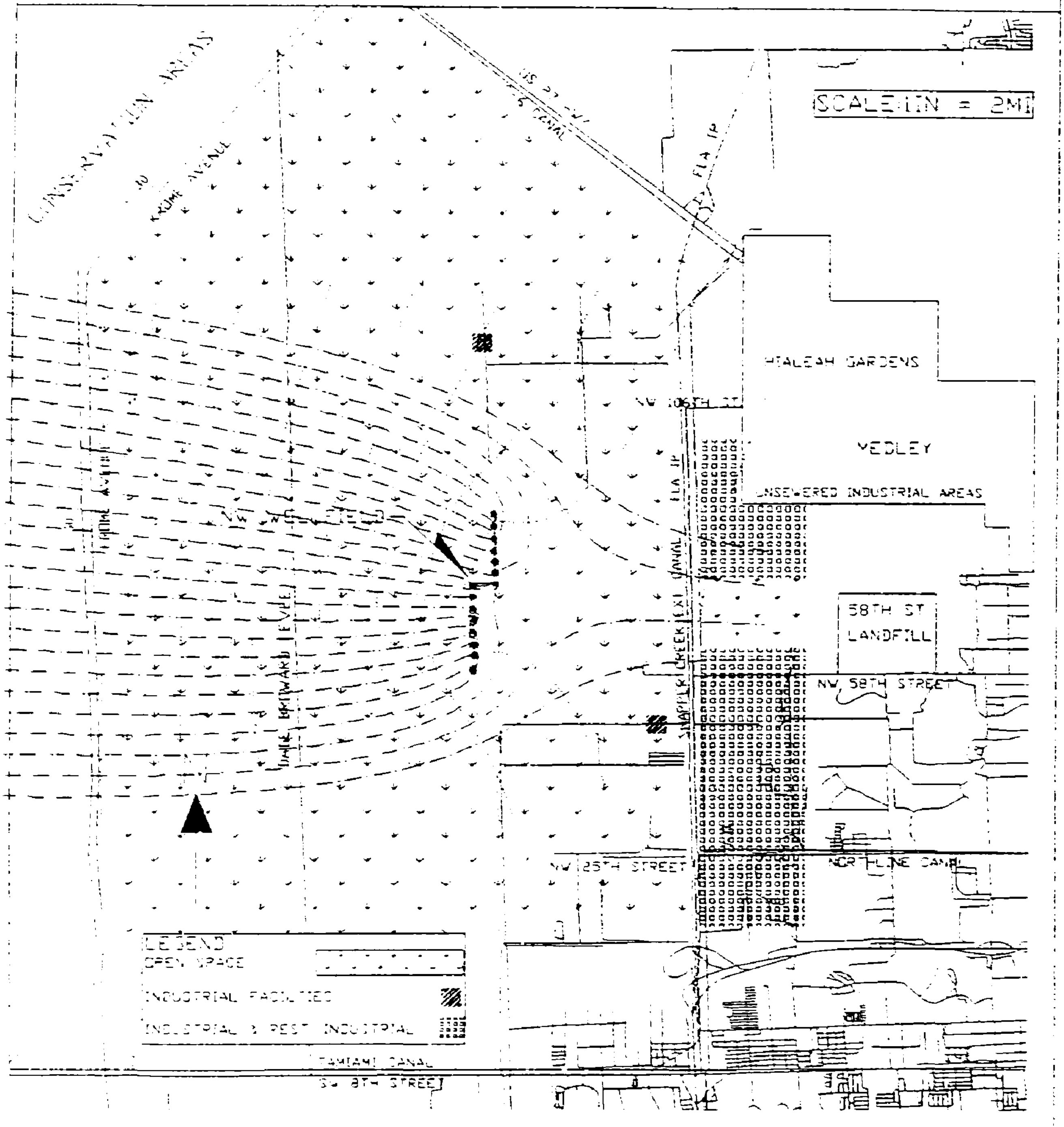
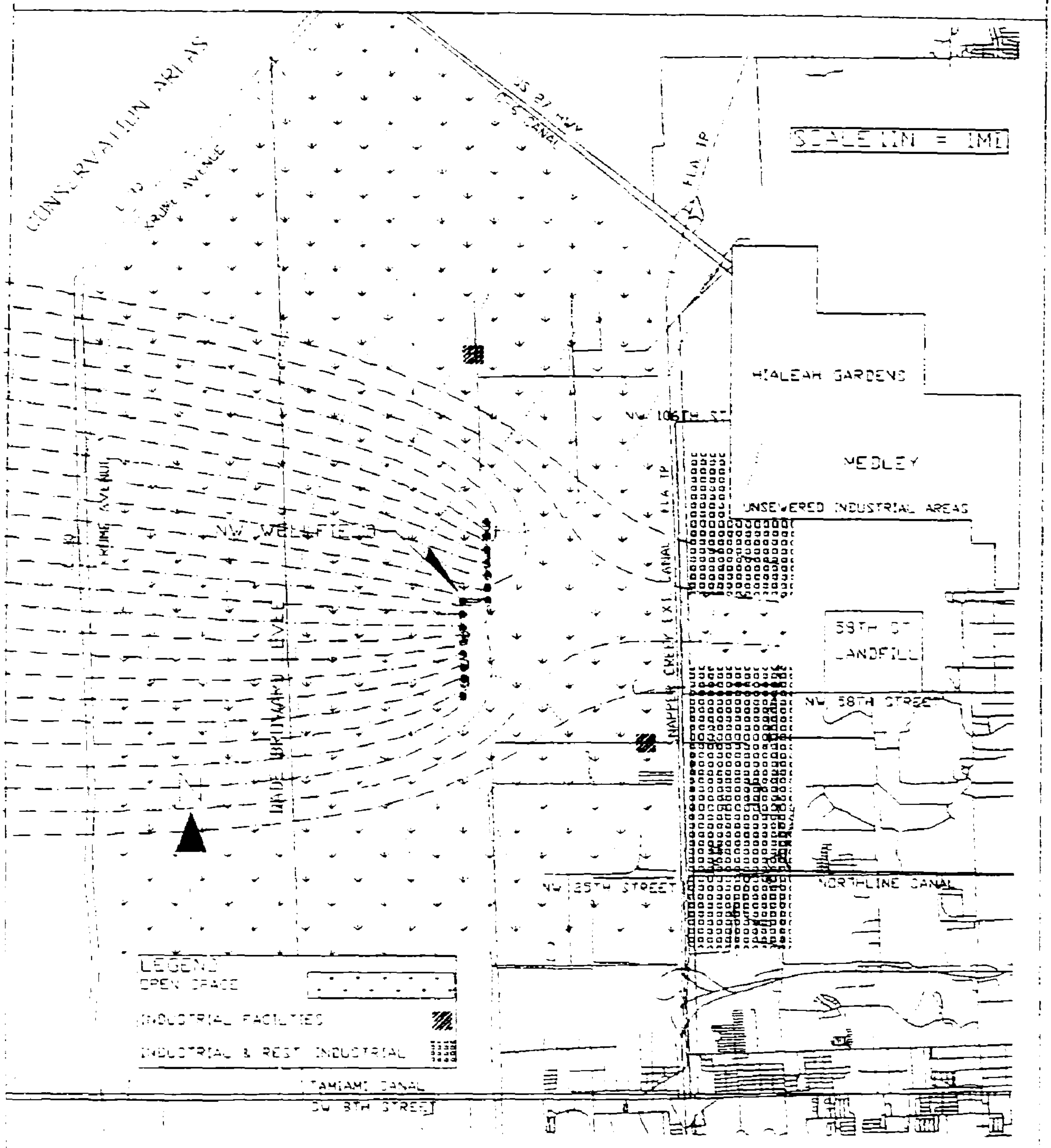


FIGURE 39 ZONE OF CONTRIBUTION FOR NW WELLFIELD USING WHAEM AT 184 MGD FOR 2025

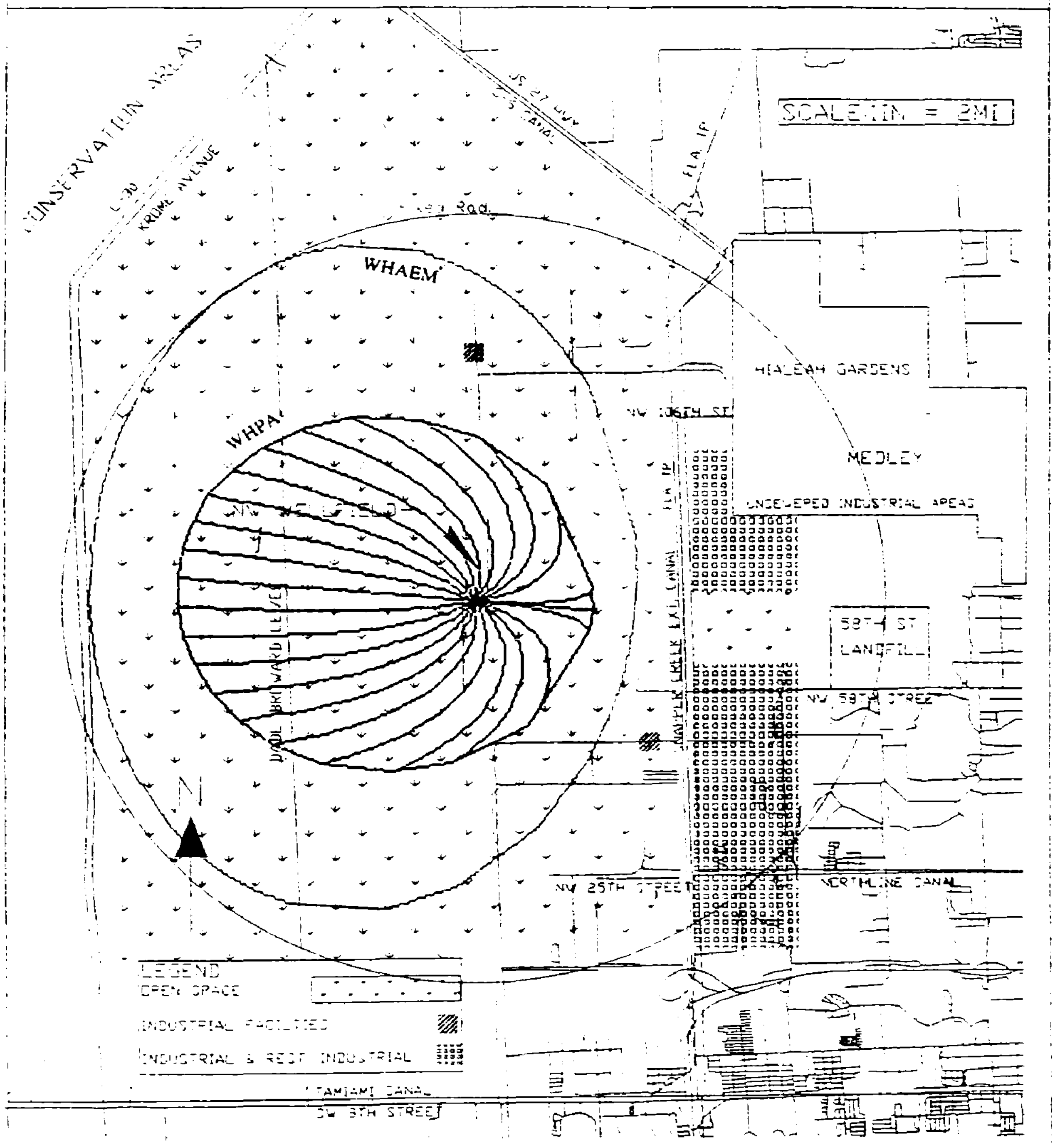


closer to becoming in contact with industrial facilities shown on the land use base map. The ZOC for 184 MGD is noticeably larger than the ZOC for a 115 MGD demand.

5.4 Comparison of Results

The superposition of Figures 27, 32, and 37, is shown in Figure 40, which compares capture zone results obtained from WHPA, WHAEM and the Calculated Fixed Radius Method. Results from all models show that WHAEM and the Calculated Fixed Radius method show larger delineation areas than those obtained from WHPA. Also, the Calculated Fixed Radius method shows larger delineation areas than the zones obtained from WHAEM, thus predicting higher exposure to all possible sources of contamination lying within the protection zone. However, the Calculated Fixed Radius method indicate results which are quite conservative, because the method itself is inaccurate and does not consider the ambient groundwater flow and hydraulic gradient. It is important to point out that it may be preferred to apply a conservative approach when dealing with the drinking water supply of large urbanized areas, such as Dade County.

FIGURE 40 OVERALL COMPARISON OF WHPA, WHAEM AND CALCULATED FIXED RADIUS METHOD FOR 500-DAY TOT AT 184 MGD (YEAR 2025)



VI. SENSITIVITY ANALYSIS

6.1 Sensitivity Analysis for the WHPA Model

Monte Carlo analysis can be used to consider the effect of uncertain parameters when one or more input variables of the capture zone model is considered random. Random variables are those with one or more potential values described by probability distributions. The uncertainty in parameters are usually due to measurement errors, data limitations, and temporal/spatial variabilities (Blandford, 1991).

Although, a comprehensive sensitivity analysis was not a main objective of this study, this section illustrates a methodology to expand on the sensitivity of predictions in a realistic situation. A Monte Carlo approach can be used to assess the uncertainty in hydraulic parameters used in the WHPA model to obtain capture zones. The approach is used to estimate the uncertainty in size and shape of the resulting capture zone. This task is accomplished by obtaining a cumulative probability distribution of a capture zone boundary, given a probability distribution of input parameters. The hydraulic input parameters which are considered as uncertain include the hydraulic conductivity, hydraulic gradient, porosity and aquifer thickness. MONTEC is applied to the 500-day capture zone of Figure 32 which represents the demand for 184 MGD. This scenario was chosen to illustrate the sensitivity of prediction for the case of the highest expected demand, and foremost the largest difference in the predicted capture zone. The uncertain parameters considered are hydraulic conductivity, hydraulic gradient and porosity. In order to run

MONTEC, the maximum permitted drawdown was calculated to be approximately 30 ft at the well, using the Theim Equation:

$$s = \frac{Q}{2\Pi Kb} \ln(\frac{R_e}{r}) \qquad (14)$$

where s is drawdown at the well, Q the pumping rate (184MGD), K the hydraulic conductivity (8666 ft/d), R_e the radius of influence of the well (26, 279 ft), b the aquifer thickness (150 ft), and r the well radius (1.75 ft).

Table 21 presents the uncertain input parameters used for the sensitivity analysis. MONTEC computer input files are shown in Appendix A2.

Fluctuations in lower and upper boundary values for hydraulic conductivity, and porosity are due mainly from the variance in soil texture. These values were obtained from the USGS (1990) report mentioned previously. Variability in hydraulic gradient was estimated from a USGS (1990) water table map.

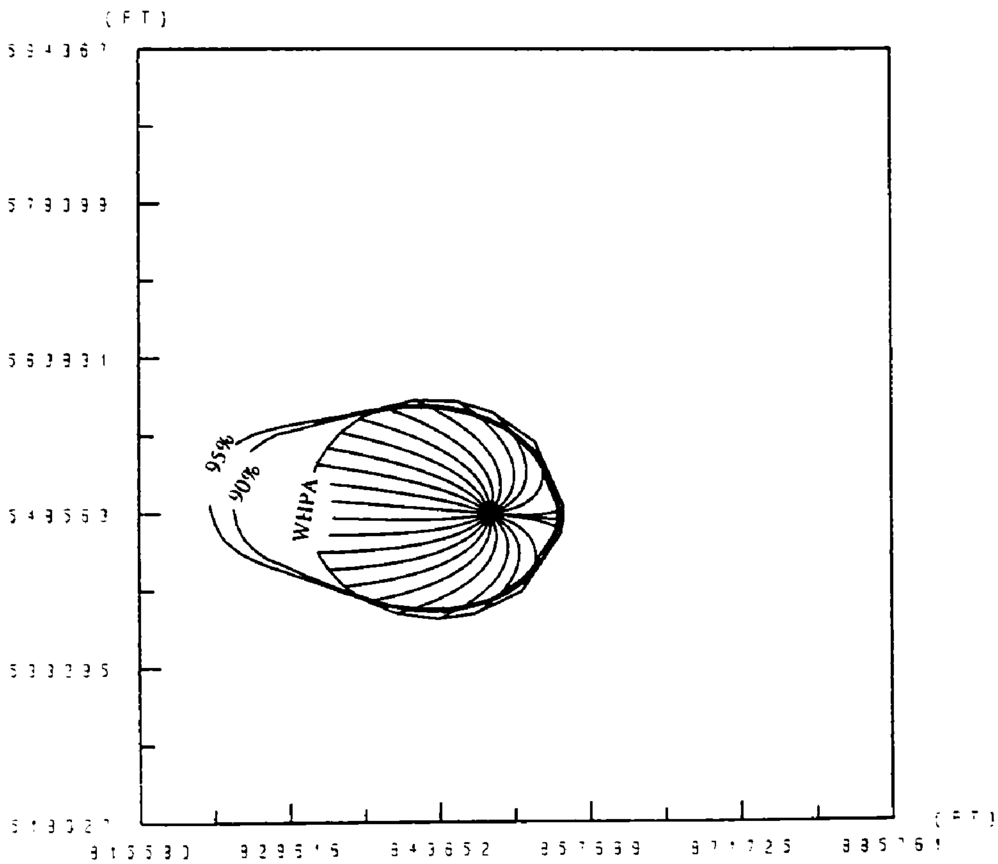
The percentile values used for WHPA delineation are 90 and 95 percent confidence levels. The 90th percentile indicates that there is a 10 percent chance that the actual capture zone boundary may exceed the bounds of the delineated capture zone. In this case a delineated capture zone calculated from the MONTEC analysis is overlayed on the delineated capture zone for any case scenario and the difference can be illustrated. The

Table 21. Monte Carlo Variables

Parameter	Distribution Type	Mean	Standard Deviation	Lower Bound	Upper Bound
Pumping Rate	Constant	184 MGD			
Hydraulic Conduct.	Normal	8,738.8 ft/d	10,422 ft/d	50 ft/d	29,000 ft/d
Hydraulic Gradient	Uniform			0.0003	0.0004
Porosity	Uniform			0.20	0.30
Thickness	Constant	150 ft			

capture zone of Figure 32 is used as the delineated capture zone to be compared to the capture zone determined from the MONTEC analysis. Figure 41 shows the 500-day modeled capture zone with pathlines and the two pear-shaped capture zones obtained from MONTEC. The two pear-shaped capture zones represent the 90th and 95th percentile capture zones; the outer pear-shaped capture zone is the 95th percentile capture zone and the smaller represents the 90th percentile capture zone. These percentile capture zones indicate that the actual capture zone is likely to be smaller or equal in size to the modeled capture zone. From the overlay of plots, the capture zone (i.e., with pathlines) is closely of the same size. However the shape of the percentile capture zones is more elongated; the elongation is due to the variance in the parameters.

Figure 41. Comparison of 500-Day (184 MGD) 90 and 95 Percentile Capture Zones with 500-Day (184 MGD) Capture Zone Using WHPA



VII. ASSUMPTIONS AND LIMITATIONS

As most studies, this effort was based on a number of assumptions which define limitations of the results. This section presents them.

7.1 Population

Information based on a 1990 census, which was documented in a Water Facilities Master Plan (Metropolitan Dade County Planning Department), estimated that in the years 1993 and 1994 a population number of 1,010,000 and 1,025,000, respectively, were being served by the Hialeah/Preston Water Treatment Plant. An approximate annual growth rate was estimated to be 1.5% for most recent years.

The Water Facilities Master Plan (MDWASAD, 1992) predicts that the water demand population projection follows a linear projection for years 1985 through 2010. It is important to note that the population growth in Dade County will be subject to a number of important factors, including high migration, age distribution, land limitations, and socio-economic characteristics, among others. For the purposes of this study, a compromising exponential growth (Rogers, 1985) at a calculated annual growth rate of 1.5% was used, considering that it provided a prediction comparable to others (MDWASAD, 1992; also see Figure 13), but yet slightly conservative. In view of this result, population was projected based on an exponential function until the year 2025. Overall, population projections are only estimates which can overestimate or underestimate.

7.2 Time Period For Study

The entire study was developed for a span of 30 years from 1995 to 2025. Population projections and future water demands were estimated for a current scenario in 1995 and in future scenarios of 2010, 2015, and 2025. These years were selected in order to compare with results obtained by the Metropolitan Dade County Planning Department in the Water Facilities Master Plan.

7.3 Modeling Assumptions

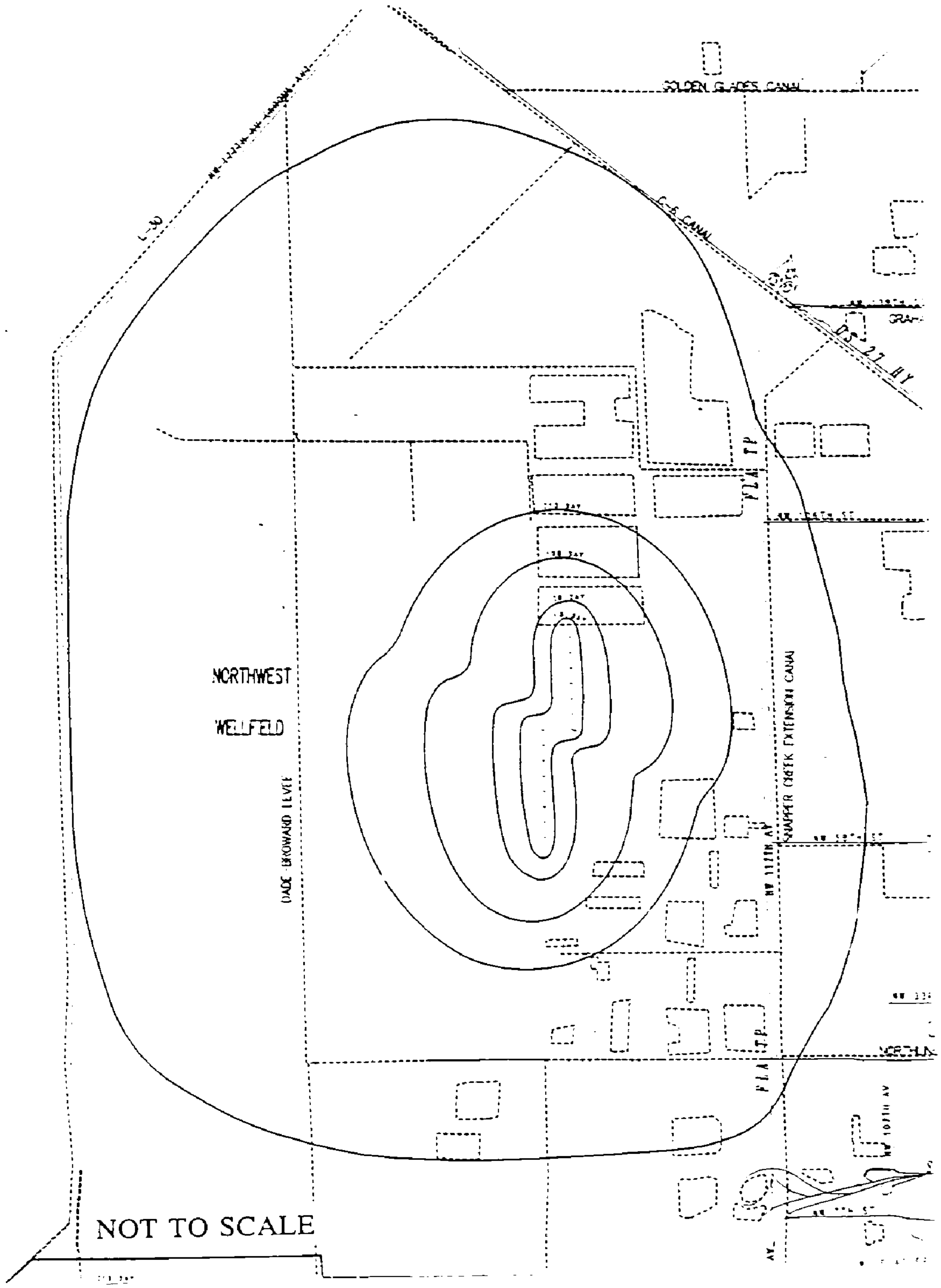
Models used in determining travel-time capture zones neglect the influence of storativity and specific yield. The unconfined aquifer is assumed to have no rainfall infiltration or vertical recharge, which yields a conservative approach. The Dupuit assumption is considered, where vertical gradients are negligible. The well is fully penetrating, pumping at a constant rate. In order to compare all three methods accordingly, well interference among the 15 wells in the Northwest Wellfield is ignored, therefore the interference caused from the cone of depression from nearby wellfields such as the Hialeah/Preston Water Treatment Plant is neglected.

VIII. CONCLUSIONS AND RECOMMENDATIONS

Figure 15 points out that the estimated Northwest Wellfield demand will surpass the current capacity of the Northwest Wellfield at 115 MGD by the year 2006. Case scenarios are illustrated in Table 16, where one well represents an entire discharge. On this basis, model results indicate that delineation areas for the year 2015 and 2025 are prone to being impacted by industrialized areas located near or within the protection boundaries for the 210 and 500-day time of travel zones. Model results obtained from WHAEM and the Calculated Fixed Radius method predict comparable areas for the four different scenarios illustrated in Table 16. WHPA, on the other hand, estimates capture zones which are smaller in size. Consequently, WHPA may underestimate the upgradient portion of groundwater flow and overestimate the downgradient recharge portion of the well, thus the location of a stagnation point is not accurate enough.

Finally, Figure 42 illustrates the existing delineation of wellhead area determined from studies performed by DERM in conjunction with other consulting agencies. WHAEM predicted computed captures zones which were smaller in area than the delineated area determined by the local county agency. The difference is due to the fact that well interference is accounted for in Dade County's model (MODFLOW). On the other hand, the Calculated Fixed Radius Method predicts areas comparable to the protection zones computed by the county and WHAEM. A main advantage of using analytical methods, such as those of this study, is their simplicity compared to more elaborate numerical models for which data is not easily available.

Figure 42. Existing Delineation Area for the Northwest Wellfield
(Source: DERM, 1985)



Some recommendations are the following:

a) Future water demands show that there will be a high presence of industrialized areas within the projected zone of contribution. Therefore the establishment of future land use patterns is critical. Any surrounding area in the ZOC should be declared urban water conservation area, specially left of the Florida Turnpike. For existing industrialized areas within the zone of contribution, stricter regulations must apply. Some possible regulations from existing and non-existing industrial facilities can be the flowing:

- New developments in the capture zone must connect to public sewers;
- Existing developments in the capture zone must connect to public sewers;
- Limit deep lake construction within outer capture zone;
- Prohibit lake construction within inner capture zones (10-30 day);
- Prohibit underground storage tanks (UST); and
- Establish outer zones for transport of hazardous materials

b) Projected capture zones are indicative of a shift in the groundwater divide from the original location which is considered to be the Florida Turnpike/Snapper Creek Canal in a direction east of this position. This would indicate that the groundwater divide lies within industrialized areas. Hence, groundwater carrying any existing contaminants would carry them on into the wellfield. As a result, canal modifications and expanded canal

maintenance for aquifer recharge should be implemented in accordance with future projected demands. Canals may be constructed in a way where recharge to the aquifer is managed or construct canals in a way that the hydraulic gradient is diverted from the ZOC so that any possible contaminants being carried by the gradient are directed elsewhere.

c) If the cost of canal modification is excessively high, then the use of treatment technologies must be considered to meet higher demands at the wellfield. This is the case of the existing use of air striping at the Hialeah/Preston Water Treatment Plant.

d) Investigate other possible sites west of the wellfield for possible water supply source, whiles maintaining a good monitoring program of groundwater quality around the wellfield. Thus improve groundwater and surface water monitoring plan.

e) Establish technical and financial assistance programs to encourage new and existing industrial facilities to start pollution prevention programs. Relocation of existing facilities should also be encouraged.

f) Complementing all above recommendations, is a continuous monitoring program to support enforcement, regulations, and creative approaches.

g) In the application of the methodology, herein presented, to realistic situations, it is critical to conduct a comprehensive sensitivity study to fully characterize the variability of results.

The overall underestimation of modeled results suggests that the uncertainty in the groundwater flow system and well interference must be carefully considered. Even though several assumptions are made for this study, modeling results obtained from WHPA, WHAEM and the Calculated Fixed Radius provide useful information in developing a wellhead protection program. Also, the modeling results from this study are reasonably within range of what the county has obtained through a more complex and accurate three-dimensional numerical model (MODFLOW). This study illustrates that communities such as Dade County who possess the necessary technical expertise and budget can use these modeling methods as a preliminary basis for the development of preliminary wellhead protection programs. More importantly, this study can be helpful in terms of practicality and feasibility for communities with limited budgets.

REFERENCES

Ahlfeld, D.P. and C.S. Sawyer (1990). "Well Location in Capture Zone Design Using Simulation and Optimization Techniques." *Journal of Ground Water*, Vol. 28(4), pp. 507-512.

Antoniello, A., K.T. Page, and J.E. Diercks (1993). "Meeting High Demand for Water Quality." *Public Works*, May issue, pp. 40-41.

Bailey, Z.C. (1992). "Hydrology of the Jackson, Tennessee, Area and Delineation of Areas Contributing Ground Water to the Jackson Well Fields." US Geological Survey, *Water Resources Investigations Report 92-4146.*

Bair, E.S., C.M. Safreed, and E.A. Stasny (1991). "A Monte-Carlo Based Approach for Determining Traveltime-Related Capture Zones of Wells Using Convex Hulls as Confidence Regions." *Journal of Ground Water*, Vol. 29(6), pp.849-855.

Barcelona, M., J.F. Keely, W.A. Pettyjohn, and A. Wehrmann (1988). "Handbook of Groundwater Protection. " *Hemisphere Publishing Corporation*, New York.

Bear, J., M. S. Beljin, and R. R. Ross (1992). "Fundamentals of Groundwater Modeling." *Ground Water Issue.* EPA/540/S92/005.

Beckwith, R.R. (1993). "Wellhead Protection Plans and the Hydrogeologist." *The Professional Geologist*, August issue, pp.10-11.

Blain, L.M.B., and H.S. Evans (1992). "Wellhead Protection: A Comparison of Seven Local Florida Programs." *Proceedings of the National Symposium on the Future Availability of Groundwater Resources.* American Water Resources Association. Raleigh, North Carolina. April 12-15, pp. 139-148.

Blandford, T. N. (1991). "WHPA A Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas." Version 2.2, US Environmental Protection Agency. *Office of Groundwater Protection*, Washington D.C., 20460.

Bonds, J. (1993). "Wellhead Protection." Florida Department of Environmental Protection. *Environmental Exchange Point*, Vol. 4(1), pp. 17.

Brahana, J.V., M.W. Bradley, J.A. Macy, and D. Mulderink (1982). "Preliminary Delineation and Description of the Regional Aquifers of Tennessee-Basal Sandstone West of the Valley and Ridge Province." US Geological Survey, *Water Resources Investigations Report 82-762.*

Camp Dresser and McKee Inc. (1982). "Wellfield Travel Time Model for Selected Wellfields in Dade, Broward, and Palm Beach Counties Florida." Prepared for Dade County. Department of Environmental Resource Management, Miami, Florida.

Caswell, B. (1993). "Evolution of a Wellhead Protection Area." *Water Works Journal,* March issue, pp. 35-38.

Chin, D.A. and P.V.K. Chittaluru (1994). "Risk Management in Wellhead Protection." *Journal of Water Resources Planning and Management*, Vol. 120(3), pp. 294-313.

Cleary, T. C.B.F., and R. W. Cleary (1991). "Delineation of Wellhead Protection Areas: Theory and Practice." *Water Science and Technology*. Vol. 24 (11), pp. 239-250.

Delin, G.N. and J.E. Almendinger (1993). "Delineation of Recharge Areas for Selected Wells in the St. Peter-Prarie du Chien-Jordan Aquifer, Rochester, Minnesota." US Geological Survey, *Water Supply Paper I19.13:2397.*

DERM, (1984). "Dade County's Current Program to Improve and Maintain the Quality of Potable Water: Wellfield Protection Study." Department of Environmental Resource Management. Miami, Florida.

DERM, (1985). "North West Wellfield Protection Plan." Dade County Planning Department, Department of Environmental Resource Management. Miami, Florida.

DERM, (1992). "Issues Regarding Pesticide, Fertilizer and Soil Amendment Use within the West Wellfield Interim Protection Area." *Planning and Evaluation Section,* Department of Environmental Resources Management. Dade County, Florida.

Dickenson, A. R. and R. S. Banks (1992). "Wellfield Protection Program for the Lee County, Florida Multi-Aquifer System." *National Symposium on the Future Availability of Groundwater Resources.* American Water Resources Association. April, pp. 129-138.

Fabian, R.S., J.B. Summers II, and E. Kalinina (1992). "TOT A Computer Program for the Delineation of Wellhead Protection Areas." *Water Management and Administration Divisions*, Oklahoma Water Resources Board.

Fish, J.E. and M. Stewart (1990). "Hydrogeology of the Surficial Aquifer System, Dade County, Florida." US Geological Survey, *Water Resources Investigations Report 90-4108.*

Freethey, G.W., L.E. Spangler, and W.J. Monheiser (1992). "Determination of Hydrologic Properties Needed to Calculate Average Linear Velocity and Travel Time of Ground Water in the Principal Aquifer Underlying the Southeastern Part of Salt Lake Valley, Utah." US Geological Survey, *Water Resources Investigations Report 92-4085.*

Gadipudi, R.K. (1994). "Evaluating the Effects of Agricultural Practices on Water Quality by Interfacing GIS with Computer Models." Florida International University. Miami, Florida.

Goswami, D. and M. K. Anderson (1992). "Delineating Wellhead Protection Areas for a Highly Conductive Shallow Sand Gravel Aquifer and its Implications: A Case Study of the Downtown Wellfield of Ames, Iowa." *Geological Society of America.* Vol. 24, pp. 17.

Guiger, N., and T.Franz (1991). "Development and Application of Wellhead Protection Area Delineation Computer Program." *Water Science and Technology.* Vol. 24(1), pp. 51-62.

Grubb, S. (1993). "Analytical Model for Estimation of Steady-State Capture Zones of Pumping Wells in Confined and Unconfined Aquifers." *Journal of Ground Water,* Vol.31(1), pp. 27-32.

Hoffer, R. (1989). "Criteria and Methods for the Delineation of Wellhead Protection Areas in the United States." *Hydrological Science and Technology.* Vol. 5(1-4), pp.37-41.

Hudak, P.F. (1993). "Groundwater Modeling Applied to Production Well Management in a Contaminated Aquifer." Environmental Geology, Vol. 23(2), pp. 119-124.

Kraemer, S.R., H.M. Haitjema, and O. D.L. Strack (1994). "Capture Zone Modeling Using the Whaem." *An International Conference on Analytical Element Modeling of Groundwater Flow.* University Place, Indianapolis, Indiana. April 19-21. pp.55-59.

Lall, U. (1995). "Yield Model for Screening Surface and Ground Water Development." *Journal of Water Resources Planning and Management,* Vol. 121(1), pp.9-21.

Landmeyer, J.E. (1994). "Description and Application of Capture Zone Delineation for a Wellfield at Hilton Head Island, South Carolina." US Geological Survey, *Water Resources Investigations Report 94-4012.*

Lennox, J. (1993). "New Regulations Foster Wellhead Protection Efforts." *Public Works,* June issue, pp.59.

Lennox, J.B., C.F. Adams, and T.V. Chaplik (1990). "Overview of a Wellhead Protection Program: from the Determination of Recharge Areas to the Development of Aquifer Protection Regulations." *Journal of the New England Water Works Association*, Vol. 104(4), pp.238-247.

McCormack, K. and R. Trovato (1991). "Why Do Wellhead Protection. Issues and Answers in Protecting Public Drinking Water Supply Systems." US Environmental Protection Agency, EPA570/9-91-014.

McElwee, C.D. (1991). "Capture Zones for Simple Aquifers." *Journal of Ground Water,* Vol.29(4), pp.587-590.

Miami Business Profile (1992-1993). *Released by Beacon Council.* Miami, Florida

Miami-Dade Water and Sewer Authority Department (MDWASAD), (1992). "Water Facilities Master Plan." Metropolitan Dade County, Miami, Florida.

Miles, J.C. and P.D. Chambet (1995). "Safe Yield of Aquifers." *Journal of Water Resources and Planning*, Vol. 121(1), pp. 1-8.

Moore, B.A. (1993). "Case Studies in Wellhead Protection Area Delineation and Monitoring." *Office of Research and Development.* US Environmental Protection Agency. EPA-600/R-93/107.

Navoy, A.S. (1992). "Simulated Effects of Projected Withdrawals from the Wenonah-Mount Laurel Aquifer on Ground Water Levels in the Camden, New Jersey, Area and County." US Geological Survey, *Water Resources Investigations Report 92-4152.*

O'Brien, J. (1993). "Wellhead Protection Prevents Groundwater Contamination." *American City and County*, Vol. 108(11), pp.38.

Page, G.W. (1987). "Planning for Groundwater Protection." *Academic Press, Inc.* Orlando, Florida.

Plomb, D.J., and K.M. Arnett (1992). "Combining Groundwater Flow Modeling, Practical Transport, and GIS for Effective Wellhead Protection in The Greater Miami River Valley, Ohio." *Proceedings of the Fifth International Conference on the Use of Models to Analyze and Find Working Solutions to Groundwater Problems.* Association of Groundwater Scientists and Engineers. Dallas, Texas. February 11-13, pp. 571-594.

Raghunath, H.M. (1982). "Ground Water." *Halsted Press,* New Delhi, India.

Ramanarayanan, T.S., D.E. Storm, M.D. Smolen, and M.A. Kizer (1992). "Comparison of an Analytical Model and a Numerical Model for Delineating Wellhead Protection Areas." *International Summer Meeting.* American Society of Agricultural Engineers. Charlotte, N.C. June 21-24, pp. 1-6.

Reilley, T. and D.W. Pollock (1993). "Factors Affecting Areas Contributing Recharge to Wells in Shallow Aquifers." US Geological Survey, *Water-Supply Paper I19.13:2412.*

Rifai, H.S., L.A. Hendricks, K.Kilborn, and P.B. Bedient (1993). "A Georaphic Information System (GIS) User Interface for Delineating Wellhead Protection Areas." *Journal of Ground Water,* Vol. 31(3), pp. 480-488.

Rogers, A. (1985). "Regional Population Projection Models." *Sage Publications,* Inc. California.

Roy, S. and N. Dee. (1989). "Local Financing for Wellhead Protection." US Environmental Protection Agency, *Office of Groundwater Protection*. EPA 440/6-89-001.

Shair, R. C. (1992). "Wellfield Protection Program in Broward County, Florida." Water Forum, *Irrigation and Drainage: Saving a Threatened Resource: In Search of Solutions.* Baltimore, MD., pp. 69-74.

Springer, A.E. and E.S. Bair (1992). "Comparison of Methods Used to Delineate Capture Zones of Wells: 2. Stratified-Drift Buried-Valley Aquifer." *Journal of Ground Water,* Vol. 30(6), pp. 908-917.

Strack, OD.L., E.I. Anderson, M. Baker, W.C. Olsen, J.C. Panda, R.W. Pennings, and D.R. Steward (1994). "CZAEM User's Guide: Modeling Capture Zones of Groundwater Wells Using Analytical Elements." *Office of Research and Development*, US Environmental Protection Agency. Ada, Oklahoma.

USEPA, (1987). "Guidelines for Delineation of Wellhead Protection Areas." *Office of Groundwater*, US Environmental Protection Agency. EPA440/6-87-010.

USEPA, (1988). "Developing a State Wellhead Protection Program. A User's Guide to Assist State Agencies Under the Safe Drinking Water Act." *Office of Groundwater,* US Environmental Protection Agency 440/6-88-003.

USEPA, (1989). "Wellhead Protection Programs: Tools for Local Governments." *Office of Water,* US Environmental Protection Agency. EPA440/6-89-002.

USEPA, (1993a). "Wellfield Protection: A Guide for Small Communities." *Office of Research and Development*, US Environmental Protection Agency. EPA625/R93/002.

USEPA, (1993b). "Wellhead Protection in Confined, Semi-Confined, Fractured and Karst Aquifer Settings." *Office of Water,* US Environmental Protection Agency. EPA810/K-93-001.

USEPA, (1994). "Groundwater and Wellhead Protection." *Office of Research and Development,* US Environmental Protection Agency. EPA/625/R-94/001.

Van der Heijde, P.K.M., A.I. El-Kadi, and S.A. Williams (1989). "Groundwater Modeling: An Overview and Status Report." U.S. Environmental Protection Agency. *International Groundwater Modeling Center.* EPA/600/2-89/028.

Wuolo, R.W., D.J. Dahlstrom, and M.D. Fairbrother (1995). "Wellhead Protection Area Delineation Using the Analytical Element Method of Ground Water Modeling." *Journal of Ground Water,* Vol. 33(1), pp. 71-83.

Zarriello, P.J. (1990). "Determination of the Contributing Area to Six Municipal Ground Water Supplies in the Tug Hill Glacial Aquifer of Northern New York, with Emphasis on the Lacona-Sandy Creek Well Field." US Geological Survey, *Water Resources Investigations Report 90-4145.*

APPENDIX A. Sample Input Files

APPENDIX A1. WHPA

```
MWCAP  HELP

 Units:

   Any set of consistant units may be used by MWCAP.  However,
   length units of feet or meters and time units of days should
   be used to ensure correct results when automatic scaling
   options are used.  These units tend to be well suited to most
   WHPA delineation problems.

 Number of Wells:

   MWCAP can delineate capture zones for a maximum of 50 pumping
   wells.  The capture zone delineation for each well will be
   performed independently of every other well, and therefore
   each well may be assigned different sets of input parameters
   (e.g. transmissivity, boundary conditions).  The coordinates
   of each well must be within the study area.


              Press any key to continue  <ESC=abort>
```

```
èêêêêêêêêêêêêêêêêêêêêêêêêêêêêMWCAP  HELPêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê

  Definition of Study Area:

    The minimum and maximum Cartesian coordinates of the study
    area define a rectangular zone within which capture zones
    will be delineated.  The lower left hand corner of the rec-
    tangle, defined by the minimum x (XMIN) and y (YMIN) coordi-
    nates, is the origin of the Cartesian coordinate system.
    Generally, XMIN and YMIN will be zero.  The origin must corr-
    espond to a known point on the WHPA study base map.
                                  Õááááááááááááááá¢(XMAX,YMAX)
                                  °               °
                                  °  * pumping    °
                                  °     well      °
                       (XMIN,YMIN)ááááááááááááááááá
    Note: For convenience sake, the origin should be at a corner
          of the base map or at some other prominant location.


                  Press any key to continue  <ESC=abort>
àêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê
```

```
MWCAP HELP

Spatial Step Length:

  The maximum step length (DLMAX) is the largest distance that
  a particle may move in one iteration. If the step length (DL)
  is too small, the computational time required to delineate
  pathlines may be unnecessarily long.  If the step size is too
  large, errors in the delineation of pathlines may occur.  As
  a rule of thumb, step lengths of one 50th to one 100th the
  size of the longest coordinate axis seem to work well.


  Note:  If the step length is left blank, a default value of
         one 100th of the x-axis length ((XMAX-XMIN)/100) will
         be used.




                       Press any key to continue
```

```
èêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêMWCAP  HELPêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê£
¤                                                                          ¤
¤ Gradient:                                                                ¤
¤   The hydraulic gradient (ft/ft or m/m = dimensionless) is most          ¤
¤   commonly measured from a map of piezometric surface or water           ¤
¤   table elevations. The average ambient gradient should be in-           ¤
¤   put to the model, and therefore gradients prior to pumping,            ¤
¤   or gradients not affected by the cone of depression should be          ¤
¤   used.                                                                  ¤
¤                                                                          ¤
¤ Direction of Ground-Water Flow:                                          ¤
¤   Ground water flows from areas of high hydraulic head towards           ¤
¤   areas of low hydraulic head; for homogeneous, isotropic                ¤
¤   aquifers the direction of ground-water flow is perpendicular           ¤
¤   to the hydraulic head contours.  At a given site, the direc-           ¤
¤   tion of ground-water flow may be variable; in this case the            ¤
¤   average, most dominant direction should be used.  The direc-           ¤
¤   tion of flow may be 0-360 degrees, with 0=due east, 90=due             ¤
¤   north, etc.                                                            ¤
¤                                                                          ¤
¤             Press any key to continue  <ESC=abort>                       ¤
àêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê¥
```

```
èêêêêêêêêêêêêêêêêêêêêêêêêêêêêêMWCAP  HELPêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê£
¤                                                                        ¤
¤ Porosity:                                                              ¤
¤   Porosity (dimensionless) is defined as the volume of the            ¤
¤   voids within the aquifer divided by the total volume of the         ¤
¤   aquifer. It must always be less than one by definition, and         ¤
¤   values of 0.15-0.30 are characteristic of most aquifers.            ¤
¤                                                                        ¤
¤ Thickness:                                                             ¤
¤   The aquifer thickness has units of ft or m.  If the aquifer         ¤
¤   has a variable thickness, an average value for the aquifer          ¤
¤   (generally in the vicinity of the pumping well) should be           ¤
¤   used.                                                                ¤
¤                                                                        ¤
¤                                                                        ¤
¤                                                                        ¤
¤                                                                        ¤
¤                                                                        ¤
¤                                                                        ¤
¤                                                                        ¤
¤                     Press any key to continue                          ¤
àêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê¥
```

```
MWCAP  HELP

 Boundary Conditions:

   If the aquifer is not infinite in areal extent, two types of
   boundary conditions may be specified:
              1) Stream boundary
              2) Barrier (no flow) boundary
   A stream will act as a source of water to the well, and
   therefore limit the capture zone size.  A barrier boundary
   permits no flow of water through it to the well, and therfore
   increases the capture zone size.  Each boundary is assumed to
   be linear (the sinuosity of a stream may not be simulated)
   and fully penetrating (the boundary condition exists over the
   entire depth of the aquifer).  Stream boundaries are most
   likely to violate this assumption.  In general, the wider and
   deeper the stream in relation to the aquifer thickness, and
   the greater the distance between the well and the stream, the
   more valid the full penetration assumption.

             Press any key to continue  <ESC=abort>
```

```
MWCAP HELP

Distance from the Well to the Boundary:

  The shortest distance (ft or m) from the pumping well to the
  boundary (stream or barrier) must be specified.  This
  distance is defined by a line segment that extends from the
  well to the boundary and intersects the boundary at right
  angles (see figures on next screen).

Orientation of the Boundary:

  The linear boundary feature (stream or low permeability rock
  formation) may be oriented at any angle (0-360 degrees) in
  relation to the study area axes and the pumping well. An ang-
  le of 0 degrees indicates a boundary that extends north to
  south to the left of the well.  An angle of 90 degrees indi-
  cates a boundary oriented east to west below the well, etc.
  See next screen for a diagram of boundary orientation.

             Press any key to continue  <ESC=abort>
```

```
èêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêMWCAP  HELPêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê±
¤                                                                        ¤
¤              |                                                         ¤
¤  boundary => |          well              well                         ¤
¤              |-----------*                 *                           ¤
¤              |<===DSW===>                  |                           ¤
¤              |                             |                           ¤
¤              |                 -----------------<= boundary            ¤
¤                                                                        ¤
¤       ANGLE = 0.0 degrees           ANGLE = 90 degrees                 ¤
¤                                                                        ¤
¤              |                -----------------<= boundary             ¤
¤  well        |                             |                           ¤
¤   *----------|                             |                           ¤
¤   <===DSW==> |                             |                           ¤
¤              |<= boundary                  * well                      ¤
¤              |                                                         ¤
¤                                                                        ¤
¤       ANGLE = 180 degrees           ANGLE = 270 degrees                ¤
¤                                                                        ¤
¤                    Press any key to continue                           ¤
àêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê¥
```

```
èèèèèèèèèèèèèèèèèèèèèèèèèèèèèèMWCAP  HELPèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèè£
¤                                                                         ¤
¤                         CAPTURE ZONE TYPE OPTIONS                       ¤
¤                                                                         ¤
¤    1) Steady-state: A steady-state capture zone is the surface          ¤
¤       or subsurface area surrounding a pumping well that will supp-     ¤
¤       ly ground-water recharge to the well over an infinite period      ¤
¤       of time.  This type of capture zone is open-ended because,        ¤
¤       given enough time, any particle of water upstream of the well     ¤
¤       within the capture zone bondaries will eventually travel to       ¤
¤       the well.  There is no time value associated with a steady-       ¤
¤       state capture zone.  All pathlines required to map the cap-       ¤
¤       ture zone boundary will be computed automatically by MWCAP.       ¤
¤                                                                         ¤
¤    2) Time-related: A time-related capture zone is the surface          ¤
¤       or subsurface area surrounding a pumping well that will supp-     ¤
¤       ly ground-water recharge to the well within some specified        ¤
¤       period of time.  A time-related capture zone is always            ¤
¤       represented by some closed shape.  Time-related capture zones     ¤
¤                                                                         ¤
¤                Press any key to continue  <ESC=abort>                   ¤
àèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèèè¥
```

```
èêêêêêêêêêêêêêêêêêêêêêêêêêêêêêMWCAP  HELPêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê
             CAPTURE ZONE TYPE OPTIONS (continued)

      are less conservative (enclose smaller areas) than steady-
      state or hybrid capture zones.  As the specified time
      increases, however, differences between the three capture
      zone types in the proximity of the well quickly become negli-
      gible.  The number of pathlines used to delineate a time-
      related capture zone may be specified by the user.

   3) Hybrid: A hybrid capture zone is a combination between a
      steady-state and a time-related capture zone.  The nose and
      sides of the hybrid capture zone are identical to the steady-
      state capture zone, but there is a "cap" on the hybrid cap-
      ture zone that corresponds to some specified time value.
      This type of capture zone can be viewed as an implementable
      alternative to the steady-state capture zone.  Refer to
      Chapter 3 in the WHPA model manual for more information on
      capture zone types.
              Press any key to continue  <ESC=abort>
àêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê¥
```

```
MWCAP HELP

Time Value:

  A time value (in days) must be specified for the time-
  related and hybrid capture zone types.  The value used will
  be a policy decision, but it should to some extent reflect
  the observed hydrogeological conditions.  CGWP generally rec-
  ommends that time periods of 10-25 years (3,650-9,125 days)
  be considered.

Number of Pathlines:

  All of the pathlines required to map the capture zone boun-
  daries for each capture zone type will be generated auto-
  matically by MWCAP.  If additional pathlines are desired, any
  integer value may be specified.  Additional pathlines are
  most often specified for time-related capture zones (gener-
  ally, 15-30 pathlines are sufficient).

                    Press any key to continue
```

```
èêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê-- MWCAP --êêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê£
□                                                                          □
□         Run Title: NW WELLFIELD DRY SEASON                               □
□                                                                          □
□             Units to use for Current Problem:  1                         □
□                     0 = meters and days                                  □
□                     1 = feet and days                                    □
□                                                                          □
□                    Number of Wells for which                             □
□                    Capture-Zones are desired:  1  <= Should be 1 if      □
□                                                      plotting heads!     □
□                         Minimum X-Coordinate:  815580.0                  □
□                         Maximum X-Coordinate:  885761.0                  □
□                         Minimum Y-Coordinate:  518027.0                  □
□                         Maximum Y-Coordinate:  594367.0                  □
□                                                                          □
□                  Maximum Spatial Step Length:  701.8                     □
□                                                                          □
□           Perform Hydraulic Head Calculation:  0.                        □
□                         (1 = yes, 0 = no)                                □
□                                                                          □
àêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê¥
 <Enter> = select value   <Esc> = options menu   <F1> = DOS shell
```

```
èêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê-- MWCAP --êêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê£
□                                                                          □
□                 CAPTURE-ZONE TYPE OPTION FOR WELL # 1                    □
□                                                                          □
□                                                                          □
□                    Capture-Zone Type Option:  2                          □
□                                                                          □
□                      0 = steady-state                                    □
□                      1 = hybrid                                          □
□                      2 = time-related                                    □
□                                                                          □
□                                                                          □
□                          Travel Time (days):  500                        □
□                                                                          □
□                 Number of Pathlines Desired:  20                         □
□                          (default = 20)                                  □
□                   Plot Capture Zone Boundary? 1                          □
□                               (0=No, 1=Yes)                              □
□                                                                          □
□                                                                          □
□                                                                          □
àêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê¥
 <Enter> = select value   <Esc> = options menu   <F1> = DOS shell
```

```
èêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê-- MWCAP --êêêêêêêêêêêêêêêêêêêêêêêêêêê£
□                                                                     □
□               BOUNDARY CONDITION INPUT FOR WELL # 1                 □
□                                                                     □
□                                                                     □
□                             Boundary Type:  0                       □
□                                                                     □
□                   0 = no boundary                                   □
□                   1 = stream boundary                               □
□                   2 = barrier boundary                              □
□                                                                     □
□                                                                     □
□                                                                     □
□                                                                     □
□                                                                     □
□                                                                     □
□                                                                     □
□                                                                     □
□                                                                     □
□                                                                     □
□                                                                     □
àêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê¥
 <Enter> = select value   <Esc> = options menu   <F1> = DOS shell
```

```
èêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê-- MWCAP --êêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê£
¤                                                                          ¤
¤                                                                          ¤
¤           AQUIFER PROPERTIES AND LOCATION FOR WELL # 1                   ¤
¤                                                                          ¤
¤                                                                          ¤
¤                                                                          ¤
¤                                                                          ¤
¤                                                                          ¤
¤                         X Coordinate (ft): 848398.0                      ¤
¤                         Y Coordinate (ft): 548478.0                      ¤
¤             Well Discharge Rate (ft**3/d): 24595642.0                    ¤
¤                  Transmissivity (ft**2/d): 1300000.0                     ¤
¤        Hydraulic Gradient (dimensionless): 0.000360                      ¤
¤           Angle of Ambient Flow (degrees): -5.00                         ¤
¤          Aquifer Porosity (dimensionless): 0.20                          ¤
¤                    Aquifer Thickness (ft): 150.00                        ¤
¤                                                                          ¤
¤                                                                          ¤
¤                                                                          ¤
¤                                                                          ¤
àêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê¥
 <Enter> = select value   <Esc> = options menu   <F1> = DOS shell
```

```
èêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê-- MWCAP --êêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê£
□                                                                        □
□                                                                        □
□          AQUIFER PROPERTIES AND LOCATION FOR WELL # 1                  □
□                                                                        □
□                                                                        □
□                                                                        □
□                                                                        □
□                                                                        □
□                        X Coordinate (ft): 848398.0                     □
□                        Y Coordinate (ft): 548478.0                     □
□            Well Discharge Rate (ft**3/d): 19115092.0                   □
□                 Transmissivity (ft**2/d): 1300000.0                    □
□       Hydraulic Gradient (dimensionless): 0.000360                     □
□          Angle of Ambient Flow (degrees): -5.00                        □
□         Aquifer Porosity (dimensionless): 0.20                         □
□                   Aquifer Thickness (ft): 150.00                       □
□                                                                        □
□                                                                        □
□                                                                        □
□                                                                        □
àêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê¥
 <Enter> = select value   <Esc> = options menu   <F1> = DOS shell
```

```
èêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê-- MWCAP --êêêêêêêêêêêêêêêêêêêêêêêêêêêêêê£
□                                                                        □
□                                                                        □
□          AQUIFER PROPERTIES AND LOCATION FOR WELL # 1                  □
□                                                                        □
□                                                                        □
□                                                                        □
□                                                                        □
□                                                                        □
□                        X Coordinate (ft): 848398.0                     □
□                        Y Coordinate (ft): 548478.0                     □
□            Well Discharge Rate (ft**3/d): 16711230.0                   □
□                 Transmissivity (ft**2/d): 1300000.0                    □
□       Hydraulic Gradient (dimensionless): 0.000360                     □
□          Angle of Ambient Flow (degrees): -5.00                        □
□         Aquifer Porosity (dimensionless): 0.20                         □
□                    Aquifer Thickness (ft): 150.00                      □
□                                                                        □
□                                                                        □
□                                                                        □
□                                                                        □
àêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê¥
 <Enter> = select value   <Esc> = options menu   <F1> = DOS shell
```

```
èêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê-- MWCAP --êêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê£
¤                                                                         ¤
¤                                                                         ¤
¤          AQUIFER PROPERTIES AND LOCATION FOR WELL # 1                   ¤
¤                                                                         ¤
¤                                                                         ¤
¤                                                                         ¤
¤                                                                         ¤
¤                                                                         ¤
¤                         X Coordinate (ft): 848398.0                     ¤
¤                         Y Coordinate (ft): 548478.0                     ¤
¤            Well Discharge Rate (ft**3/d): 15372276.0                    ¤
¤                 Transmissivity (ft**2/d): 1300000.0                     ¤
¤       Hydraulic Gradient (dimensionless): 0.000360                      ¤
¤          Angle of Ambient Flow (degrees): -5.00                         ¤
¤         Aquifer Porosity (dimensionless): 0.20                          ¤
¤                   Aquifer Thickness (ft): 150.00                        ¤
¤                                                                         ¤
¤                                                                         ¤
¤                                                                         ¤
¤                                                                         ¤
àêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê¥
 <Enter> = select value   <Esc> = options menu   <F1> = DOS shell
```

APPENDIX A2. WHPA (MONTE CARLO)

```
èêêêêêêêêêêêêêêêêêêêêêêêêêêêêMONTEC  HELPêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê£
¤                                                                        ¤
¤ Number of Monte Carlo Runs:                                            ¤
¤                                                                        ¤
¤   The maximum number of Monte Carlo runs that may be specified         ¤
¤   is 1,000.  The maximum number of runs should be used for all         ¤
¤   final analysis.  For screening purposes, a smaller number of         ¤
¤   runs is generally sufficient (approximately 250-500).                ¤
¤                                                                        ¤
¤ Capture Zone Percentiles:                                              ¤
¤                                                                        ¤
¤   A maximum of 5 capture zone percentiles may be specified.            ¤
¤   The percentile values may be input as decimal fractions or           ¤
¤   as percentages (e.g. the 95 th percentile may be entered as          ¤
¤   95 or 0.95).  The smallest percentile that may be specified          ¤
¤   is 0.0, and the largest is 100% ( or 1.0).  Generally, 90th          ¤
¤   or 95th percentiles are used for regulatory purposes.                ¤
¤                                                                        ¤
¤                                                                        ¤
¤                                                                        ¤
¤                      Press any key to continue                         ¤
àêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê¥
```

```
MONTEC  HELP

 Distribution Type:
   One of the 7 distribution types must be assigned to  each
   of the aquifer input parameters Qw,K,i,n,b (see section 9.4.2
   of documentation). A distribution type of 0 (constant) should
   be used for variables that are not considered uncertain.  The
   user will be prompted only for the statistical input parame-
   ters that are required for a given distribution. For example,
   to define a uniform distribution, only the upper and lower
   bounds of the distribution are required.

 Upper and Lower Distribution Bounds:
   Some distribution types have no lower or upper bounds by
   definition (e.g. normal); however, it may be desirable in
   some instances to impose limits on the values that a random
   variable may assume.  For example, if Qw (pumping rate) has
   a normal distribuion, lower and upper bounds based on field
   observations and realistic projections of possible pumping

             Press any key to continue  <ESC=abort>
```

```
èêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêMONTEC  HELPêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê£
¤                                                                          ¤
¤   rates might be imposed.  If lower and upper bounds are used            ¤
¤   to constrain the values that a parameter may assume,  the              ¤
¤   bounds should be set as far away from the mean of the dist-            ¤
¤   ribution as is physically reasonable.  Note that imposing              ¤
¤   artificial bounds on a distribution will cause some bias in            ¤
¤   the sampling procedure.                                                ¤
¤                                                                          ¤
¤   Note: If the lower and upper bounds of a distribution are set          ¤
¤         equal to one another, MONTEC will not constrain the              ¤
¤         generated random variables to lie within any bounds.             ¤
¤         Therefore, if bounds are not desired simply select the           ¤
¤         default (0.0) for each bound.                                    ¤
¤                                                                          ¤
¤                                                                          ¤
¤                                                                          ¤
¤                                                                          ¤
¤                                                                          ¤
¤                                                                          ¤
¤                         Press any key to continue                        ¤
àêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê¥
```

```
MONTEC HELP

Capture Zone Type:
  MONTEC requires that a time-related capture zone be used.  A
  time-related capture zone is the surface or subsurface area
  surrounding a pumping well that will supply ground-water
  recharge to the well within a specified period of time.

Time Value:
  A time value (in days) must be specified for the time-
  related capture zone.  The value used will be a policy
  decision, but it should to some extent reflect the observed
  hydrogeological conditions.  CGWP generally recommmends that
  time periods of 10-25 years (3,650-9,125 days) be considered.

Number of Pathlines:
  Generally, 15-30 pathlines are sufficient for the delin-
  eation of time-related capture zones .  MONTEC may auto-
  matically trace additional pathlines if they are required
  to obtain an accurate representation of the capture zone.
                    Press any key to continue
```

```
èêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê-- MONTEC --êêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê£
¤                                                                              ¤
¤         Run Title: NW WELLFIELD DRY SEASON                                   ¤
¤                                                                              ¤
¤            Units to use for Current Problem:  1                              ¤
¤          (0 = meters and days, 1 = feet and days)                            ¤
¤                                                                              ¤
¤                     Aquifer Type Selection:  0                               ¤
¤          (0 = confined, 1 = leaky-confined)                                  ¤
¤                                                                              ¤
¤                                                                              ¤
¤                      Minimum X-Coordinate:  815580.0                         ¤
¤                      Maximum X-Coordinate:  885762.0                         ¤
¤                      Minimum Y-Coordinate:  518027.0                         ¤
¤                      Maximum Y-Coordinate:  594368.0                         ¤
¤                                                                              ¤
¤                Maximum Spatial Step Length:  701.8                           ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                                                              ¤
àêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê¥
 <Enter> = select value    <Esc> = options menu    <F1> = DOS shell
```

```
èêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê-- MONTEC --êêêêêêêêêêêêêêêêêêêêêêêêêêêêêê£
¤                                                                      ¤
¤                                                                      ¤
¤          AQUIFER PROPERTIES AND LOCATION FOR WELL # 1                ¤
¤                                                                      ¤
¤       Note: restricted to one well only per MONTEC run               ¤
¤                                                                      ¤
¤                        X Coordinate (ft): 848398.0                   ¤
¤                        Y Coordinate (ft): 548478.0                   ¤
¤               Effective Well Radius (ft): 1.75                       ¤
¤          Angle of Ambient Flow (degrees): -5.00                      ¤
¤                                                                      ¤
¤               Maximum Permitted Drawdown                             ¤
¤                 at the Pumping Well (ft): 0.50                       ¤
¤                                                                      ¤
¤                                                                      ¤
¤                                                                      ¤
¤                                                                      ¤
¤                                                                      ¤
¤                                                                      ¤
¤                                                                      ¤
àêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê¥
 <Enter> = select value   <Esc> = options menu   <F1> = DOS shell
```

```
-- MONTEC --

        ** MONTE CARLO RUN SPECIFICATIONS **

         Number of Monte Carlo Runs: 500

          Number of Desired Capture:
                   Zone Percentiles: 2

                 Percentile No.  2

             Percentile Value:  90.00
             Percentile Value:  95.00

 <Enter> = select value   <Esc> = options menu   <F1> = DOS shell
```

```
èêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê-- MONTEC --êêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê£
¤                                                                              ¤
¤           ** UNCERTAIN INPUT PARAMETER DISTRIBUTION DATA **                  ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                                                              ¤
¤                              DISCHARGE RATE                                  ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                        VALUE:  24595642.0                    ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                                                              ¤
àêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê¥
 <Enter> = select value   <Esc> = options menu   <F1> = DOS shell
```

```
èéééééééééééééééééééééééééééééééé-- MONTEC --éééééééééééééééééééééééééééééééé»
¤                                                                              ¤
¤         ** UNCERTAIN INPUT PARAMETER DISTRIBUTION DATA **                    ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                                                              ¤
¤                         HYDRAULIC CONDUCTIVITY                               ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                        MEAN:  8738.8                         ¤
¤                         STANDARD DEVIATION:  10422.0                         ¤
¤                                LOWER BOUND:  50.0                            ¤
¤                                UPPER BOUND:  29000.0                         ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                                                              ¤
¤                                                                              ¤
àéééééééééééééééééééééééééééééééééééééééééééééééééééééééééééééééééééééééééééééé¥
 <Enter> = select value   <Esc> = options menu   <F1> = DOS shell
```

```
èêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê-- MONTEC --êêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê£
¤                                                                            ¤
¤           ** UNCERTAIN INPUT PARAMETER DISTRIBUTION DATA **                ¤
¤                                                                            ¤
¤                                                                            ¤
¤                                                                            ¤
¤                              HYDRAULIC GRADIENT                            ¤
¤                                                                            ¤
¤                                                                            ¤
¤                                   LOWER BOUND:  0.000300                   ¤
¤                                   UPPER BOUND:  0.000400                   ¤
¤                                                                            ¤
¤                                                                            ¤
¤                                                                            ¤
¤                                                                            ¤
¤                                                                            ¤
¤                                                                            ¤
¤                                                                            ¤
¤                                                                            ¤
¤                                                                            ¤
¤                                                                            ¤
àêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê¥
 <Enter> = select value   <Esc> = options menu   <F1> = DOS shell
```

```
èêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê-- MONTEC --êêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê£
□                                                                            □
□           ** UNCERTAIN INPUT PARAMETER DISTRIBUTION DATA **               □
□                                                                            □
□                                                                            □
□                                                                            □
□                                  POROSITY                                  □
□                                                                            □
□                                                                            □
□                                   LOWER BOUND:  0.20                       □
□                                   UPPER BOUND:  0.30                       □
□                                                                            □
□                                                                            □
□                                                                            □
□                                                                            □
□                                                                            □
□                                                                            □
□                                                                            □
□                                                                            □
□                                                                            □
□                                                                            □
àêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê¥
 <Enter> = select value   <Esc> = options menu   <F1> = DOS shell
```

```
-- MONTEC --

        ** UNCERTAIN INPUT PARAMETER DISTRIBUTION DATA **


                      AQUIFER THICKNESS

                                 VALUE:  150.0

 <Enter> = select value   <Esc> = options menu   <F1> = DOS shell
```

```
èêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê-- MONTEC --êêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê£
□                                                                              □
□                 CAPTURE-ZONE TYPE OPTION FOR WELL # 1                        □
□                                                                              □
□                                                                              □
□                      Capture-Zone Type Option: 2                             □
□                                                                              □
□                         0 = steady-state                                     □
□                         1 = hybrid                                           □
□                         2 = time-related <= (must use for Monte              □
□                                               Carlo option)                  □
□                                                                              □
□                                                                              □
□                            Travel Time (days): 500.00                        □
□                                                                              □
□                   Number of Pathlines Desired: 20                            □
□                        (default = 20)                                        □
□                                                                              □
□                                                                              □
□                                                                              □
□                                                                              □
àêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêêê¥
 <Enter> = select value   <Esc> = options menu   <F1> = DOS shell
```

APPENDIX A3. WHAEM

```
<AQUIFER><GIVEN><REFERENCE><WELL><LINESINK>
<HEAD>(X,Y)<DISCHARGE>(X,Y)<CONTROL><SUMMARY><HELP><RETURN>
sum
GIVEN SUMMARY
UNIFORM FLOW ADDED                          : YES
RAINFALL ADDED                              :  NO
PLEASE PRESS ENTER FOR CONTINUED DISPLAY

WELL SUMMARY
TOTAL NUMBER OF WELLS                       :    15
 WITH GIVEN STRENGTH                        :    15
 WITH HEAD SPECIFIED                        :     0
MAXIMUM NUMBER OF WELLS                     :   150
FACTOR FOR GIVEN DISCHARGE =    1.000000E+00
PLEASE PRESS ENTER FOR CONTINUED DISPLAY

LINE-SINK [CONSTANT] SUMMARY
TOTAL NUMBER OF LINESINKS                   :    0
 WITH GIVEN STRENGTH                        :    0
 WITH HEAD SPECIFIED                        :    0
MAXIMUM NUMBER OF LINESINKS                 : 150
\\\  Module=CHECK                  Level=1    Routine=INPUT                ///
<AQUIFER><GIVEN><REFERENCE><WELL><LINESINK>
<HEAD>(X,Y)<DISCHARGE>(X,Y)<CONTROL><SUMMARY><HELP><RETURN>
```

```
MAXIMUM NUMBER OF WELLS                    :  150
FACTOR FOR GIVEN DISCHARGE =    1.000000E+00
PLEASE PRESS ENTER FOR CONTINUED DISPLAY

LINE-SINK [CONSTANT] SUMMARY
TOTAL NUMBER OF LINESINKS                  :    0
 WITH GIVEN STRENGTH                       :    0
 WITH HEAD SPECIFIED                       :    0
MAXIMUM NUMBER OF LINESINKS                : 150
\\\  Module=CHECK               Level=1    Routine=INPUT                ///
<AQUIFER><GIVEN><REFERENCE><WELL><LINESINK>
<HEAD>(X,Y)<DISCHARGE>(X,Y)<CONTROL><SUMMARY><HELP><RETURN>
aquifer
\\\  Module=CHECK               Level=2    Routine=AQUIFER CHECK        ///
<SUMMARY><RETURN>
sum
AQUIFER   PERMEABILITY      :  2.641000E+03
          THICKNESS         :  4.571000E+01
          ELEVATION BASE    :  0.000000E+00
          POROSITY          :  0.200000E+00
          TIME FACTOR       :  1.000000E+00
          ELEVATION TOP     :  4.571000E+01
\\\  Module=CHECK               Level=2    Routine=AQUIFER CHECK        ///
<SUMMARY><RETURN>
```

```
          ELEVATION TOP      :  4.571000E+01
\\\  Module=CHECK                 Level=2    Routine=AQUIFER CHECK      ///
<SUMMARY><RETURN>
ret
\\\  Module=CHECK                 Level=1    Routine=INPUT              ///
<AQUIFER><GIVEN><REFERENCE><WELL><LINESINK>
<HEAD>(X,Y)<DISCHARGE>(X,Y)<CONTROL><SUMMARY><HELP><RETURN>
given
\\\  Module=CHECK                 Level=2    Routine=GIVEN CHECK        ///
<SUMMARY><UNIFLOW><RAIN><HELP><RETURN>
sum
GIVEN SUMMARY
UNIFORM FLOW ADDED                     : YES
RAINFALL ADDED                         :  NO
\\\  Module=CHECK                 Level=2    Routine=GIVEN CHECK        ///
<SUMMARY><UNIFLOW><RAIN><HELP><RETURN>
uniflow
DISCHARGE RATE Q0       4.350000E+01
DIRECTION IN DEGREES  -5.000000E+00; IN RADIANS  -8.726646E-02
\\\  Module=CHECK                 Level=2    Routine=GIVEN CHECK        ///
<SUMMARY><UNIFLOW><RAIN><HELP><RETURN>

\\\  Module=CHECK                 Level=2    Routine=GIVEN CHECK        ///
<SUMMARY><UNIFLOW><RAIN><HELP><RETURN>
```

```
\\\  Module=CHECK                  Level=2    Routine=WELL CHECK        ///
<SUMMARY><RANGE>({<GIVEN>/<HEAD>},START) [END]<INPUT><CONTROL><HELP><RETURN>
range given 1,15
\\\  Module=CHECK                  Level=2    Routine=WELL CHECK        ///
<SUMMARY><RANGE>({<GIVEN>/<HEAD>},START) [END]<INPUT><CONTROL><HELP><RETURN>
input
 NR            XW            YW     DISCHARGE        RADIUS       LABEL
  1  2.587391E+05  1.685559E-05  2.899000E+04  5.330000E-01
  2  2.587461E+05  1.683194E+05  2.899000E+04  5.330000E-01
  3  2.587525E+05  1.680758E+05  2.899000E+04  5.330000E-01
  4  2.587525E+05  1.678324E+05  2.899000E+04  5.330000E-01
  5  2.587668E+05  1.676306E+05  2.899000E+04  5.330000E-01
  6  2.587738E+05  1.674148E+05  2.899000E+04  5.330000E-01
  7  2.587808E+05  1.671783E+05  2.899000E+04  5.330000E-01
  8  2.583773E+05  1.671576E+05  2.899000E+04  5.330000E-01
  9  2.583773E+05  1.669347E+05  2.899000E+04  5.330000E-01
 10  2.583843E+05  1.666983E+05  2.899000E+04  5.330000E-01
 11  2.583980E+05  1.664684E+05  2.899000E+04  5.330000E-01
 12  2.583913E+05  1.662389E+05  2.899000E+04  5.330000E-01
 13  2.584051E+05  1.660094E+05  2.899000E+04  5.330000E-01
 14  2.584190E+05  1.658076E+05  2.899000E+04  5.330000E-01
 15  2.583913E+05  1.655016E+05  2.899000E+04  5.330000E-01
\\\  Module=CHECK                  Level=2    Routine=WELL CHECK        ///
<SUMMARY><RANGE>({<GIVEN>/<HEAD>},START) [END]<INPUT><CONTROL><HELP><RETURN>
```

```
ENTER COMMAND WORD FOLLOWED BY ? FOR BRIEF HELP FROM ANY MENU
<AQUIFER>       <WINDOW>[(X1,Y1,X2,Y2)/<ALL>/<PUSH>/<POP>]   <HELP>
<GIVEN>         <MAP>                                        <SWITCH>[FILE]
<REFERENCE>     <LAYOUT>                                     <SAVE>
<WELL>          <GRID>(NUMBER OF POINTS)                     <READ>
<LINESINK>      <PLOT>                                       <PAUSE>
<SOLVE>         <TRACE>                                      <RESET>
<CHECK>         <CURSOR>                                     <PSET>
                                                             <STOP>
check
\\\  Module=CHECK              Level=1    Routine=INPUT              ///
<AQUIFER><GIVEN><REFERENCE><WELL><LINESINK>
<HEAD>(X,Y)<DISCHARGE>(X,Y)<CONTROL><SUMMARY><HELP><RETURN>
well
\\\  Module=CHECK              Level=2    Routine=WELL CHECK         ///
<SUMMARY><RANGE>({<GIVEN>/<HEAD>},START)[END]<INPUT><CONTROL><HELP><RETURN>
range given 1
\\\  Module=CHECK              Level=2    Routine=WELL CHECK         ///
<SUMMARY><RANGE>({<GIVEN>/<HEAD>},START)[END]<INPUT><CONTROL><HELP><RETURN>
input
 NR           XW            YW      DISCHARGE        RADIUS      LABEL
  1  2.585791E+05  1.671679E+05  4.356060E+05  5.330000E-01
\\\  Module=CHECK              Level=2    Routine=WELL CHECK         ///
<SUMMARY><RANGE>({<GIVEN>/<HEAD>},START)[END]<INPUT><CONTROL><HELP><RETURN>
```