APPLICATION OF THE EPA WHPA MODEL FOR DELINEATION OF WELLHEAD PROTECTION AREAS IN THE GLENDALE AND EASTERN STATES WELLFIELDS, NEW CASTLE COUNTY, DELAWARE

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For
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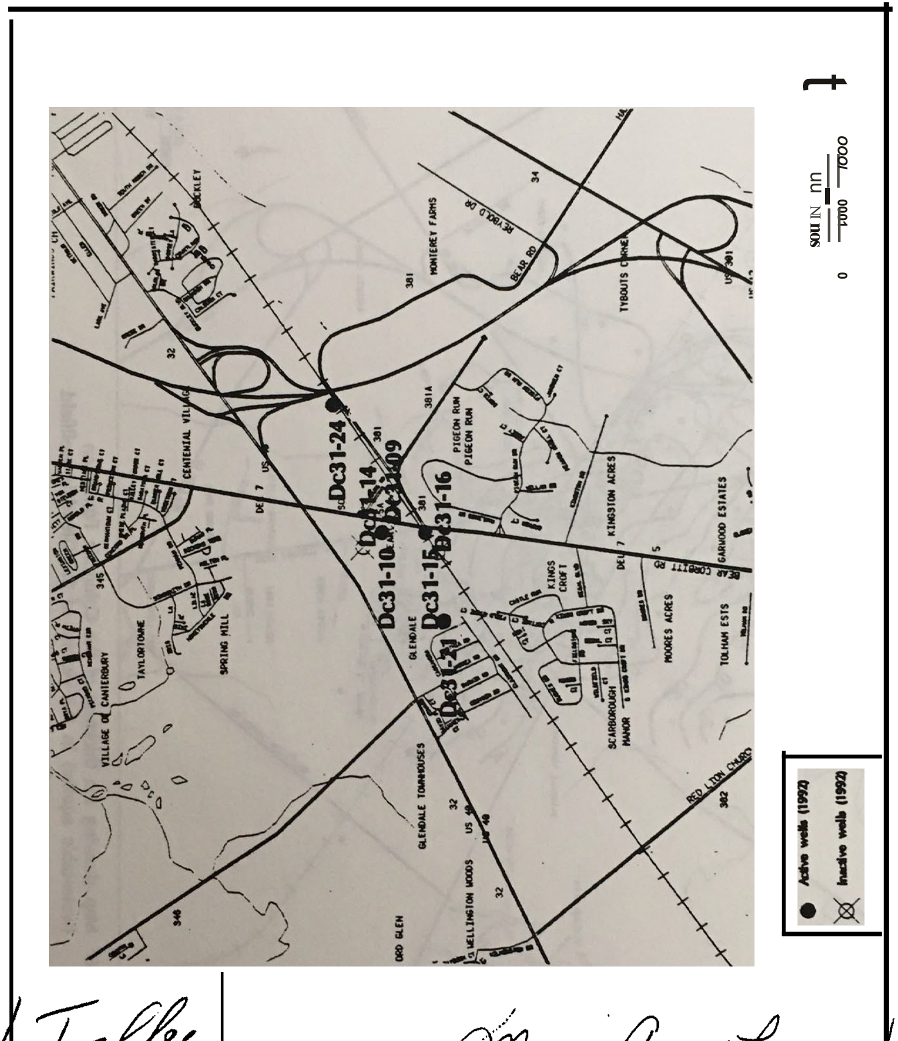

Figure 5. Glendale wellfield showing locations of active and inactive public water supply wells.

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ILLUSTRATIONS

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TABLES

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INTRODUCTION

Ba c kground

A federal Wellhead Protection Pr
Amendments to the Safe Drinking Water am (WHP) was established in the 1986
protect ground waters that ares . Th purpose of the program is to
element of the **program** is to d l?urces of public water supply. A major
e·ach well or wellfield throughe t :eat wellhead protection areas (WHPAs)
for such **as ground-water** flow h utilization of available hydrologic data
·other information that an'i : v gei discharge and aquifer properties, and
A wellhead protection area is def a dstat! considers necessary to map WHPAs.
surrounding a water well or wellfi: d as ...the surface and subsurface area
through which contami t • supplyinga public water system
water well or wellfier: E; e ;:;nablyElikely to move toward and rea h such
areas is based on guid li ' bl• p. S-1). The need to delineate such
" e nes esta ished by the EPA. The guidelines

··.assume that WHPA delineation and protection will be targeted to three general threats. The first is the direct introduction of contaminants to the area immediately contiguous to the well through improper well construction road runoff, and accidental spills. A second basic threat is from microbi l contaminants such as bacteria and viruses.- The third major threat is the broad range of chemical contaminants, including inorganic and naturally occurring or synthetically-derived organic chemicals" (EPA, 1987, page ES-3).

The New Castle County Water and Sewer Office and later, the Water Resources Agency for New Castle County (WRA), have long been concerned with ensuring th quantity and protecting the quality of both surface and ground water that 1s used for water supply purposes in the county. As part of their continuing effort to ensure both quantity and quality to meet current and future demands for water, the WRA developed the "Water Resource Protection Area Program Revision• in November 1987 (WRA, 1987b).

As an initial introduction to wellhead.protection area delineation, the WRA enlisted the technical expertise of the Delaware Geological Survey (DGS) and Yater Supply Branch of the Delaware Department of Natural Resources and Environmental Control (DNREC) to delineate wellhead protection areas in New Castle County. This effort culminated in the preliminary delineation of wellhead protection **areas** and the production of a set of three maps that show wellhead protection areas as well as ground-water recharge protection areas (Yater Resource Protection Areas for City of Newark, City of Wilmington, New Castle County, **Delaware;** WRA, 1987a). The wellhead protection areas were delineated on the basis of review of geologic and hydrologic information, and the current understanding of the hydrogeologic framework based on decades of work by the DGS in New Castle County. At this time, the WRA is interested in developing and utilizing state of the art methodology to refine one previously delineated **wellhead** protection area (Glendale) and to delineate one new wellhead protection area (Eastern States).

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Purpose and Scope

The primary purpose of this investigation is to evaluate criteria and methodologies suggested for use by the EPA in the 1987 report "Guidelines for Delineation of Wellhead Protection Areas" and to determine their applicability to delineating wellhead protection areas at two public water supply wellfields (Glendale and Eastern States), both of which are located in the Atlantic Coastal Plain province of New Castle County. In addition to these guidelines, the EPA has developed PC-based computer models that can be used for wellhead delineation (A Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas, Version 2.0; EPA, 1991). The programs contain semi analytical capture zone solutions. In this current project, this wellhead protection area (WHPA) code is evaluated for its applicability in delineating wellhead protection areas in the Glendale and Eastern States wellfields.

The Glendale wellfield was selected in part because of the detail of historical hydrogeologic information available for the site that can be used in the USEPA modules. In addition, the area within and around the wellfield is undergoing rapid development which could lead to a reduction in ground water recharge and an increase in the potential for ground-water quality degradation. The Glendale wellfield, which has had wells in operation since 1959, contains four active wells with a combined alloc tion of 1.8 mgd (million gallons per day). One is completed in a water-table aquifer in the Columbia Formation and possibly part of the Potomac Formation. Three are completed in a semi-confined aquifer in the Potomac Formation.

The Eastern States wellfield is relatively new in that ground-water withdrawals began in 1981. This wellfield was selected for several reasons: (1) the area is relatively undeveloped with a potential for rapid development that has already begun; (2) the wellfield contains wells in both Delaware and Maryland that exhibit interference with one another; (3) the quantity and quality of ground water must be protected to ensure proper management of the wellfield to provide for continuous water supplies; (4) the area has limited ground-water resources available; (5) a significant amount of geologic and hydrologic data are available; and (6) a report by the Maryland Water Resources Administration (1989) suggests that the producing aquifer is less confined than was previously thought.

The Eastern States wellfield contains two active wells in an aquifer in the Potomac Formation in Delaware. The allocated withdrawal rate is 1.3 mgd. A third well operated by the Town of Elkton, Maryland is also completed in the Potomac Formation. The allocation for this well is 0.8 mgd. All three wells were included in the evaluation because they are completed in the same aquifer and are hydraulically connected.

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The first step in defining a wellhead protection area is to develop an understanding of the geologic and hydrologic framework that controls the occurrence and movement of ground water. Delineation involved the use and analysis of existing geologic and hydrologic information and the application of relevant USEPA modules. Because of the complex geologic and hydrologic framework in both the Glendale and Eastern States areas, compilation and analysis of data prior to application of WHPA code required several weeks.

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Input data used in the models were derived from data analysis. Daily pumpage figures used in the models were derived from DNREC permitted allocations for wells Da43-03 and Da44-06 and from 1987 pumpage for well Ce-Bf-59 (Maryland Water Resources Administration, 1989).

Acknowledgments

Funding was provided by the WRA from the FY 1989-1991 Capitol Budgets of New Castle County in support of its Water Resources Protection Area Program Additionally, the WRA provided funds for a staff person to assist in evaluating wellhead delineation computer models from a grant it received from the U. S. EPA for developing a pilot wellhead protection data management program.

The WRA also provided information and staff support. In particular, Mr. David Racca from the WRA assisted in the development of maps and figures, and provided guidance related to Geographic Information System applications. Bruce Kraeuter, Artesian Water Company, provided water use data and well construction information for several wells in the Glendale and Eastern States wellfields. Stewart Lovell, Water Supply Branch, DNREC, provided well and wellfield allocation information. The New Castle County Department of **Planning** provided consultants reports for proposed development pro ects in.the vicinity of the two wellfields from which geologic and hydrologic information was extracted. The USEPA WHPA code was provided by Fred Sterniolo, USEPA.

METHODOLOGY

WHPA Delineation Criteria

Many criteria can **be used** to define the boundaries of a wellhead protection **area**. The U.S. Environmental Protection Agency described five delineation criteria (**EPA**, 1987).

1. Distance - utilizes a radius measured from a pumping well toa point of concern. Kost direct way of delineating a wellhead **protection area. Has** frequently been used as a first step in **delineation.**

2. **Drawdown- refers** to the extent to which the water level in the **aquifer will be lowered** under specific pumping conditions. Is **outlined by a •cone** of depression• or "**area** of influence." A **drawdown must be selected, e.g.** one ft. Is calculated uslng an equation such as Theis.

3. Time of Travel- refers to the maximum time for a contaminant to reach a well.

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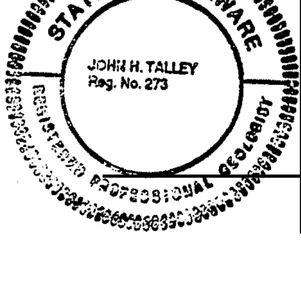

4. Flow Boundaries - criteria is based on the concept of determining the locations of ground-water divides and/or other physical features that control ground-water flow.

5. Assimilative Capacity - based on concept of using the. ability of aquifer materials to attenuate contaminants to acceptable levels before they reach a well.

Terminology

A review of the terminology of ground-water hydraulics is helpful in considering these different criteria. Figure 1 illustrates various zones associated with ground-water transport in a hypothetical aquifer over five and ten year periods of pumping. As background, note that the terrain is sloping, with the nearby ridge acting as a ground-water divide and that the prepumping water level is indicated as a surface more or less parallel to the overlying ground surface.

One approach to delineating wellhead protection areas is to use a drawdown criterion, such as that area around the well in which the prepumping water level is reduced by at least one foot due to the pumping well. By focusing on the cone of depression (synonymous with the zone of influence) in Figure 1, the drawbacks of this approach become clear. As a well is pumped, a funnel-shaped cone of depression in ground-water head develops around the well, with boundaries defined where the prepumping water level has not dropped. In plan view, the cone of depression is ovate and elongate down gradient from the well. The greater drawdown near the well is indicated by the closely spaced drawdown contours around the pumping well. The problem with using this approach to defining wellhead protection areas is that the ground-water gradient, and not the values of head alone, control the direction of water flow. Thus, the cone of depression may not coincide with the area which contributes water to the well. In general, the cone of depression includes areas down gradient which do not contribute water to the well and excludes areas up gradient which will contribute to the well during future withdrawals.

A more sophisticated approach to wellhead delineation is to use zones of. transport (ZOT) or zones of contribution (ZOC), which incorporate the time-of travel and flow boundary criteria as well as the drawdown criterion. In plan view (Figure 1) the ZOT is ovate and elongate in the up gradient direction. The down gradient limit of the ZOT occurs at the stagnation point, or point of zero ground-water flow. The stagnation point indicates the divide between flow toward and from the well and occurs <u>within</u> the cone of depression (ZOI) where ground water head has been dropped by **the pumping** well. Up gradient, the ZOT extends indefinitely, unless a flow boundary such as a ground-water divide is reached. Thus, the ZOT defines the area which will provide water to a well over a specified period of time.

A ZOC (synonymous with capture zone) **is a** ZOT that is determined by using a specific period of pumping in the USEPA modules. Note in Figure 1

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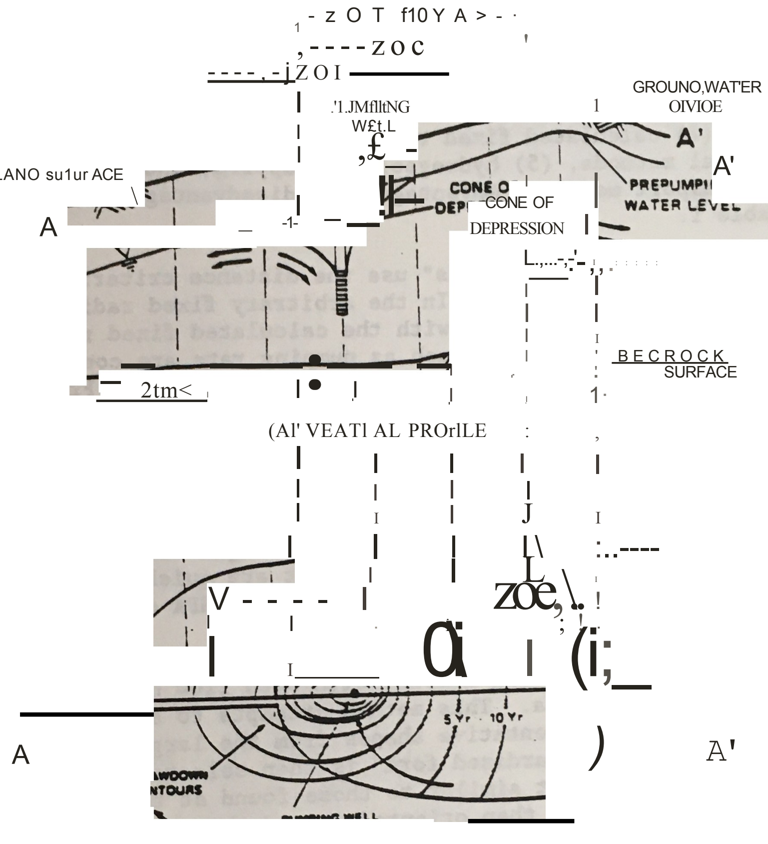
CRITERIA: DRAWDOWN AND TIME-OF-TRAVEL



(B) PLAN VIEW

LEGEND:

ZOC Zone of Contribution

ZOI Zone of Influence

ZOT Zone of Transport

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Figure 1. EPA criteria, drawdown, and time-of-travel. (From EPA, 1987, p. 2-21)

that the down gradient limits of the ZOC and ZOT are the same. Up gradient, as the ime of travel is increased from five to ten years, the ZOC increases in size, gradually approaching the ZOT of indefinite time.

EPA METHODOLOGY

The EPA (1987) described six specific methods to implement criteria used in mapping wellhead protection areas. The six methods, in order of increasing cost, sophistication, and technical requirements are: (1) arbitrary fixed radius, (2) calculated fixed radius, (3) simplified variable shapes, (4) analytical methods, (5) hydrogeologic mapping, and (6) numerical flow/transport models. Advantages and disadvantages of each method are listed in Table 1.

The two "radius methods" use the distance criterion to define circular wellhead protection areas. In the arbitrary fixed radius method, the radius of the circle is arbitrary; with the calculated fixed radius approach, a few aquifer or well properties such as pumping rate are considered in calculating the radius to describe the circular protection area. From the above discussion, it is clear that the capture zones (those areas which supply water to wells) in a given geographical area will rarely be closely approximated by the same symmetric, circular areas surrounding all pumping wells. These methods have most value in isotropic, homogeneous aquifers with no complexities such as stream boundaries, ground-water divides, or other complexities associated with most hydrogeologic settings. These approaches alone are not technically defensible, but are quick and inexpensive and can be applied in the draft or "first cut" stage of WHPA delineation.

In the simplified variable shapes method, "standardized forms" are generated using analytical models, with both flow boundaries and time of travel used as criteria. This method attempts to simplify implementation by selecting a few representative shapes from the large array of possibilities. The appropriate "standardized form" is then selected for hydrogeologic and pumping conditions most similar to those found at the wellhead. The "standardized form" is then oriented-around the well according to ground-water flow patterns. The variable shapes are calculated by first computing the down gradient and lateral boundaries of the capture zone, then-using a time of travel criterion to cap the up gradient boundary. Although more sophisticated than the radius approaches, this method is also not applicable to geologically complex areas, and is not very defensible since standard forms are applied to many hydrogeologic settings.

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The final three approaches, analytical methods, hydrogeologic mapping, and numerical flow/transport models, can incorporate much site-specific information and are more directly applicable to geologically complex areas than the other three. A combination of these three approaches was used to define the Glendale and Eastern States wellhead protection areas.

As described by the EPA (1987), the analytical method is the application of uniform flow equations (Todd, 1980) to define the capture zone (ZOC) of a pumping well in an area where the water table or potentiometric surface is sloping. Although this approach has been used successfully in several areas, we did not evaluate these equations in the Glendale and Eastern States wellfields.

Tobie 1. EPA ffMtllodology, and adYanlagN and diMdYanlallN al •ch me41lod. (EPA. 1987).

METHOD	ADVANTAGES	DISADVANTAGES
ARBITRARY FDCED RADIUS	I. Requirea rala_.,- technical axp«tjN. 2. . . . x p - . 3. Raia--,..... In that• large numb• of welhead .,..,can be delinNNd in • lhort period ol lme. 4. - . . . . l o w - -	1. High <MgrN of uncertainty due to lack of avuability « appWealion of technical informalion. 2. May tend to IJnN orav.protect welhNd arMa. 3. Noti.chnicalydel-,lible.
CAI.CULATED FDCED RA0ff.IS	1. F l a q u s M - - ____. . . . . 2. - l l w l y - t o e p p l y . 3. - l l w l y . . . . ln-•wvenu- of ......_d areu can be delineated in a lhofl periodd time. 4. -ti w l ylowCOIi: bu-t - art,, nry ftx'ed radiue bec:auae mote -ii r.-......inflo armali.o_n..a_nd •xp«tjN	I. Large p,obabilily lo,"""•__., WI geo6ogically complex ar•a. Often requiree hydraulic chanl-• ol aquilon. many UlUfflPIN>na: wiill'1 rnpeet to 2. Not ve,y tachnically dol-,oible.
SIMPUFIED VAIIABI.E SHAPES	1. Eaaily applied once!he ot.pee haw - - . i c , p . d . 2. FlaqusM- - e x p « t j M . 3. More rellned llwl lbced radiua. 4. Coata ol l......,_..tlon a l t• dr,oiopment d r o m . l a m o d e r a i . .	1. Large probability lo, - in gaclogicdy c o m p l e x . , ... 2. Not ve,y technically delenaible since a,_ "Otllndardized lonno" are appMd to many hydrag olaa'c Mtllnga.
ANALYTICAL IIETH008	1. -auily- by para- hydrag1alagi• andenginNn quufed 2Requirea--...-hydraullc lllat lMld .,.-Yto-ted araa•. 3-• -lher.i,y comparioona - p e c t i o n 4la-.c lbgmy to bea valid a cll lor a..-.g drawdown near	1.Hydrologlc-aquil•----• ad —inlbml cpilatlon 0, -- 2. la more coclly In - ij requir• analyeia lranlpiration are noc a=cted lor. b y - . . i l > - ' 8 • inhydrogeology.
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NUMERICAL FLOW/ TIIANIPOIII'MO	1.,.-., , , 2. _bl g l l degrNolacuracyand anc1....agla lagla .- ....compl ex. locali zed . . 3 .c an .,,-- -lrom 4.lage weil...nap liouleto-lint	1. Requlrwcoo----and llaining in hya a a a, and moelling. 2. Reciulrw•--ol...- hydrogeologic inlolmaljono.. - 3. C o e t l y . - o l - - - -

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Yith·respect to the Glendale and Eastern States wellfields, analytical equations were applied to field pump test data to determine hydraulic characteristics of the aquifers. These parameters were then used as inputs for more complex USEPA modules.

Numerical flow/transport models are appropriate in geologically complex areas where simpler approaches fail to consider boundaries and inhomogeneities which can significantly affect the shapes of capture zones around wells. · Necessarily, these models require considerable site-specific inputs such as aquifer hydraulic conductivity, thickness, porosity, pre-pumping gradients and directions of flow, and specific well information such as well diameter, period of operation, and rates of discharge. They may account for recharge to the water-table aquifer or to a semi-confined aquifer through leakage, and for ground-water boundaries such as streams or ground-water divides. The more ·sophisticated and complex the model, the more input parameters must be calculated, measured, or estimated.

"When possible, even the best modeling efforts should be field checked with the technique of hydrogeologic mapping, which involves collection and analysis of geologic and hydrologic data to develop a hydrogeologic framework. It involves utilizing a_number of techniques such as aquifer test analysis, water-level data collection and analysis, analysis of.geophysical, geologists', and drillers' logs, analysis of water-quality data, and analysis of pumpage records. Data analysis and interpretation enable one to construct structure contour maps, thickness maps of aquifers and confining units, hydrogeologic cross-sections, water-table and potentiometric surface maps, and to determine hydraulic characteristics of aquifers. This field oriented approach lends more credibility and defensibility to wellhead protection area delineation in geologically complex areas than the more simplified methods.

There are nearly as many separate ground-water flow models as there are unique hydrogeologic situations. Van der Heijde and Beljin (1988) authored an EPA sponsored project in which they evaluated 64 models for possible use in delineating wellhead protection areas. In the late 1980s, the EPA contracted for the development of wellhead protection area software that could be used to assist in delineating wellhead protection areas. The resultant model (WllPA) is PC-based and user friendly. The WllPA model consists of four independent modules that use time-of-travel as a required input parameter for delineating capture zones. The modules include RESSQC, MWCAP, GPTRAC, and MONTEC. MONTEC is used primarily for sensitivity analysis; thus, there are essentially three modules available to delineate capture zones. Table 2 contains a description of the WllPA modules and Table 3 contains required input parameters. These modules were used to delineate wellhead protection areas in the Glendale and Eastern States wellfields.

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Table 2. Description of WHPA model computational modules. (From EPA 1991, p. 5.2)

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

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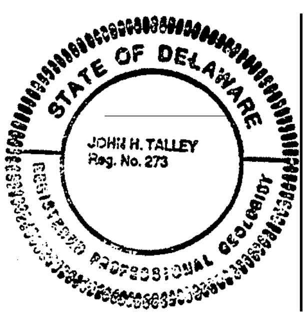

Table · 3. Required input for WHPA model computational modules. (From EPA, 1991, p. 5.3.)

Required Laput	RESSQC	MWCAP	GPTRAC Semi-anat,ticaJ	GPTRAC Numeric:ii
Units used	■	■	●	■
Aquifer type•	●	■		
Stuciy area limits	●		●	●
Maximum stc:p length		■	●	
No. of pumping weils	■	●	●	●
No. of recharge weils	●		●	●
Well locations	●	●	●	●
Pumpingiinjection ratc::s				●
Aquifer transmissivity	●	●	●	●
Aquifer porosity	■	■	●	■
Aquifer thic:kn=s	■	●	●	●
Angie of ambient tlow	■	■		
Ambient hydraulic gradient	●	●	●	
Areal recharge rate			●	
-Confining layer hydraulic conductivity			●	
Confining layer thicicl=			●	
Boundary condition type		●	●	
Perpendicular climnce from well to boundary		■		
Orientation of boundary		■	●	
Capture zone type		■		
No. of padilines used *to* delinC3te capwri: zcnes	●	●	●	●
Simulation time	●		●	
Capture zcne time	■	■		●
Rectangular grid parameters	●		●	■
No. of forward/revet= patbliaes				●
Starting coordinates fer corward/reverx pad:finc:s	●		●	
Nodal head values				●
No. of lleterogenecus aquifer zcnes				●
Heterogeneous 3C!Uifer pro es				●

•Confined, unconfim:d or le:lky-confmed.

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GEOLOGIC SETTING, NEV CASTLE COUNTY

New Castle County encompasses parts of two regional geologic provinces: the Appalachian Piedmont and the Atlantic Coastal Plain (Figure 2). The Piedmont province north of the Fall Zone is characterized by gently rolling hills underlain by very old (late Precambrian-early Paleozoic) crystalline rocks mantled by a weathered zone. The surface of this complex slopes seaward, forming the basement complex for the wedge-shaped mass of Coastal Plain sediments (Figure 3). The Atlantic Coastal Plain is comprised of unconsolidated gravels, sands, silts, and clays that range in thickness from near zero along the Fall Zone to approximately 2,300 ft in the southeastern part of the county (Figure 3). Within the Coastal Plain of New Castle County, ground water is available and is withdrawn from aquifers in the following geologic units: the Potomac, Magothy, Englishtown-Mt.Laurel and Columbia formations and the Rancocas Group (Figure 2; Table 4).

Units that are part of the water-table or unconfined aquifer systems are particularly susceptible to contamination because of their hydrologic characteristics and position with respect to land surface. These aquifers occur in the surficial Columbia Formation and in sandy zones in formations that directly underlie the Columbia. In **many** areas in the Coastal Plain of northern New Castle County, aquifers in the Potomac Formation are relatively close to the surface and function as water-table or leaky confined aquifers.

A more in-depth description of the Columbia and Potomac formations is presented because these two formations occur in the vicinity of the Glendale and Eastern States wellfields, the wellfields in which wellhead areas were delineated as part of this project.

In general, the Columbia Formation contains the surficial or water-table aquifer. This formation consists of orange, tan, and yellow fine-, medium-, and coarse-grained sands and gravels. Gravel deposits, cobbles, and boulders are present with most of the coarser material located in the northern portion of **Delaware** (Jordan, 1964). The sediments are fluvial in origin and •...represent deposits of a major stream system...• (Jordan, 1964, p. v). The dispersal pattern suggests that the sediment entered Delaware from the northeast, **from** the valley of the Delaware River between Wilmington, DE and Trenton, NJ and spread south and southeast across Delaware (Jordan and Talley, 1976). In New Castle County, the thickness of the deposits is generally less that 40 ft; the saturated thickness is usually not enough to sustain high yielding production wells. Two exceptions to this situation occur when: (1) sands in the Columbia are in direct contact with underlying Potomac sands, and (2) where sands in the Columbia have been channeled into the Potomac Formation and are locally 111Uh thicker than usual. In both cases the total saturated thickness is generally higher than average and wells yielding up to several hundred gallons per minute may be constructed. This situation prevails in the Glendale **area**.

The Potomac Formation consists of clays, silts, and sands, and some **gravel. Sands are** generally white, gray, and rust-brown, while silts and clays **are variegated** white, yellow, and red. The Potomac was deposited in a

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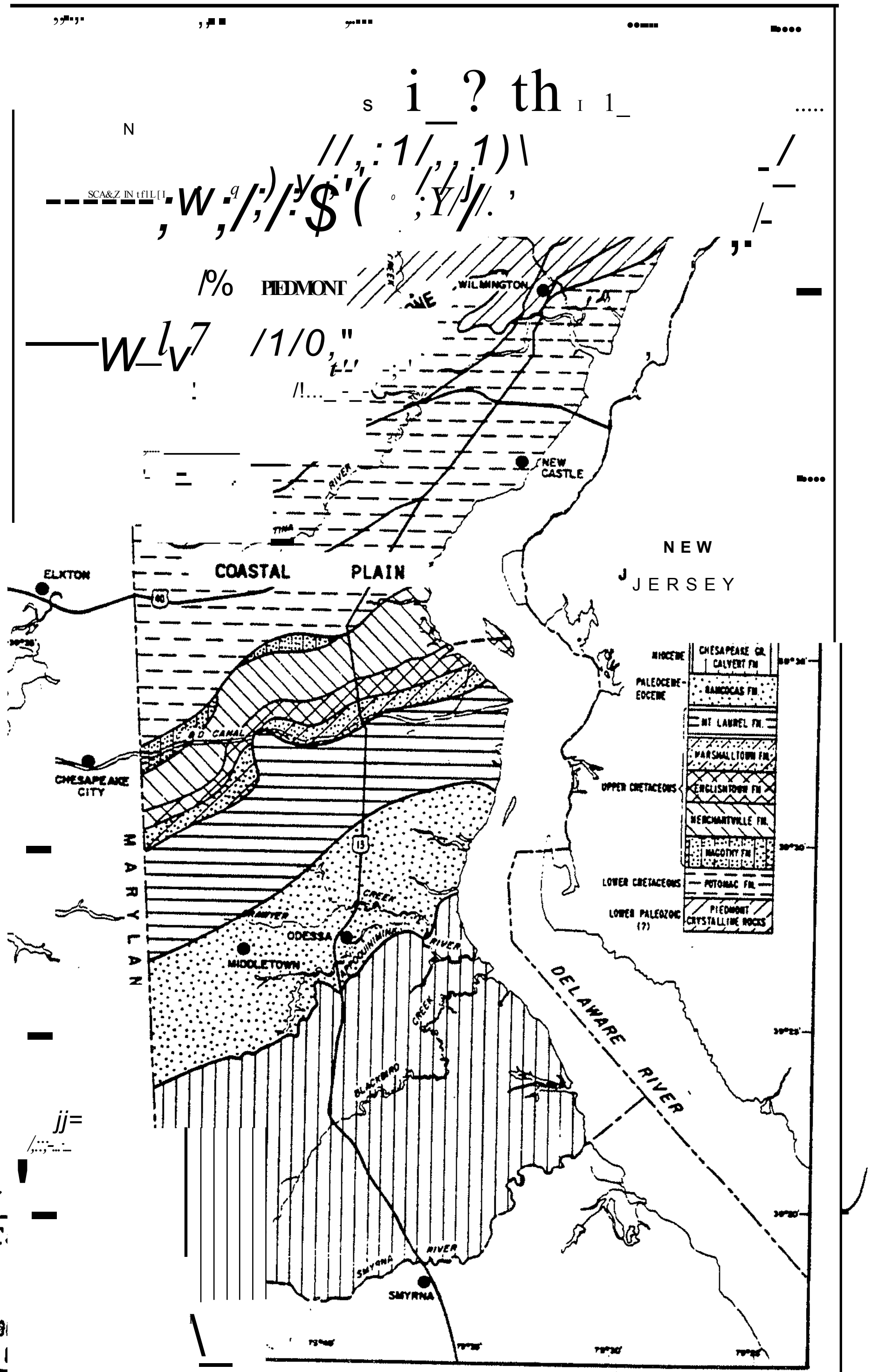

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Figure 2. Generalized geologic map of New Castle County, Delaware (Pleistocene removed). From Sundstrom and Pickett, 1971, page 8.

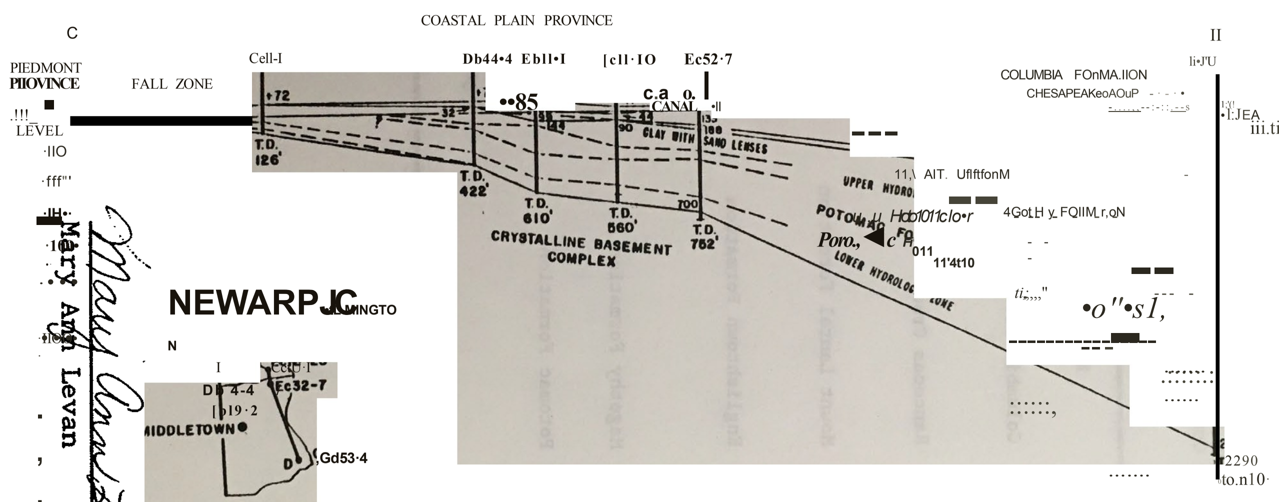

Figure 3. Generalized geologic cross-section of New Castle county, Delaware (modified from Sundstrom and Pickett, 1971).

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Table 4. Distribution of hydrologic units in the Coastal Plain of New Castle County, Delaware.

AGE	**NAME**	**ROCK TYPE**
Pleistocene	Columbia Formation	Gravelly coarse and medium sand with some interbedded silts
Eocene-Paleocene	Rancocas Group	Glauconitic fine to coarse sand, silt, and sandy silt
Upper Cretaceous	Mount Laurel Formation	Glauconitic fine to medium sand with some silt
	Englishtown Formation	Sparingly glauconitic fine sand with thin interbedded layers of silty sand
	Magothy Formation	Sand and silt, interbedded
Lower Cretaceous	Potomac Formation	Silt and clay with interbedded fine to coarse sand, and some gravel

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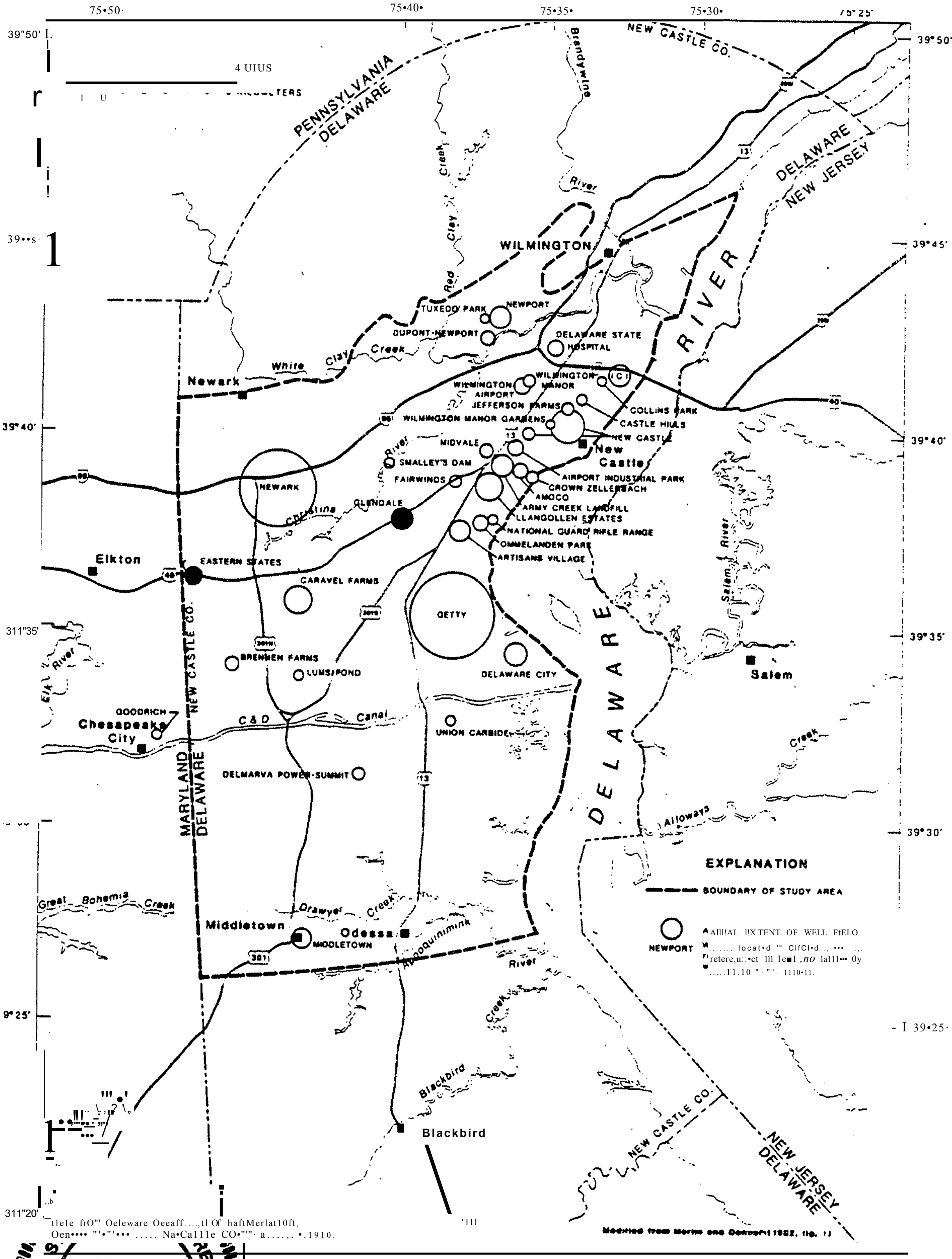

Figure 4. Location of major public and industrial water supply wellfields in the Potomac Formation in New Castle Countyt Delaware. Glendale and Eastern States wellfields are denoted by dark circles. (from Martin, 1984)

deltaic depositional environment (Groot, 1955) and ranges in thickness from zero near the Fall Zone to about 1,600 ft in southeastern New Castle County **(Figure** 3). Jordan (1962) noted that the geometry is very complex in that individual beds of sand, silt, and clay are generally restricted both vertically and horizontally and are, therefore, difficult to correlate over short distances. Sundstrom et al. (1967, p. 18) reported that individual sand bodies"...are confined essentially to the channels of the depositing streams..• and"..are elongate and tabular, not sheet-like" and "Because they are so confined, the sand bodies are considered to be subsidiary elements within the finer-grained matrix.•

Because of the complexity of the environment of deposition and **similarity** in lithology, attempts to subdivide the Potomac into individual formations have proved unsuccessful. Nevertheless, the Potomac has been informally subdivided into two sandy zones (lower and upper hydrologic zones) with two intervening silty and clayey zones by Sundstrom et al. (1967) and into three sandy zones (lower, middle, and upper) and three confining zones by **Rasmussen** and others (1957) and Martin (1984).

The hydrologic units within the Potomac are very important in that most of the ground water used in northern New Castle County is obtained from wells completed in the Potomac Formation. The locations of major wellfields in the Potomac Formation are shown on Figure 4; Glendale and Eastern States wellfields are noted by dark circles. Approximately 20 mgd are currently withdrawn from aquifers in the Potomac.

GLENDALE WELLFIELD

The Glendale wellfield is located near the intersection of U. S. Route 40 and **Delaware** route 7 approximately 7 miles southeast of Newark, Delaware (Figures 4 and 5). Four wells are currently operating in the wellfield, three in the Potomac Formation (Dc31-10, Dc31-21, Dc31-24) and one in the Columbia Formation (Dc31-15).

Hydrogeologic Framework

The hydrogeologic framework in the Glendale **area** is complex. The **Columbia Formation range■** in thickness from 30 to about 70 ft and forms a **charmel like deposit whose** long axis is oriented parallel to U.S. Route 40 **(Figure 6). A generalized** cross-section (Figure 7) through the Glendale **wellfield from Voodruff** (1977) **shows** surficial sands in the Columbia Formation **separated from sand■ in the Potomac** Formation by an irregular confining layer **of clay. An alternate hypothesis is** that the entire section of sand **c011priaing the water-table aquifer may** not consist entirely of the Columbia **Formation, but may be comprised** of sands of the Columbia on sands of the **Potomac. Detailed subsurface mapping** confirms the complexity of the Potomac **described earlier** in that individual beds of sand, silt, and clay are very difficult to **correlate** vertically or laterally. Review of available geologic **and hydrologic information confirms** that the aquifer in the ColUllbia Formation functions u avatar-table aquifer and that the sands in the Potomac function

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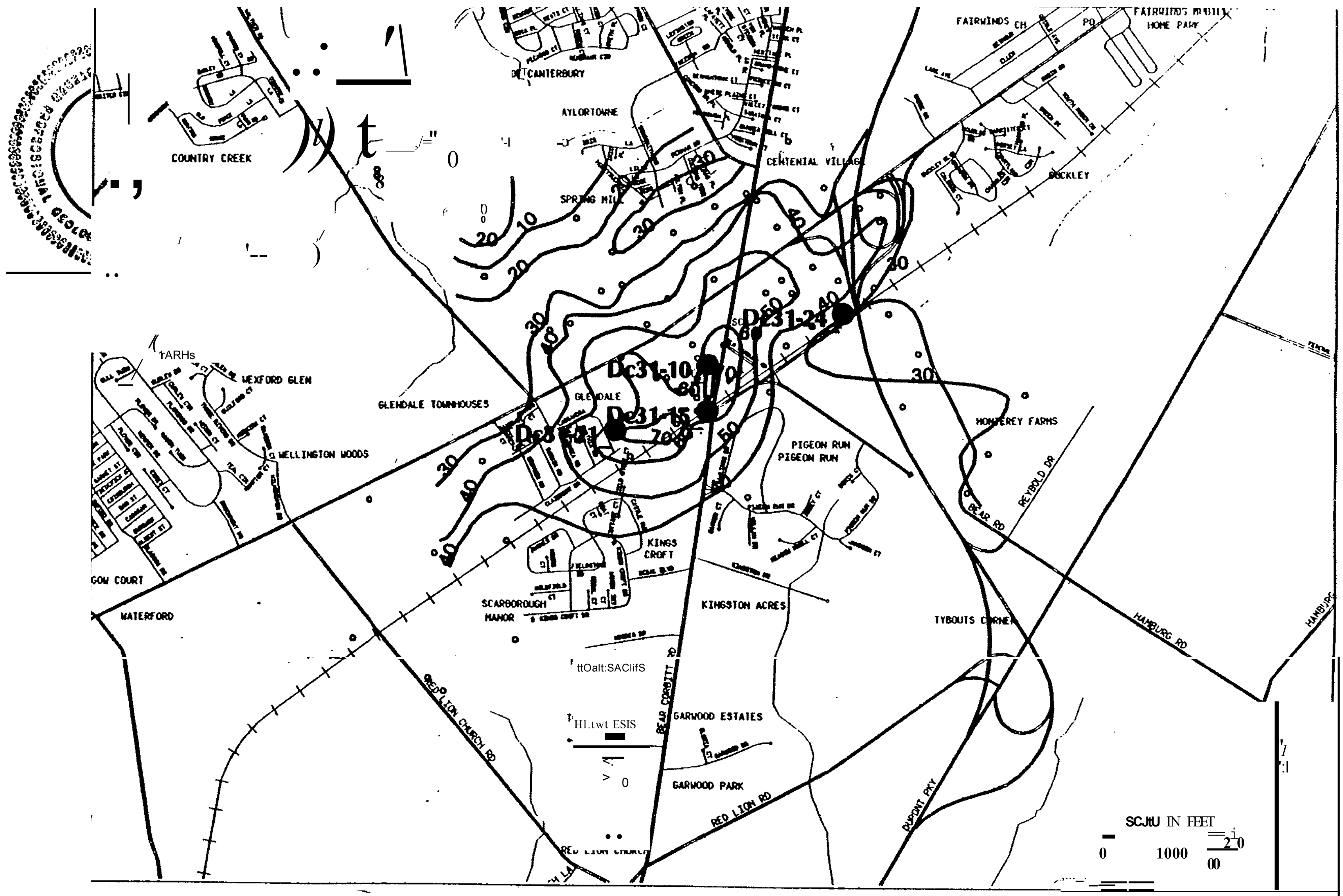

Figure 6 Map showing the thickness of the Columbia Formation (water-table aquifer) in the vicinity of the Glendale wellfield.

o Denotes control points

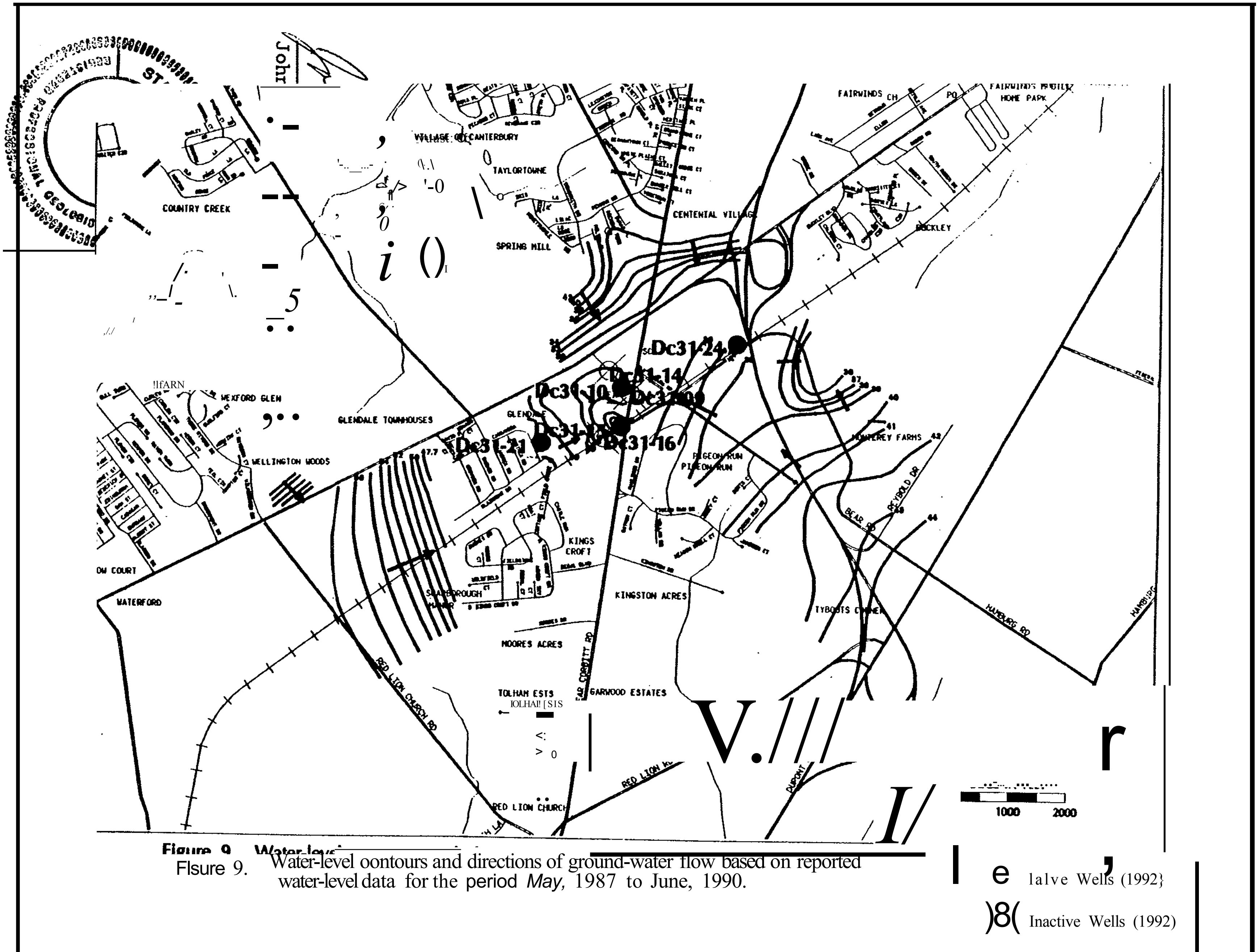

Figure 9. Water-level contours and directions of ground-water flow based on reported water-level data for the period May, 1987 to June, 1990.

as a semi-confined or leaky aquifer system. Results of a tr'itium analysis of water. from well Dc31-10 (Potomac Formation) strongly suggests that water currently being pumped from the well is less than 30 years old. The supports the theory that the aquifers in the Potomac Formation in the Glendale wellfield are leaky. Martin and Denver (1982) utilized the Hantush-Jacob leaky artesian analytical solution to determine transmissivity and coefficient of storage.

Water levels in the Columbia Formation have been influenced by pumpage from the Columbia and probably from the Potomac in the Glendale area. Comparison of analyses of drainage basin and water-level data contained on Hydrologic Atlas No. 64 (Boggess and Adams, 1963) and Hydrologic Atlas No. 60 (Adams and Boggess, 1963) with recent data contained in six consultants' reports indicate that directions of ground-water flow have changed and water levels have declined as a result of pumping in the Glendale wellfield dur.ing the past 33 years (Figures 8 and 9).

Pumping History and Allocations

As indicated below, the development of the Glendale wellfield has been complex with wells being constructed and put on line from 1959 to 1976, with wells completed in water-table and leaky confined aquifers in two formations, and with a complicated pumping history.

Wells, both active and inactive, in the Glendale wellfield are shown on Figure 5. A total of seven public supply wells have been operated at some time at Glendale since pumping began in 1959 (Table 5).

Table 5. Public water supply wells in the Glendale wellfield.

Well	Local Id.	Period of Operation	Hydrologic Unit	Current Status
Dc31-14	Glendale # 1	1959-	Columbia	Abandoned
Dc31-[illegible]5	Glendale # 2	1960-1992	Columbia	In Use
Dc31-09	Glendale # 3	1961-	Columbia	Obser.
[illegible]	Glendale# 4	1961-	Columbia	Obser.
Dc31-16	Glendale# 4R	1979-1985	Columbia	Not in Use
Dc31-10	Glendale# 5	1973-1992	Middle Potomac	In Use
Dc31-21	Glendale# 6	1974-1992	Middle Potomac	In Use
Dc31-[illegible]4	Glendale# 7	1976-1992	Middle Potomac	In Use

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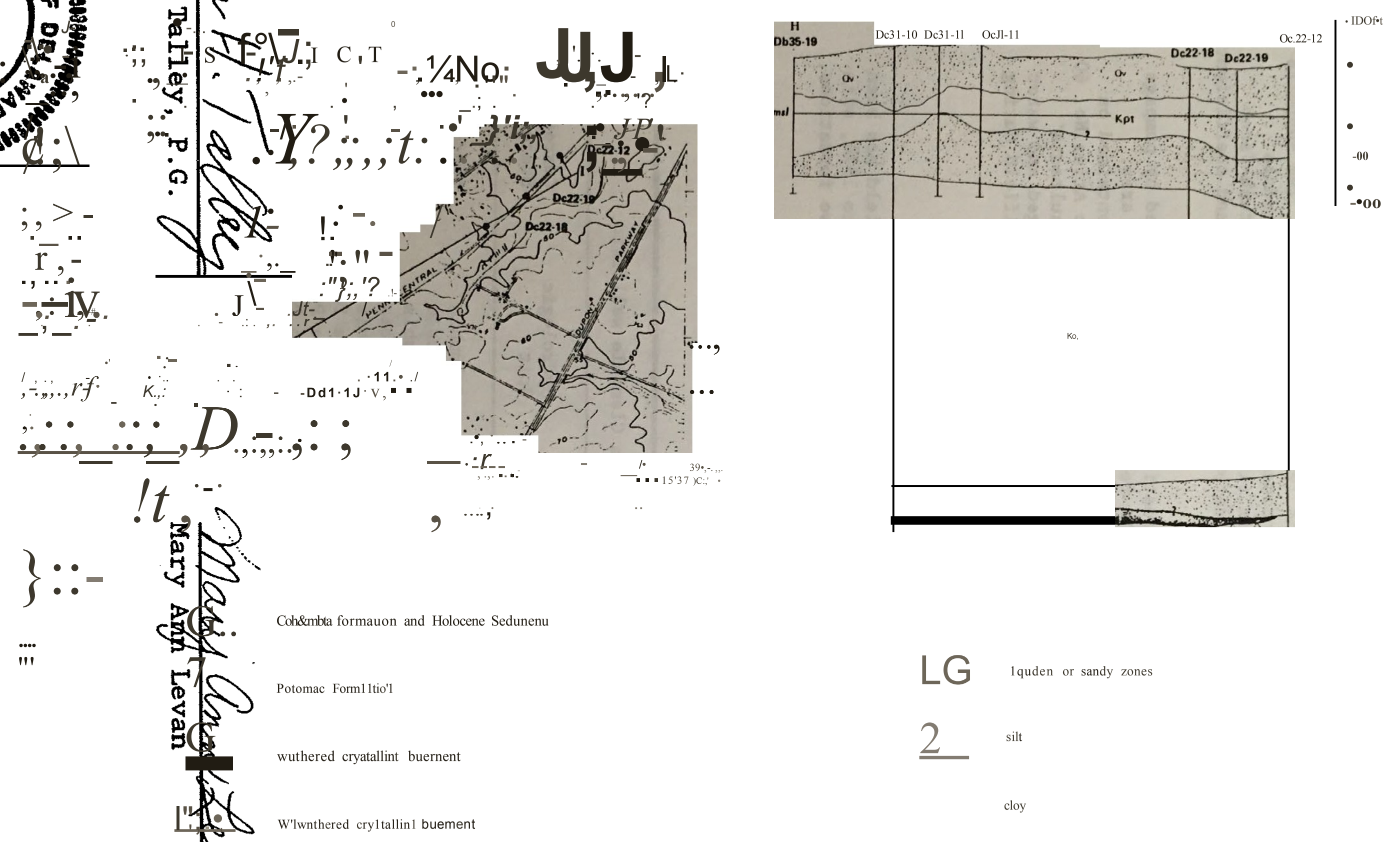

Figure 7. Generalized cross-section (H-I) through the Glendale wellfield. (from Woodruff, 1977)

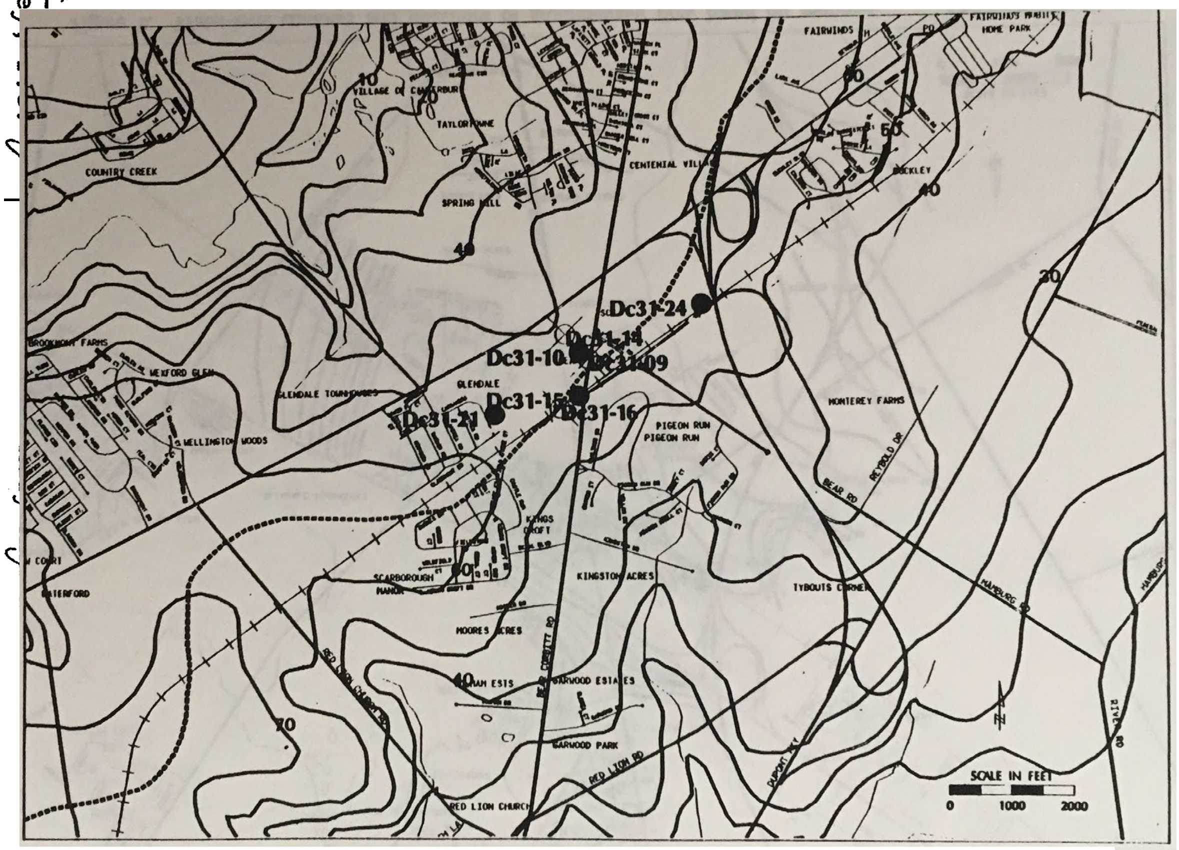

Figure 8. Map showing walll!r-level mntours, directions of ground-water flow and drainage divide near Glendale In 1963.
(Modified from hlams & Boaaess, 1963, and Boaaess & Adams, 1963.)

e ktlve Wells (19921
)8(lnadlve Wells (1992)
f.l Drainage Divide

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Table 7. Pumpage records for the Glendale wellfield, 1973-1990. (Source, Artesian Water Company.)

YEAR	PUMPAGE (mgd)	YEAR	PUMPAGE (mgd)
1973	1.18	1980	1.91
1974	2.12	1981	1.41
1975	1.77	*	
1976	1.83	1988	1.38
1977	1.65	1989	1.54
1978	1.53	1990	0.73
1979	1.73		

The average yearly pumping rate for these 12 years of record is 1.56 mgd, which is close to the 1.8 mgd allocated to the four currently pumping wells.

***Missing** data, 1982-1987

APPLICATION OF THE WHPA MODEL AT GLENDALE

Because of the complexity of the geology and associated hydrology near Glendale, none of the EPA wellhead protection modules are directly applicable to system analysis For example, the assumptions of aquifer homogeneity and steady and uniform ground-water flow common to all modules do not hold in the Glendale area. In addition, each module has specific limitations and capabilities as described previously (Tables 1 and 2).

In comparing available EPA modules, it became clear that for a given module run, only a single aquifer type (unconfined, semi-confined, or confined) could be chosen. Thus, the semi-confined Potomac/unconfined Columbia aquifer system could not be analyzed in single trial runs. The decision was, therefore, made to model the Potomac and Columbia aquifers separately, and overlay the results. Thus, some interpretation was used in finalizing the outline of the delineated areas.

John H. Talley, P.G. **Mary Ann Levan**

After evaluating the modules while **taking** into account the geohydrology of the Glendale area, the GPTRAC module was selected for all module runs for the following reasons: (1) both unconfined and leaky confined aquifers can be analyzed; (2) area recharge can be accounted for; and (3) the effects of well interference can be accounted for.

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Input Parameters

Input parameters for the four Glendale wells were determined using the results of hydrogeologic mapping, aquifer test analysis, analysis of well logs, use of data in published reports, and allocation permits from the Water Supply Branch of DNREC. A data form used for WHPA runs is shown in Table 8. The process of defining wellhead protection areas required many successive module runs and comparison of run results while taking hydrogeologic criteria into consideration.

Module runs were made for several simulation times. One group of trials was run for the actual time of operation of the wells. Thus, for well Dc31-15 (Columbia Formation), the simulation time was 31 years (1960-1991) and for the Potomac wells, the simulation time was 16 years (1975-1991). The overlay of these outputs was considered the "long run capture zone.• Since some pre pumping and present day water-level data are available, the results were compared to the results of module long runs to check the validity of the modeling approach (a form of calibration). In addition, run times of five and ten years were used to delineate capture zones.

Pumping Well Inputs

For each pumping well in the wellfield, the GPTRAC module requires inputting the type of aquifer in which the well is screened (confined, semi confined, unconfined) and the pumping rate. In all runs, the aquifer in the Columbia was considered to be unconfined while the aquifer(s) in the Potomac was considered semi-confined or leaky.

Although the wells in the Glendale wellfield are not pumped continuously at constant rates, the WHPA modules require input of a single (constant) pumping value for each well. Because of inadequate data, and to take a conservative approach, DNREC well allocations were used for pumping inputs. Since the allocations are the **maximum** permitted withdrawals, delineated areas may actually be larger than they would be if actual pumping rates are less that the allocated rates. For the Potomac wells, the following pumping rates **were used**; DcJl-10, 53,472 cf/day (400,000 gpd); DcJl-21, 43,446 cf/day (325,000 gpd); and for DcJl-24, 77,000 cf/day (576,000 gpd). Because of a lack of historical data (pumping rates and period of operation), only well DcJl-15 was included in the Columbia Formation. There was no way to adequately account for intermittent pumping from he other wells in the Columbia during the 31-year period of record. The allocation for this well is 67,375 cf/day (504,000 gpd). Pumping well inputs are summarized in Table 9.

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STATE OF DELAWARE
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Reg. No. 273
REGISTERED PROFESSIONAL GEOLOGIST

Table 8. Sample data sheet used for WHPA module runs.

MODULE NAME	RUN NUMBER
CAPTURE ZONE TYPE:	SIMULATION TIME

PUMPING WELL INPUTS
- # Pumping Wells:
  - **Well ID**
  - Formation
  - Aquifer Type
  - Pumping Rate
  - Well Radius

AQUIFER PROPERTIES
- Aquifer Transmissivity
- Aquifer Thickness
- Aquifer Porosity
- Ambient Hydraulic Gradient
- Angle of Flow

AQUIFER BOUNDARIES
- Boundary Type
- Orientation
- Perpendicular Distance

RECHARGE
- # Recharge Wells:
- Recharge Well Pumping Rate
- Confining Layer K
- Confining Layer b

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STATE OF DELAWARE
JOHN H. TALLEY
Reg. No. 273
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The Colwabia aquifer was developed first, with three Columbia wells in operation in 1961, 12 years before the first pumping from wells in the Potomac. Water withdrawals during that period cannot be directly estimated as there are no pumpage records and no records of when individual Columbia wells were taken out of service. The three Potomac wells were constructed in 1973, 1974, and 1976. As with the wells in the Columbia Formation, records of pumpage are incomplete.

Individual allocations for all wells are presented in Table 6; the current total allocation for the wellfield is 1.8 mgd.

Table 6. Permitted and allocated withdrawals from individual wells in the Glendale wellfield as of December 1987 (Source, DNREC).

Yell	Local Id.	Allocation	Hydrologic Unit
Dc31-14	Glendale# 1	0.144 mgd	Columbia
Dc31-15	Glendale# 2	0.504 mgd	Columbia
Dc31-09	Glendale# 3	0.216 mgd	Columbia
	Glendale# 4		Columbia
Dc31-16	Glendale# 4R	0.144 mgd	Columbia
	Total	1.008 mgd	
Dc31-10	Glendale# 5	0.400 mgd	Middle Potomac
Dc31-21	Glendale# 6	0.325 mgd	Middle Potomac
Dc31-24	Glendale# 7	0.576 mgd	Middle Potomac
	Total	1.301 mgd	

* The total permitted daily withdrawal from the Glendale wellfield is 1.81 mgd fr- wells Dc31-15, Dc31-10, Dc31-21, and Dc31-24.

Artesian Water C011pany has provided available pumpage data for the period 1973-1990 (Table 7). Although there are some gaps in the record and **pumpage** for individual wells cannot be partitioned, one can get a sense for the range in ground-water discharges for the period of record.

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Mary Ann Levan

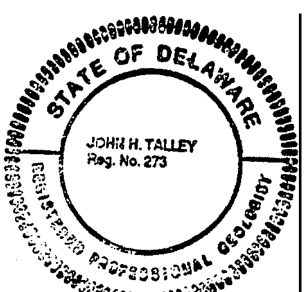

Table 10. Transmissivity, storage, and confining bed vertical conductivity In the Potomac Formation Glendale wellfield. (Martin and Denver 1982).

PUMPING WELL NUMBER	DATE, DURATION OF TEST AND PUMPING RATE	OBSERVATION WELLS AND DISTANCE FROM PUMPING WELL (ft)	TRANSMISSIVITY (ft2/day)	COEFFICIENT OF STORAGE (dimensionless)	CONFINING BED VERTICAL CONDUCTIVITY (ft/dav)
Dc31-10	6-20-73 45 hours 524gpm	Dc31-13 (51)	912	2.5x 10-3	0.71
	11-14-73 24hours 400gpm	Dc31-13 (51) Dc31-25 (787)	454 601	2.6 x 10-3 6.3x 10-5	1.4 0.017
Dc31-21	4-22-74 48 hours 310 gpm	Dc31-13 (1750) Dc31-25 (910)	475 1580	6.5 x 10-5 1.6x10-4	0.012 0.012
Oc31-24	2-?-75	Dc31-10 (2200) 24 hours 508 gpm	2780	2.1x10-4	

M.M.Martln using the Hantush-Jacob leaky artesian method.
Analysis for the Dc31-24 pumping well was done by P.Williams using the Stallman single-boundary artesian method.

STATE OF DELAWARE
JOHN H. TALLEY
Reg. No. 273
REGISTERED PROFESSIONAL GEOLOGIST

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Mary Ann Levan

As described earlier, the Glendale wellfield is located on a drainage divide. Pre-pumping directions of ground-water flow in the unconfined aquifer were probably to both the north and south away from the divide (Figure 8). The WHPA model does not allow for multiple gradients. Therefore, a very small gradient of 0.00001 was used to simulate pre-pumping conditions. Aquifer property inputs are summarized in Table 11.

Table 11. -Aquifer properties input for the Glendale wellfield.

Well ID:	Dc31-15	Dc31-10	Dc31-21	Dc31-24
Transmissivity:	3000	1500	1500	1500
Thickness:	60	34	34	34
Porosity:	0.25	0.25	0.25	0.25
Hydraulic Gradient:	0.00001	0.0015	0.0015	0.0015
Angle of **Flow**:	325°	325°	325°	325°

Aquifer Boundaries

There were no boundary inputs for the Glendale wellfield.

Recharge.Inputs

Average recharge to the water-table aquifer in the Coastal Plain in northern New Castle County is about 14 inches per year or about 668,000 gallons per day per square mile. For the unconfined aquifer, recharge was input as .0032 ft/day.

For the Potomac, recharge occurs by water infiltrating into the unconfined portions of the Potomac either where sands occur at land surface or where sands in the Potomac Formation directly underlie sands in the Columbia Formation, or by leakage th ough leaking confining beds. The rate of recharge through fine-grained sediments depends on the continuity- and thickness of the confining beds, and hydraulic conductivity. The thickness of the confining beds above the aquifers screened in the Potomac at Glendale ranges from 20 ft at well Dc31-10 to 41 ft at well Dc31-24. For model purposes, an average thickness of 30 ft was used.

John H. Talley, P.G. **Mary Ann Levan**

Reported values of confining bed vertical hydraulic conductivity (k') range from 0.012 to 1.4 ft/day (Table 10). Preliminary runs with Potomac well Dc31-24 showed that the value of k' used had a large effect on capture zone size with a relatively high value of 0.7 giving an area less than half the size of a low k' value of 0.012 (Figure 10).

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Reg. No. 273
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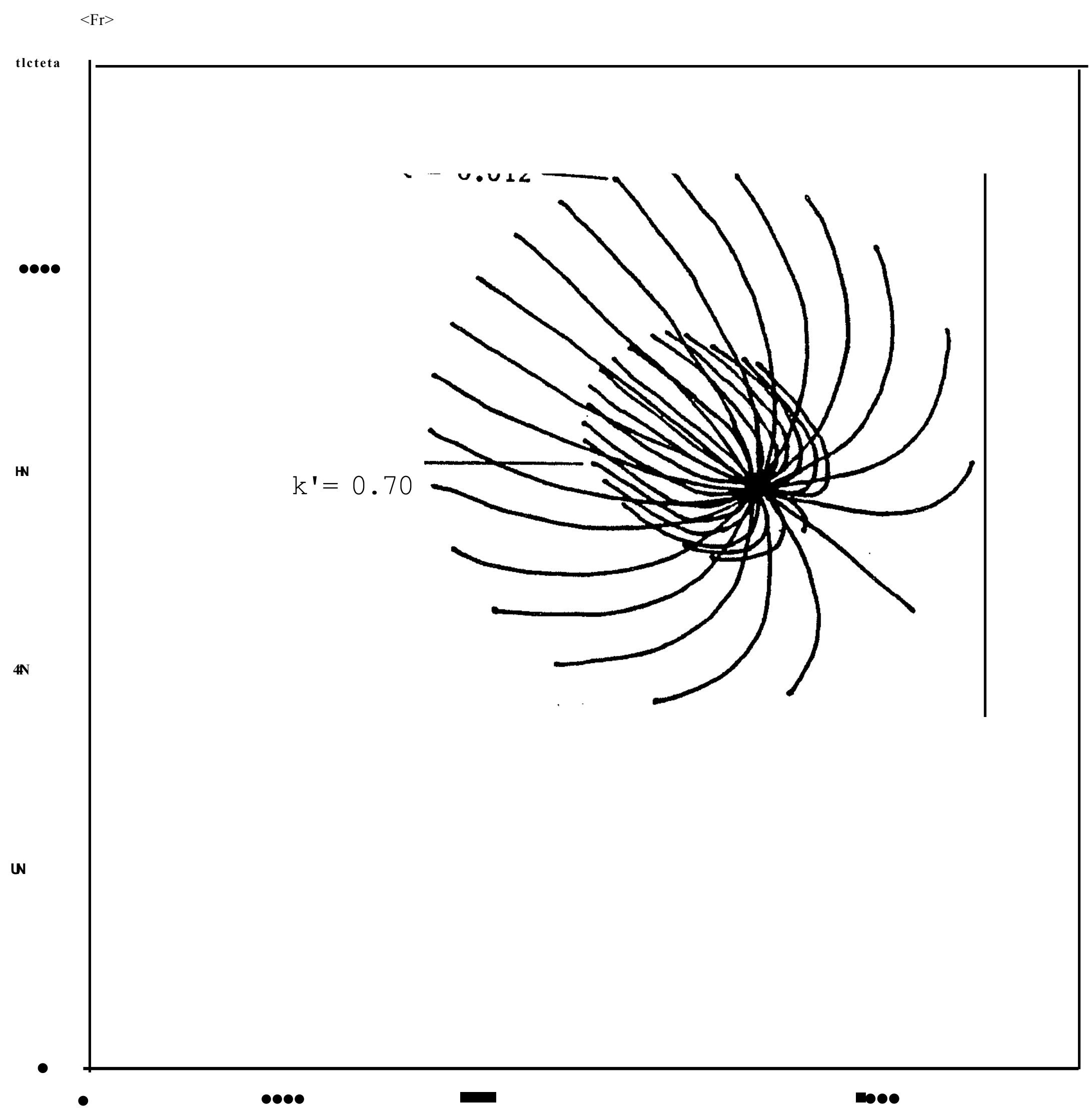

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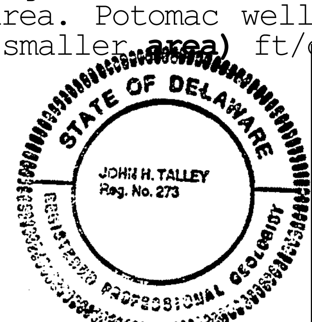
Figure 10. GPTRAC trial runs to show effect of k' on capture zone area. Potomac well DcJl-24 with k'=0.012 (larger area) and 0.70 (smaller area) ft/day.



Because of the significance of this factor to model output, a sensitivity analysis was done with the MONTEC module to establish k' inputs. The MONTEC module uses the statistical Monte Carlo approach of evaluating a problem or equation multiple times by inputting a distribution of inputs for each parameter under evaluation. A Monte Carlo run requires inputs of the type of distribution of the parameter, and of the parameters which describe the distribution such as the mean, standard deviation, etc. For example, a parameter which has a uniform distribution can have values as low as some minimum or as great as some maximum, and all intermediate values would have equal chances of occurrence. The distribution of digits from 1 to 1,000 would be such a uniform distribution, with a minimum of 1 and maximum of 1000.

. Hydraulic conductivity is typically extremely variable, with several orders of magnitude between minimum and maximum values. Many such parameters are log normally distributed. Whereas a frequency distribution of the untransformed values is skewed toward the lower values, the logarithms of the values follow the normal curve. In the Monte Carlo analysis of k', the lognormal distribution type was used with an average value of 0.1 as an intermediate value between the approximate reported range of 0.01 to 1.0 (Table 10). The module was run with 1,000 repeats, indicating that the program used the lognormal distribution of k' to generate 1,000 separate k' input values and generate 1,000 capture zones.

Rather than evaluate all 1,000 capture zones, the outcomes are grouped to correspond roughly to values of k'. As k' gets smaller (less leaky), the capture zone gets larger. Thus, a plot which includes only .1% of the capture zones will plot only one trial run (1/1000 - .1%) and will correspond with the highest value of k' generated during the Monte Carlo simulation. A plot which includes 10% of the capture zone areas will correspond with the "high k'" values, and a plot which includes 95% of the capture zones will correspond with areas produced by the "low k'" values.

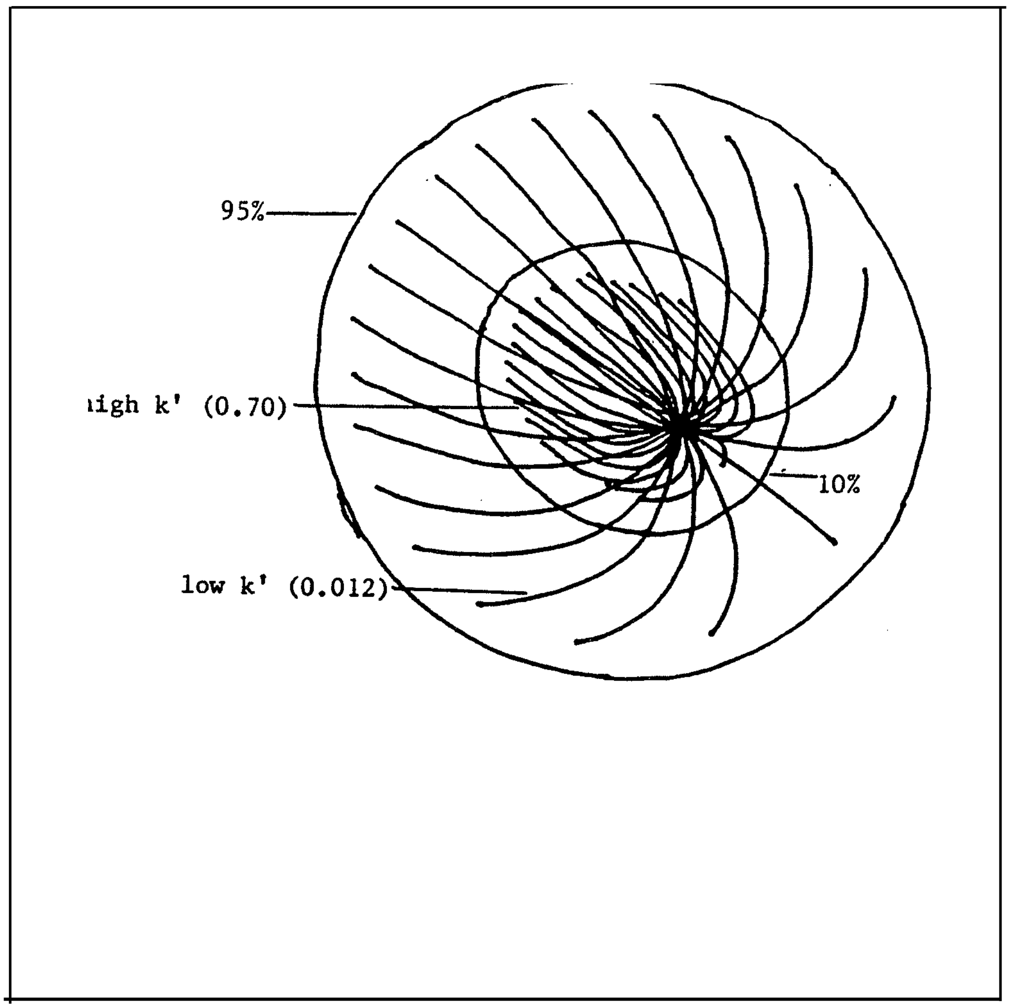
When these capture zones are overlaid on the GPTRAC runs for Potomac well Dc31-24 (Figure 11), the 10% MONTEC capture zone area corresponds well with the high GPTRAC k' input of 0.7 ft/day, and the 95% MONTEC capture zone area corresponds well with the low GPTRAC k' input of 0.012 ft/day. It was concluded that these two k' values were adequate to describe the effect of k' on capture zone area.

John H. Talley, P.G. MODULE RUNS **Mary Ann Levan**

Three simulation times were used in the module runs; 31 years/16 years (long run), ten years, and five years. For **each** simulation time, the model was run with a low, average, and high **k' value**, making a total of 9 trials. The trial inputs and outcomes are summarized in Table 12.

STATE OF DELAWARE JOHN H TALLEY Reg. No. 273 PROFESSIONAL GEOLOGIST

An example of the capture zones defined by the GPTRAC program is shown in Figure 12 (Trial, long run time, low k'). Sixteen-year capture zones around each of the three Potomac wells are shown oriented in the direction of



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Mary Ann Levan

Figure 11. overlay of 10% and 95% MONTEC capture areas on low and high k' GPTRAC runs shown in Figure 10. The choices of 0.012 and o.70 include most of the k' range as modeled in the 1000 repeat Monte Carlo runs.

STATE OF DELAWARE
JOHN H. TALLEY
Reg. No. 273
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Table 12. Model run scenarios and results for the Glendale wellfield.

RUN NUMBER	TEST DESCRIPTION	COLUMBIA **PARAMETERS**	POTOMAC **PARAMETERS**	WHPAAREA mi^2	ACRES
1 (t-Igure 13)	Long run **lowk'**	**T=3000** b=60 ft t=11315 days (31 years)	T=1500 b=34 ft t=5840 days (16 years) k'=0.012	2.47	1581
2 (Figure 14)	Long run average k'	same	k'=.10	1.38	883.
3 (Figure 15)	Long run high k'	same	k'=.70	0.96	614
4 (Figure 17)	10-year run lowk'	T=3000 b=60ft t=3650 days (10 years)	T=1500 b=34 ft t=3650 days (10 years) k'=.012	1.79	1146
5 (Figure 18)	10-year run average k'	same	k'=.10	1.09	698
6 (Figure 19)	10-year run high k'	same	k'=.70	0.706	452
7 (Figure 21)	5-year run **lowk'**	T=3000 b=60ft t=1825 days (5 years)	T=1500 b=-=34 ft t=1825 days (5 years) k'=0.012	1.14	730
8 (Figure 22)	5-year run **average k'**	same	k'=.10	0.765	490
9 (Figure 23)	5-yearrun high k'	same	k'=.70	0.464	297

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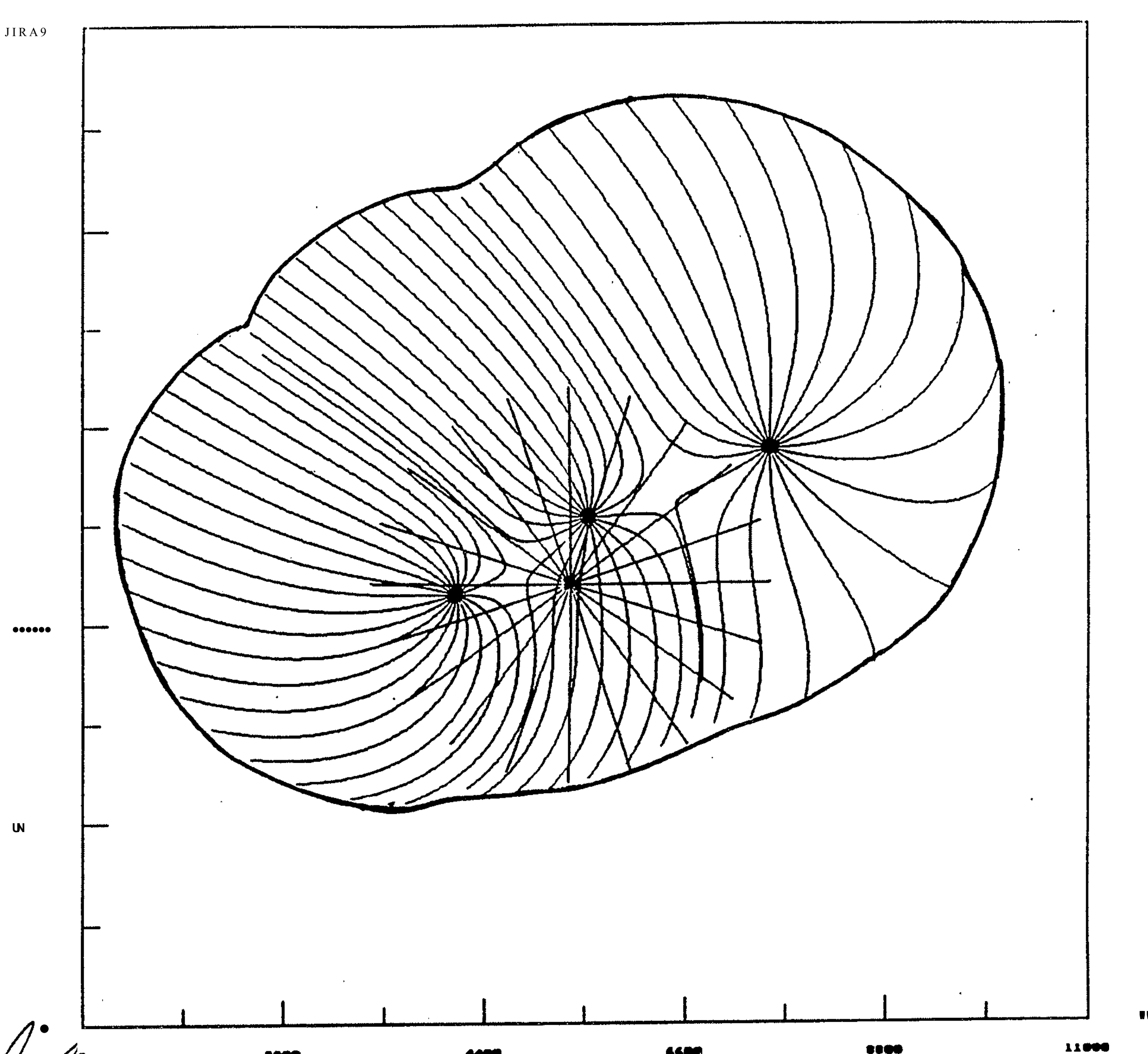

Figure 12. "Particle track lines" as drawn by computer module used to delineate wellhead protection areas. The 3 elongate, interfering capture zones are for the Potomac wells, the symmetric zone is for the Columbia well. The overall WHPA is defined by the outline of all the capture zones. Example is run 1, GPTRAC long run, low k'.

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STATE OF DELAWARE
JOHN H. TALLEY
Reg. No. 273
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ambient flow, more elongate up gradient than down gradient. · These capture zones. are **skewed,** indicating that these wells have sufficiently high pumping rates and a long enough pumping time to interfere with one another. The 31-year capture zone for the Columbia well was determined in a separate GPTRAC run and overlaid at the location of well Dc31-15. The symmetry is due to the nearly zero flow gradient. The overall wellhead protection area is delineated by the outline of these combined areas. In the remaining figures, the WHPA outlined areas are superimposed on topographic maps, and the individual "particle track lines" are not shown.

The outcomes of the long runs are shown in Figures 13, 14, and 15. With this run period, the wellhead protection area is roughly oval-shaped, with the long axis oriented northeast-southwest. The value of the confining bed conductivity (k') has a significant effect on the size of the delineated areas as indicated earlier. For the lowest k' ("tightest confining layer"), the area is 2.47 mi^2; this decreases to 1.38 mi^2 for the average k', and to 0.96 mi^2 for the highest k' ("leakiest confining bed"). These module run results are summarized in Figure 16.

The outcomes of the ten year runs are shown in Figures 17, 18, and 19, and summarized in Figure 20. Confining bed vertical conductivity (k') has an effect on both the size and shape of the delineated wellhead protection area. Recall that the k' factor affects only the semi-confined Potomac wells; the recharge factor for the Columbia well is constant for all runs. Therefore, as k' increases, the Potomac capture zones get smaller while the Columbia capture zone remains the same. The Columbia capture zone is particularly prominent in the high k' run, where the Potomac capture zones are smallest (Figure 20). Again the effect of k' on area is clear, with the wellhead protection area decreasing from 1.79 mi^2 to 0.706 mi^2 as k' is increased from 0.012 to 0.70.

·The outcomes of the five year runs are shown in Figures 21, 22, and 23, and summarized in Figure 24. In all runs, the outlines around individual wells are fairly clear, and the area decreases in size from 1.14 mi^2 to 0.765 mi^2, to .464 mi^2 with increasing k'.

Discussion

For purposes of comparison, the five and ten year and "long run" outcomes for each k' value are presented in Figures 25, 26, and 27. Although the scope of this study did not allow for direct field measurement of k', supporting evidence suggests that the confining bed conductivity value is closer to the average than the lowest k'. It, therefore, appears appropriate to use the **average k'** value in delineating the appropriate wellhead protection area. Our conclusion that the Potomac is leaky in the vicinity of the Glendale wellfield is supported by results of a tritium analysis from a water sample obtained from well Dc31-10 (Potomac Formation). Based upon the enrichment of the atmosphere and surface water in tritium during the advent of nuclear testing in the 1950's, the tritium count of a water sample provides a semi-quantitative index of its age. Potomac sample counts were dated at approximately 30 years old which provides an estimate of the maximum time of

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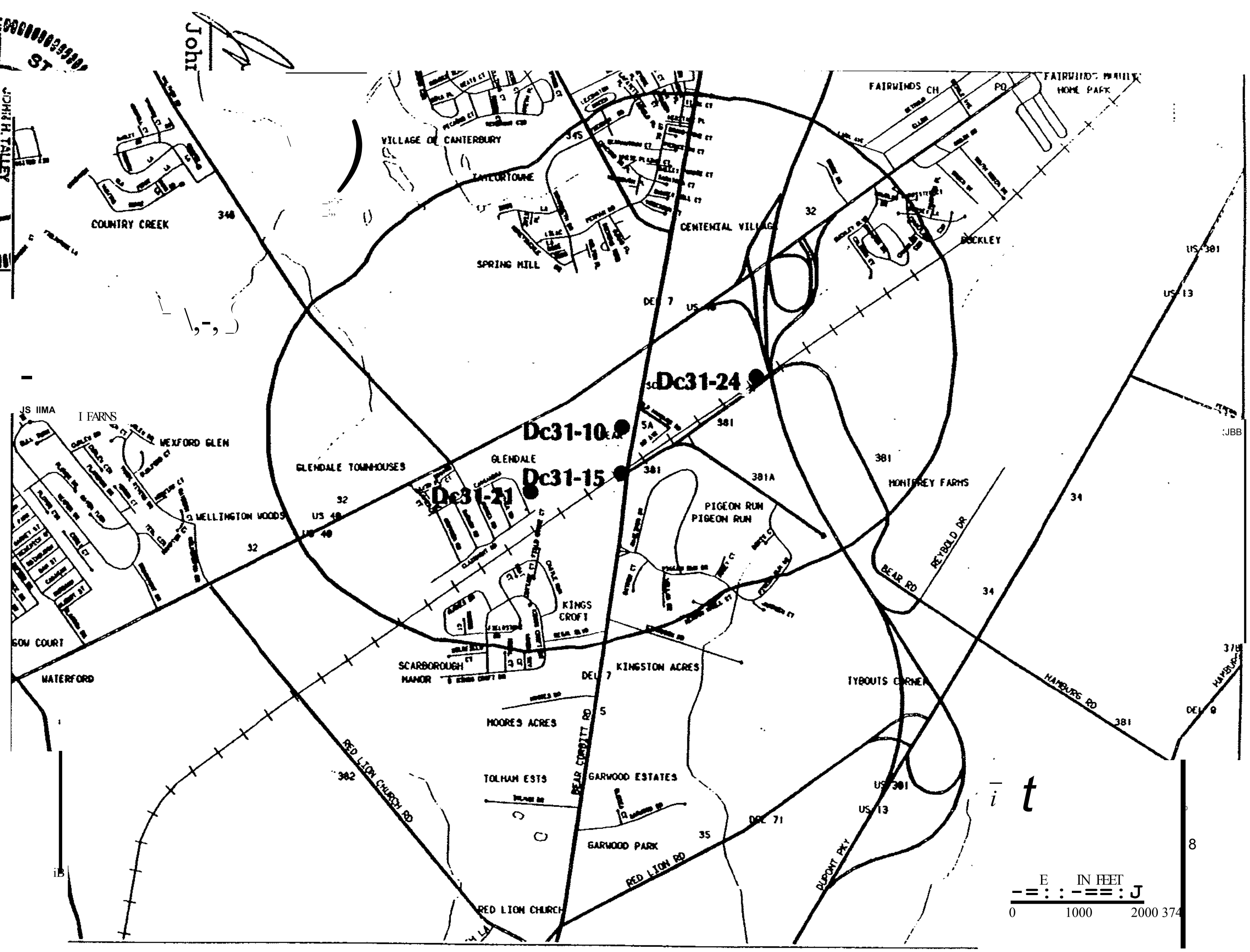

Figure 13. Run 1. WHPA outline with long run, low k'. Unronfined G:>lumbia 31 years with .0032 ft/yr l'ft:harge; semi-<Dnfined Potomac 16 years with k' - 0.012 This is the ma;t mnsefVative trial run; area - 2.47 sq. mi.

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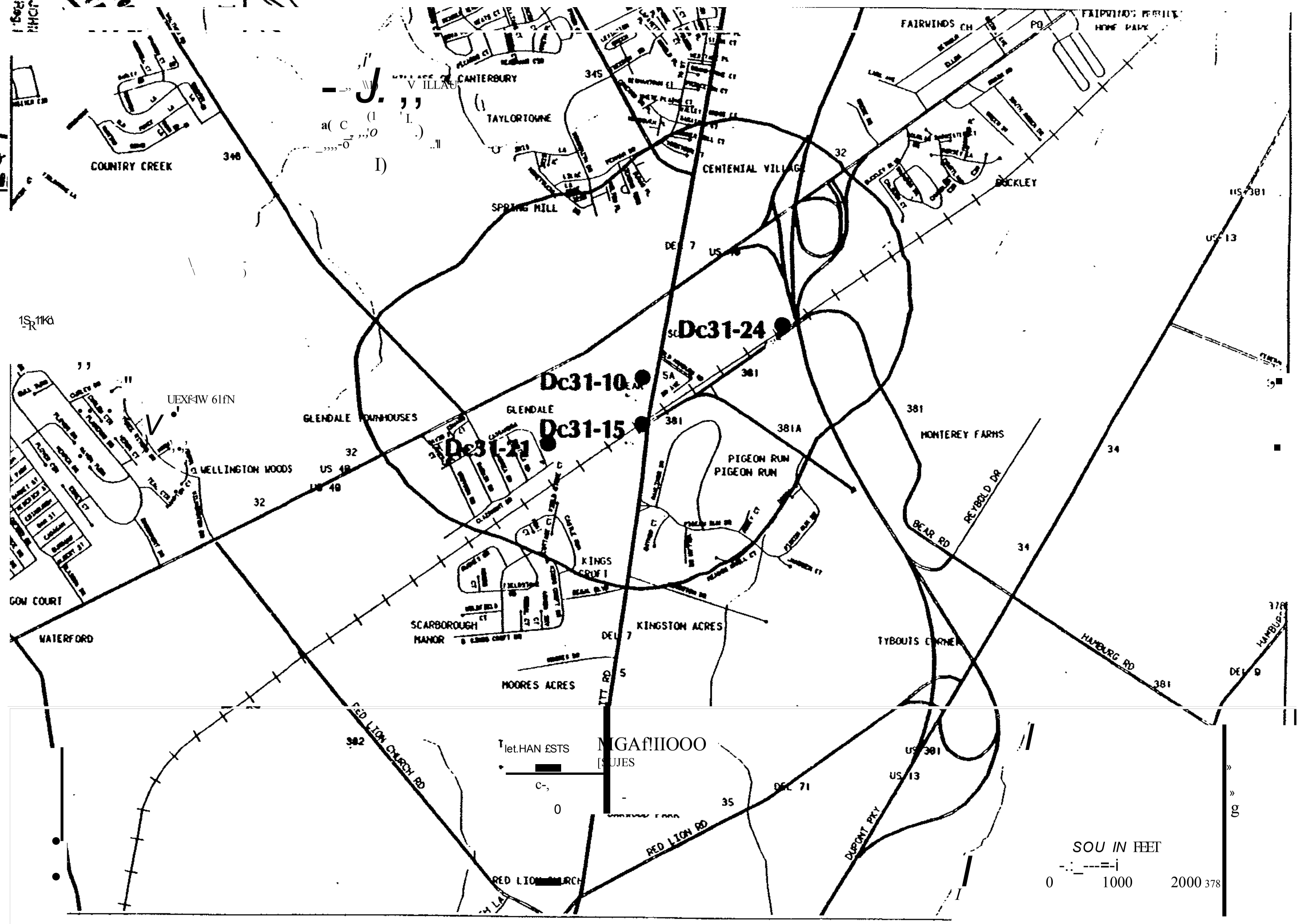

Figure 14. Run 2. WHPA outline with long run, average k'. Unmnfined Columbia 31 years with .0032 ft/yr recharge; semi-oonfined Potomac 16 years with k' - 0.10. Changing k' from 0.012 to 0.10 drop; the area from 2.47 sq. mi. to 138 sq. mi.

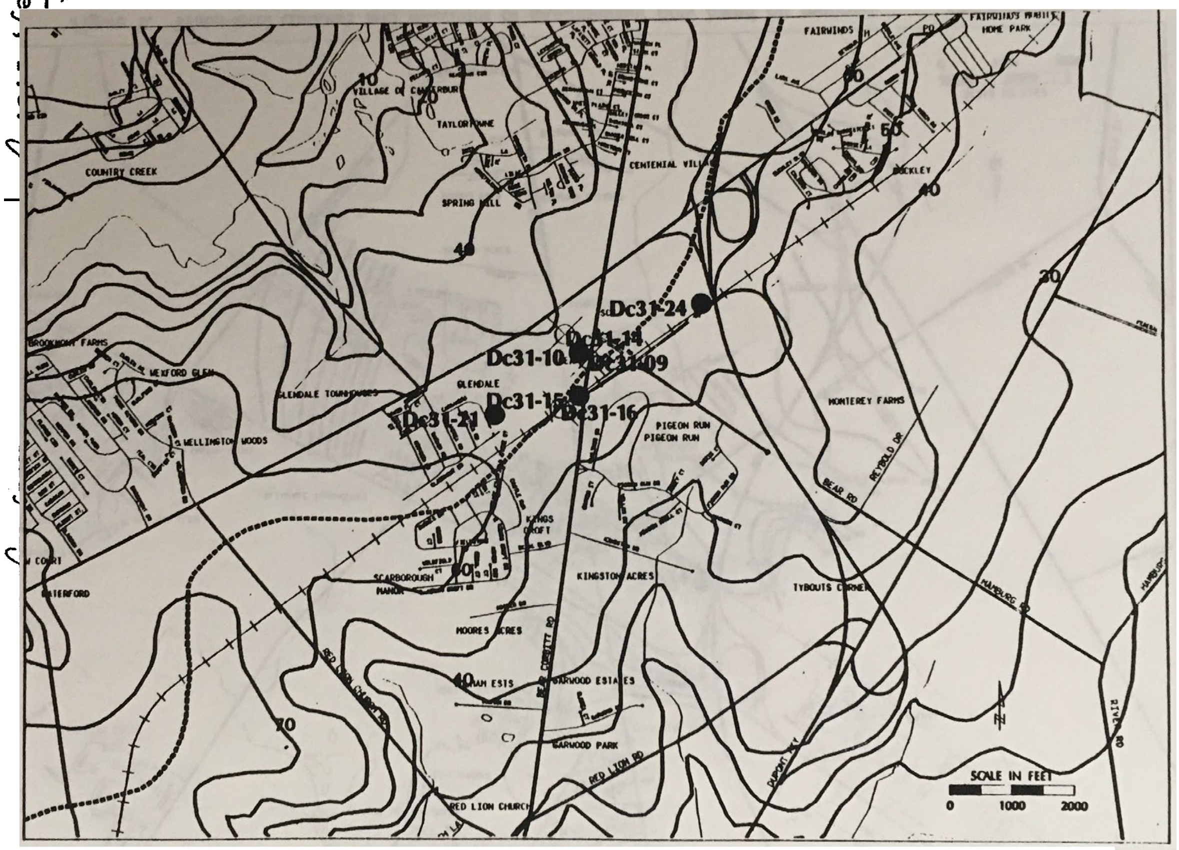

Figure 8. Map showing walll!r-level mntours, directions of ground-water flow and drainage divide near Glendale In 1963.
(Modified from hlams & Boaaess, 1963, and Boaaess & Adams, 1963.)

e ktlve Wells (19921
)8(lnadlve Wells (1992)
f.l Drainage Divide

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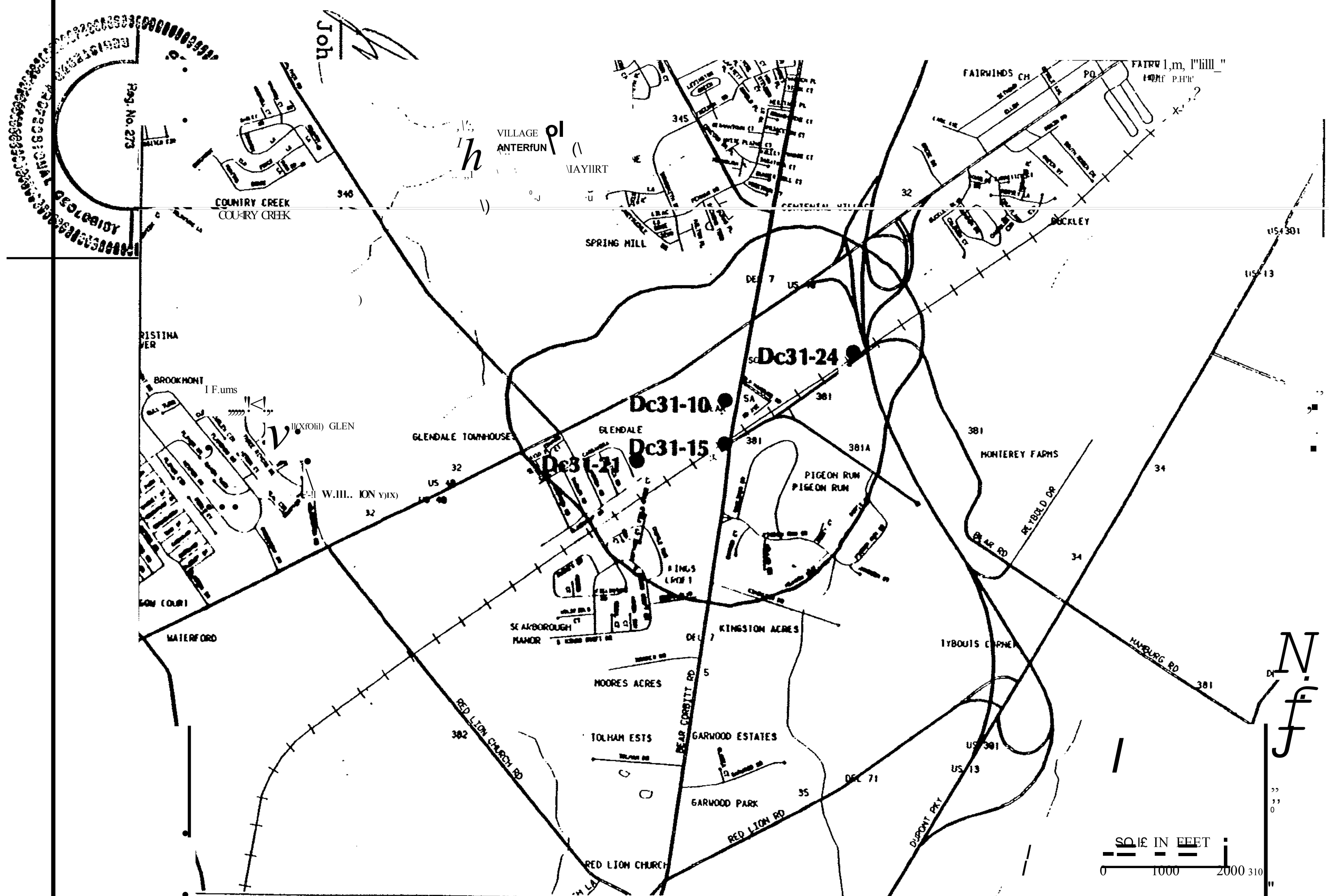
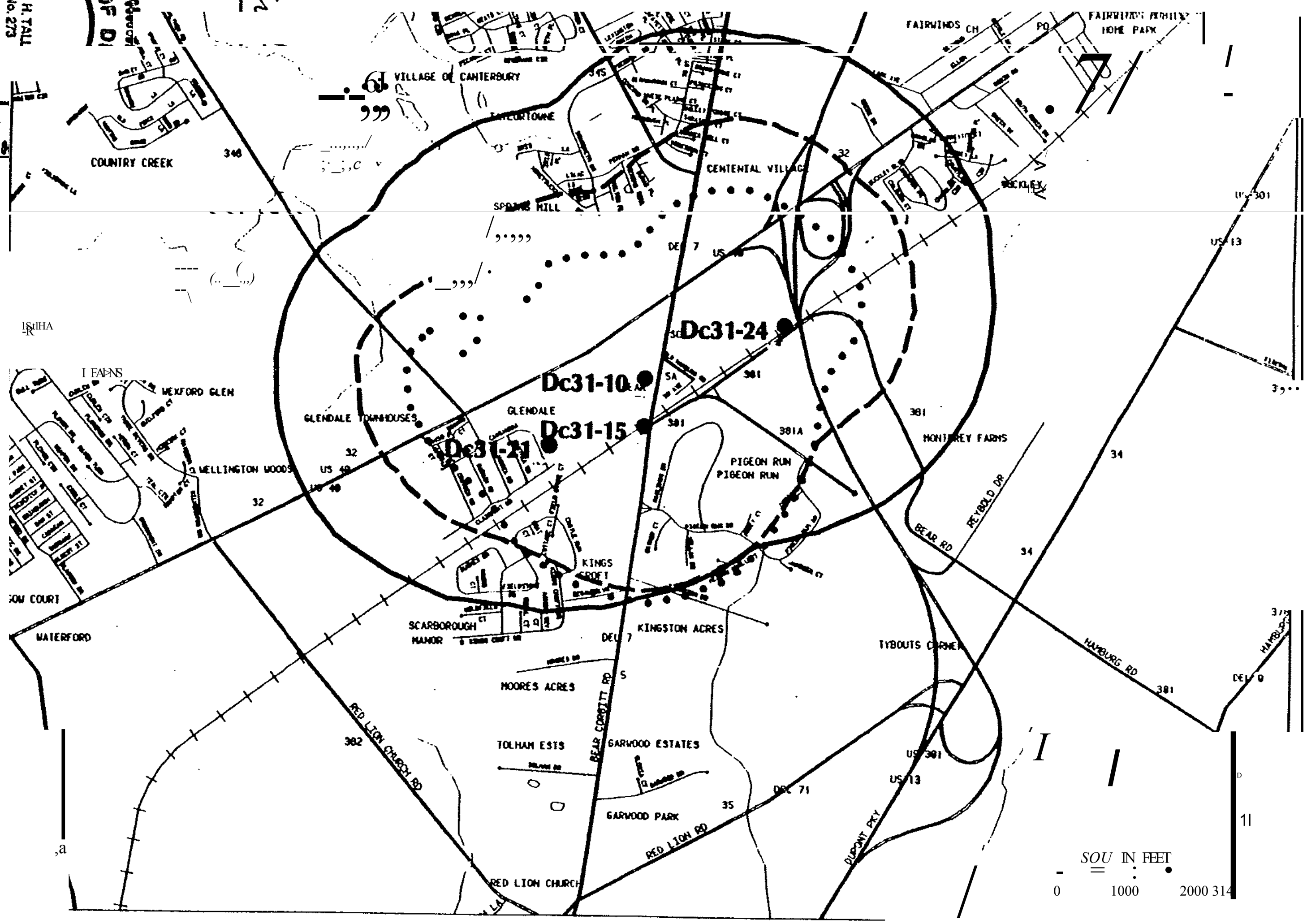


Figure 15. Run 3. WHPA outline with long run, high k'. Unmnfined Columbia with .0032 ft/yr ra:harge; seml-0>nfined Potomac 16 years with k' - 0.70. Changing k' from (l 10 to (170 drops the area from 138 sq. mi. to 0.96 sq. mi.



Run 1, k'	0.012
-	0.10
Run 2, k'	0.70
Run 3, k'	

figure 16 Summary of WHP/6 defined with long run time (31 years for the Columbia well, 16 years for the Potoma: wells). *16* the oonductlvlty of the bed oonfining the Potomac wells increases from 0.012 to 0.10 to 0.70, the WHP areas docline from 2.47 sq. mi. to 138 sq. mi. to 0.96 sq. mi.

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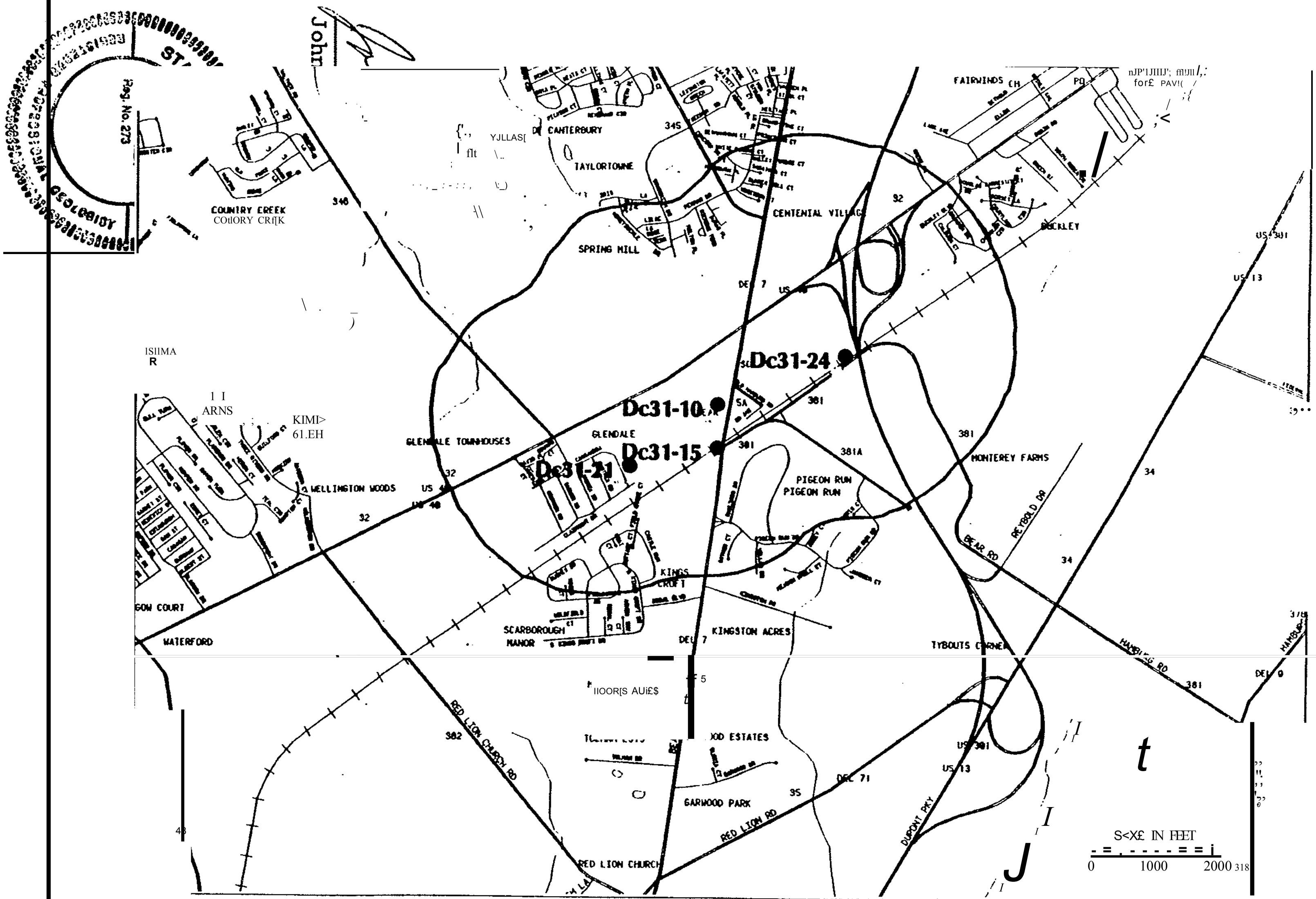


Fisure 17. Run 4. WHPA outline with 10-year run, low k'. Unmnfined Cnlumbia with .0032 ft/yr re::harge; semi-confined Potomac with k' - 0.012 This is the mO§t ronservative 10 year run, area - 1.79 sq. ml.

0

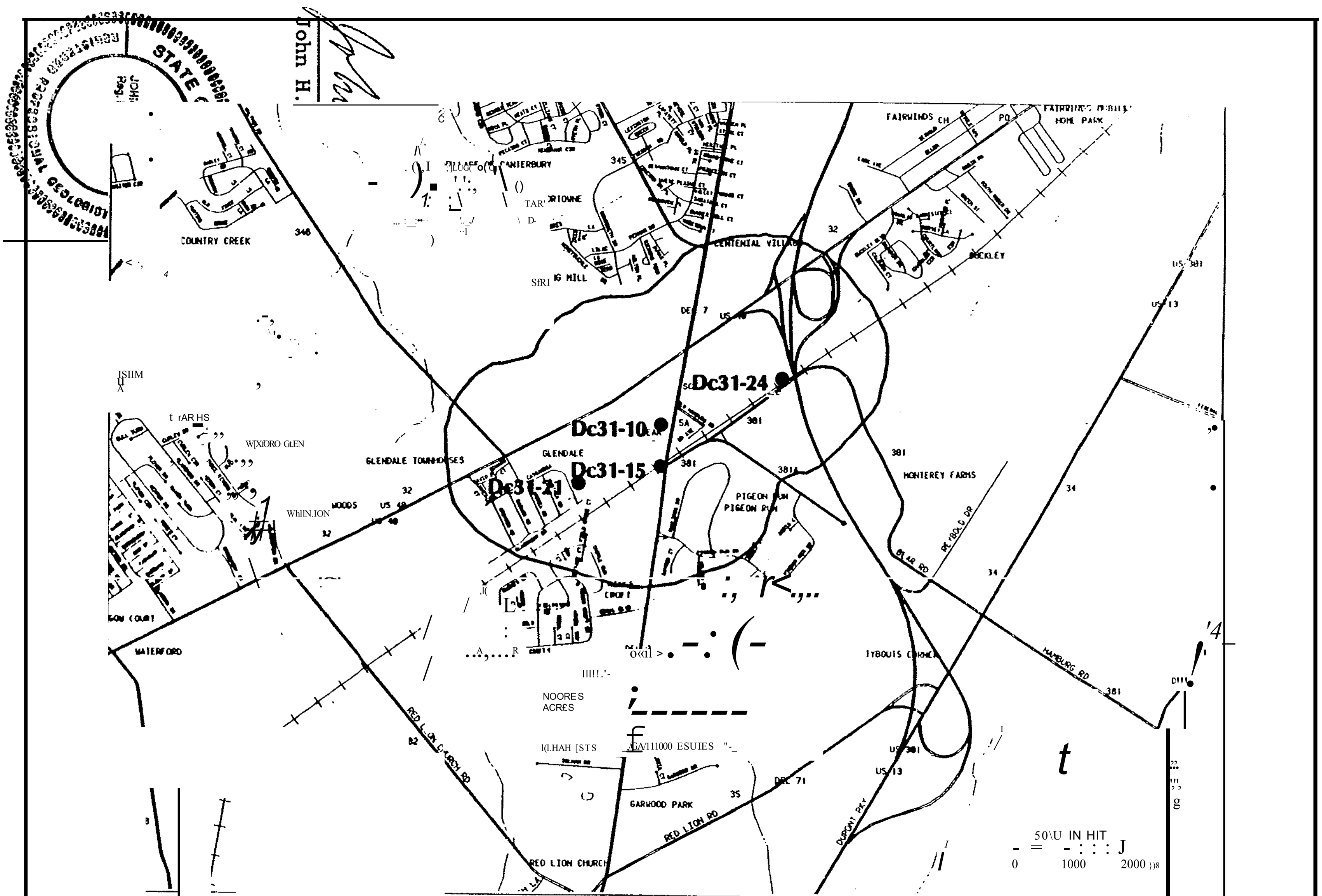


Figure 18. Run 5. WHPA outline with 1 year run, average k'. Unoonfined Columbia with .0032 ft/yr m:harge; semi-oonfined Potomac with k' - 0.10.
Area - 1.09 sq. mi.

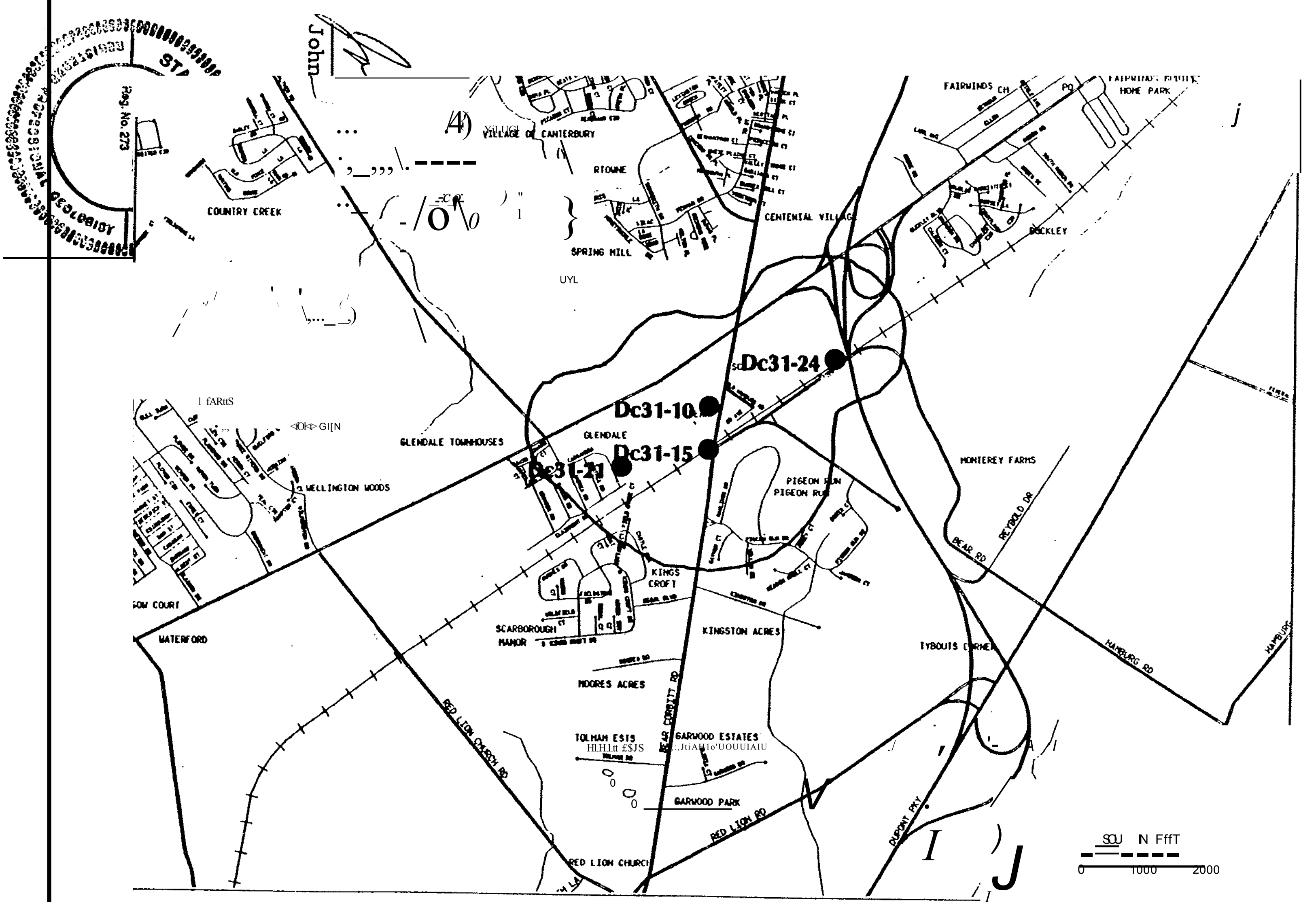


Figure 19. Run 6 WHPA outline with 10-year run, high k'. Unmnfined Columbia with .0032 ft/yr m:harge; semi-<Dnfined Potomac with k' - 0.70.
Area - 0.706 sq. mi.

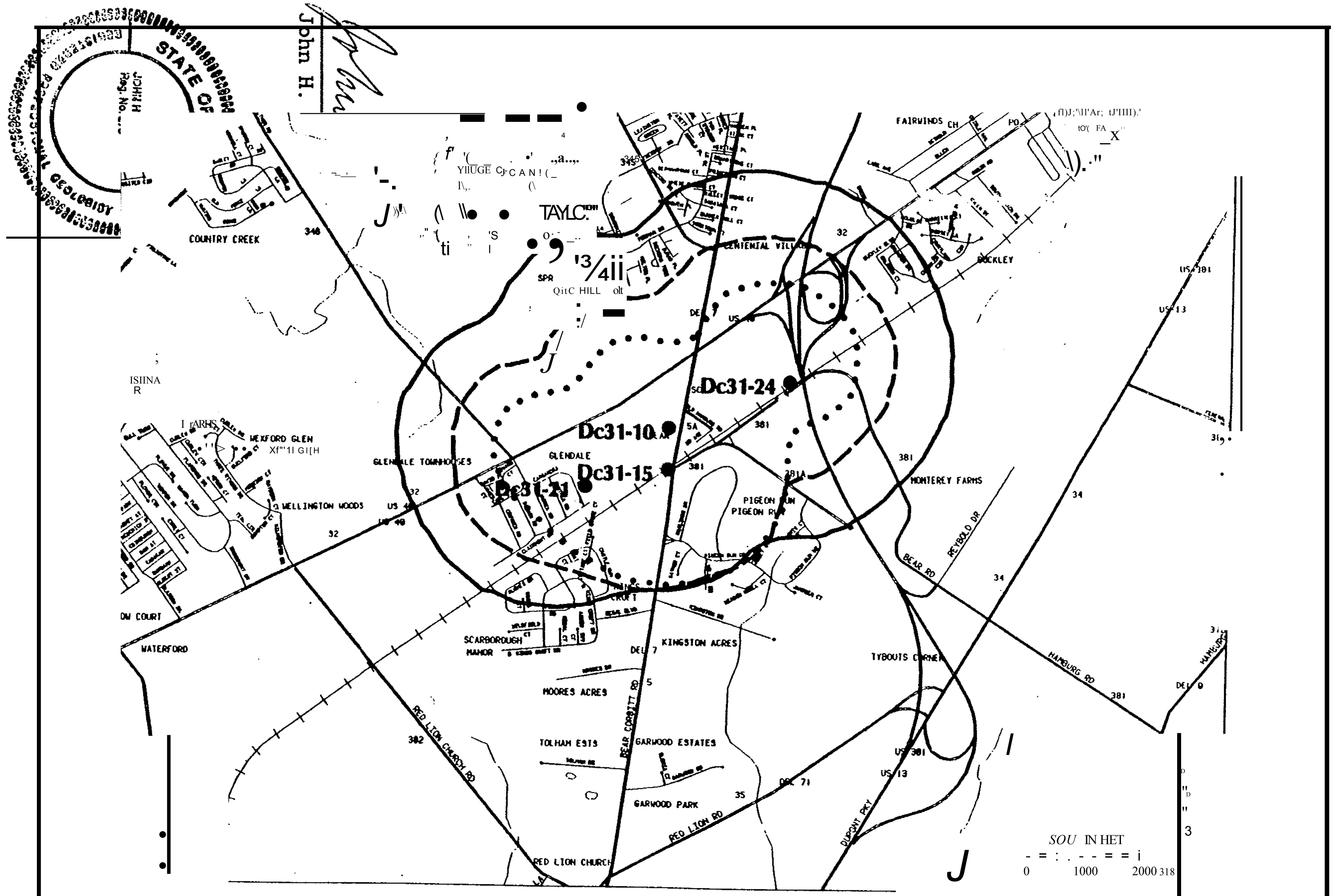


Figure 20. Summary of **WHP/6** defined with 10-year run time for all wells. *16* the ronductivity of the bed ronfining the Potomac wells inc:re.95 from 0.012 to 0.10 to 0.70, the WHP areas decline from 1.79 sq. mi. to 1.09 sq. mi. to 0.706 sq; mi.

Run 4, k' - 0.012
Run S, k' - 0.10
Run f4 k' - 0.70

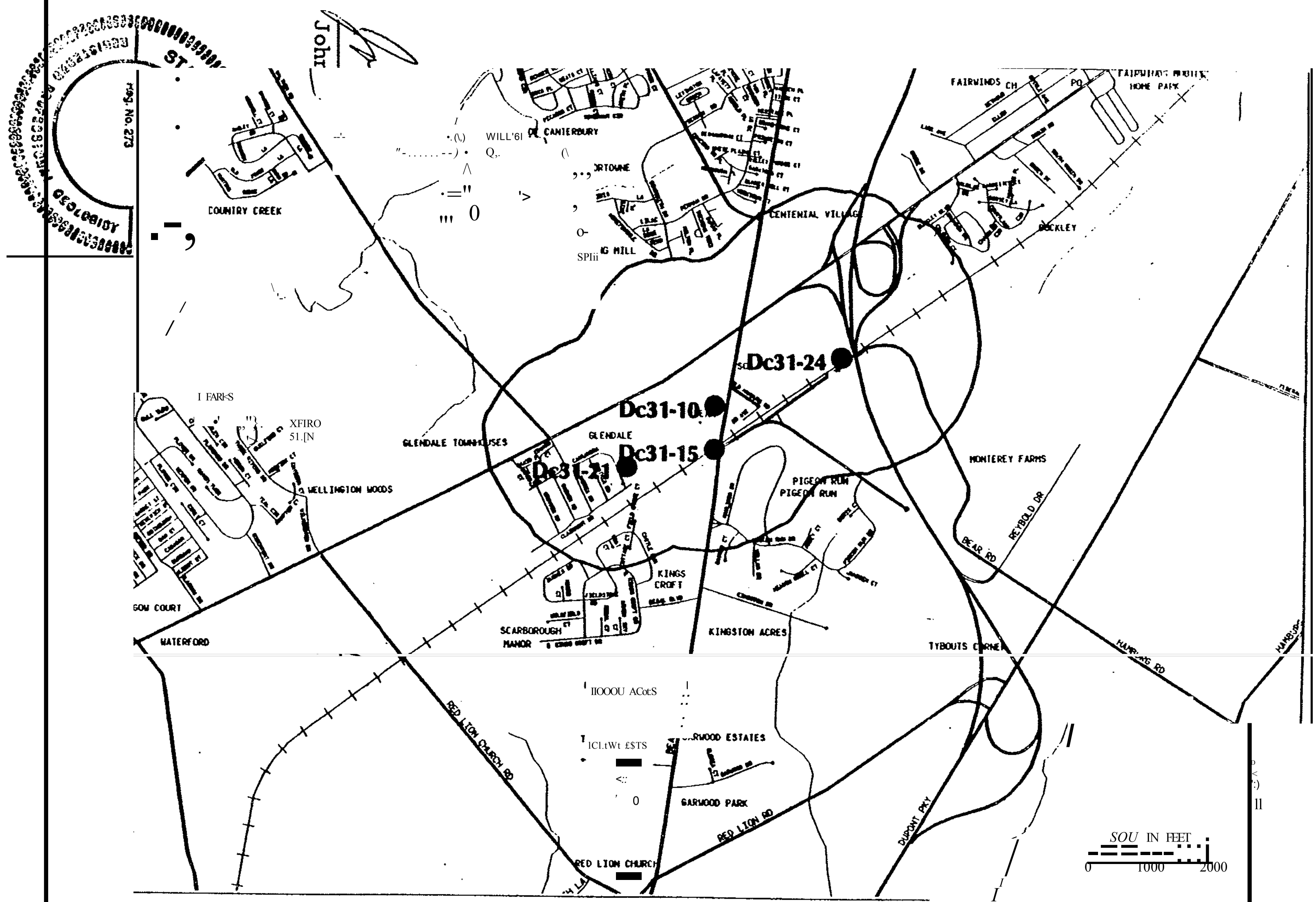


Figure 21. Run 7. WHPA outline with S-year run, low k'. Unronfined Columbia with .0032 ft/yr recharge; seml-oonfined Potomac with k' - 0.012 This is the most oonservative 5-year run; area - 1.14 sq. mi.

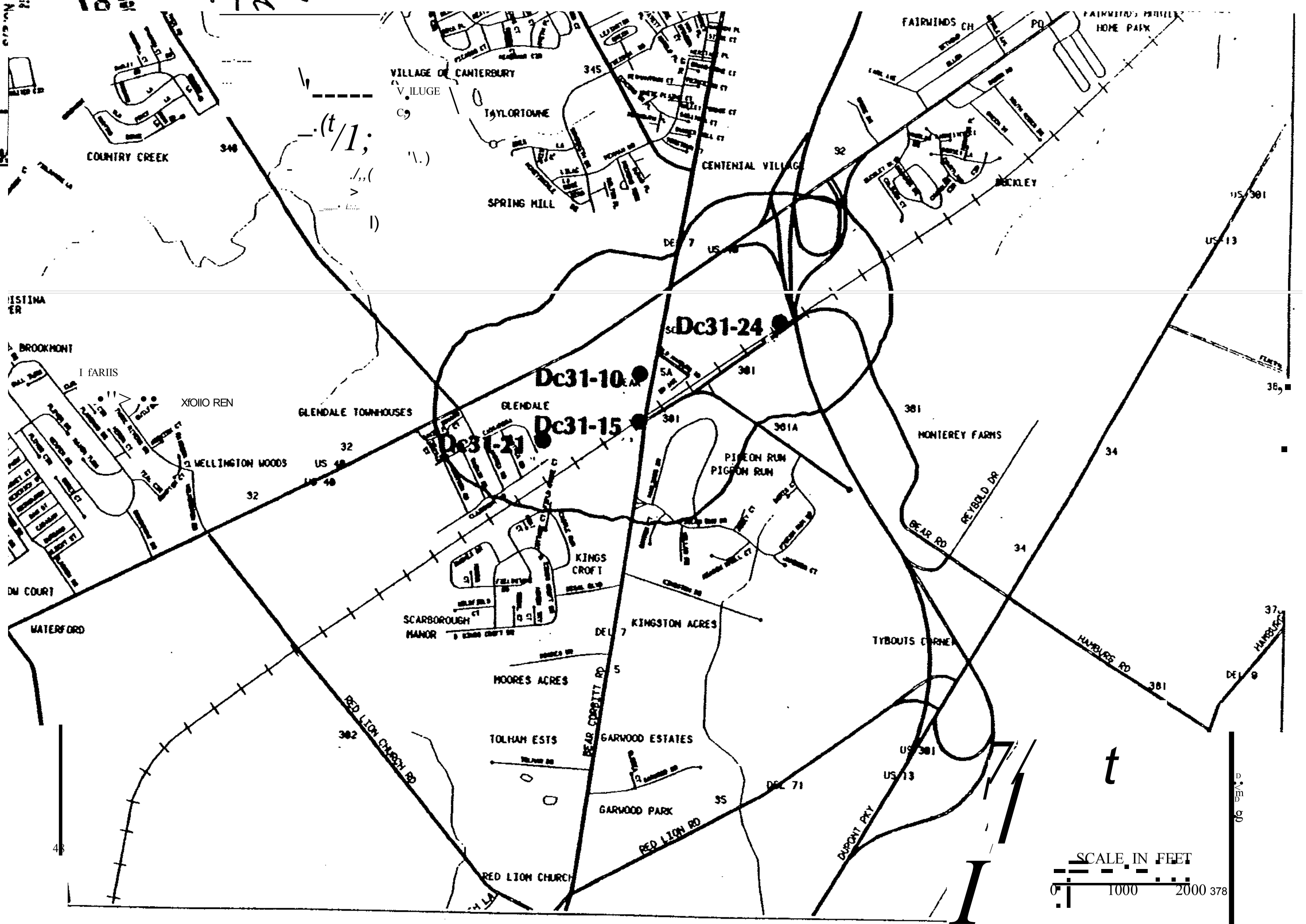


figure 22. Run 8. WHPA outline with 5-year run, average k'. Unoonfined Columbia with .0032 ft/yr recharge; seml-oonfined Potomac with k' - 0.10.
/vea - 0.765 sq. mi.

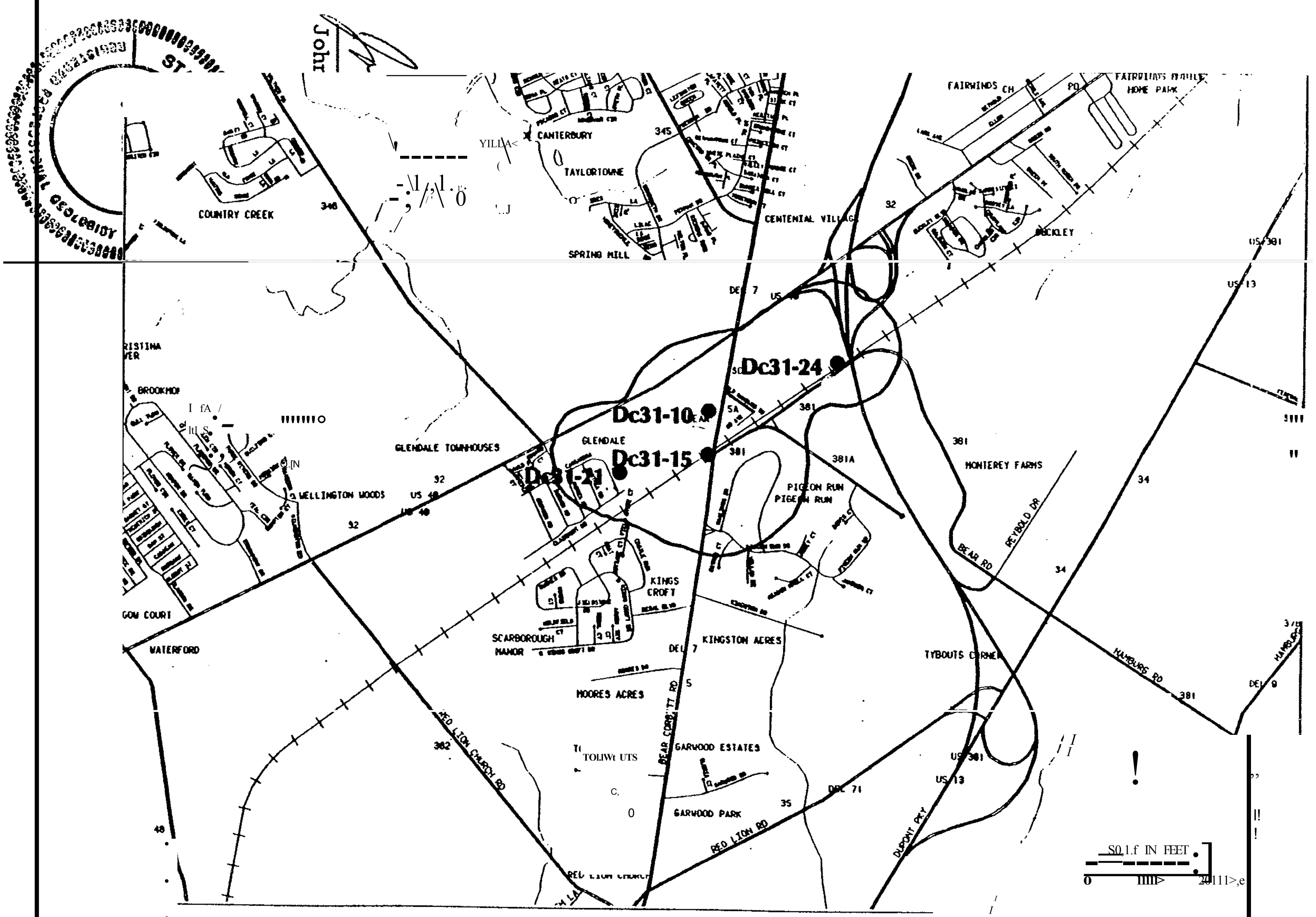


figure 23. Run 9. WHPA outline with 5-year run, high k'. Unronfined Columbia with .0032 *ft/yr* !Wlarge; semi-confined Potomac with k' - 0.70. **Area - 0.464 sq.** mi. This is the l t ooll!lef"Vative trial run, with the shortest run time and the leakiest oonfining bed, and therefore the smallest WHPA

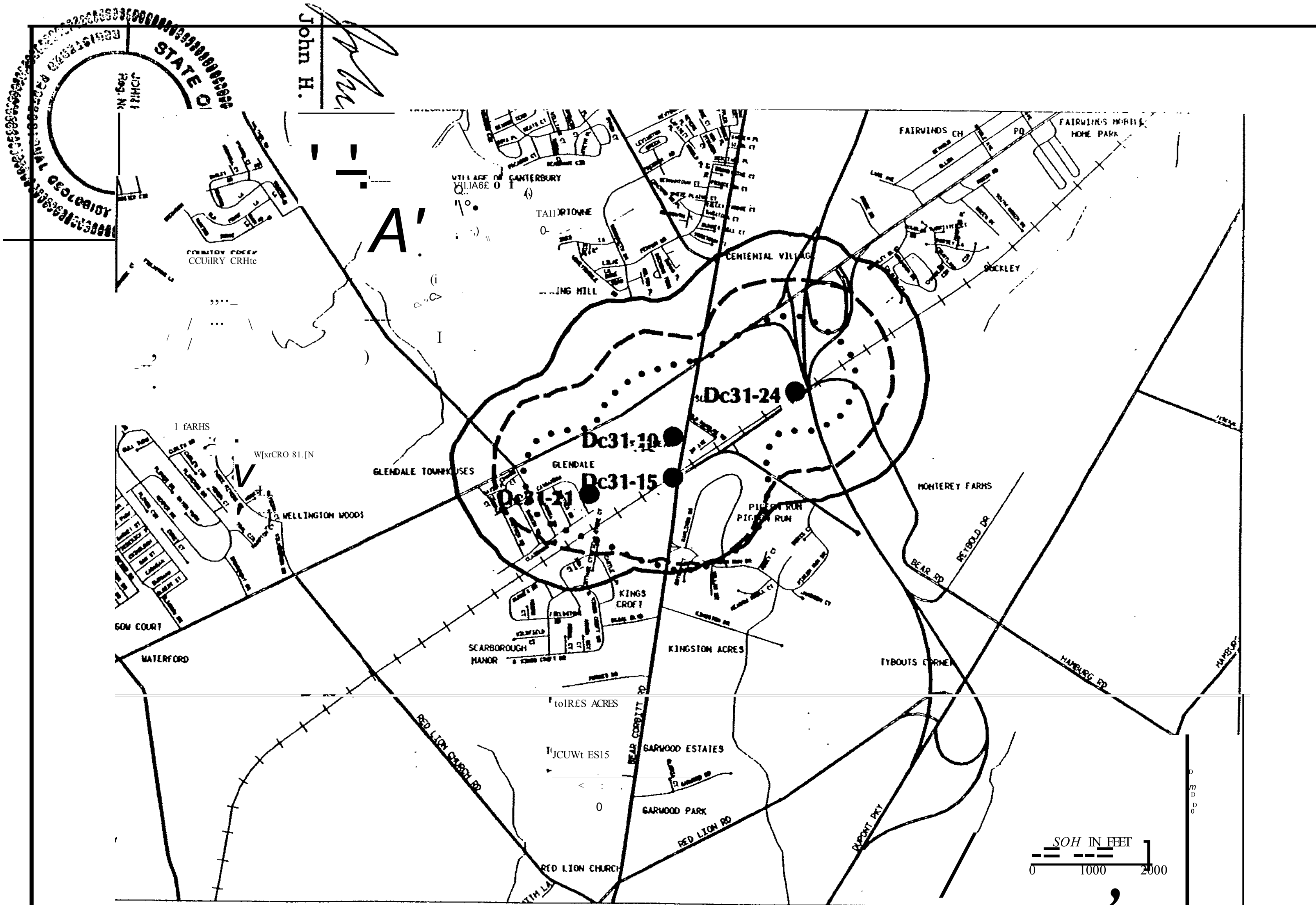
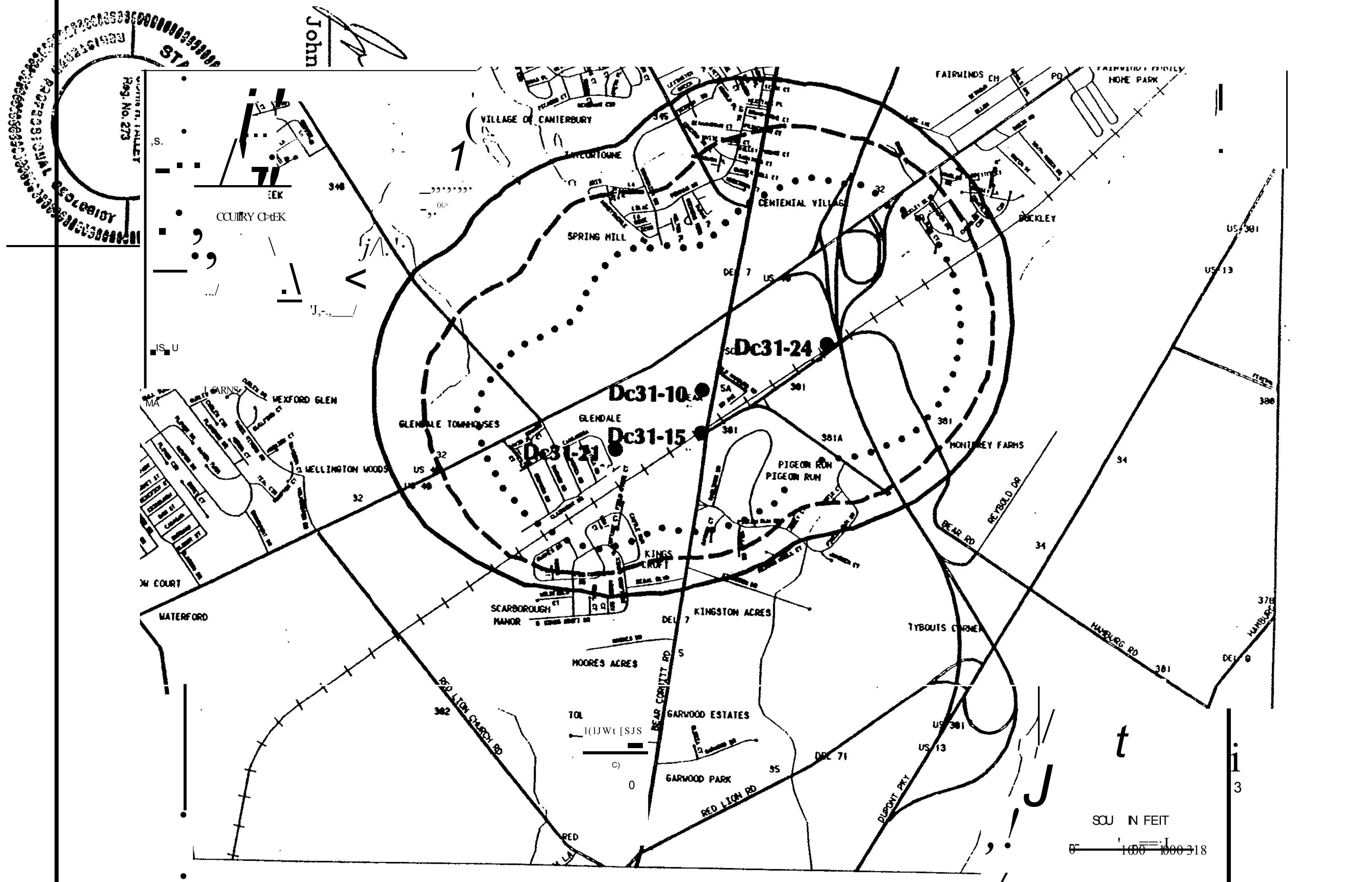


Figure 24. Summary of WHP'6 defined with 5-year run time for all wells. If the oonductivity of the bed confining the Potomac wells i n c from 0.012 to 0.10 to 0.70, the WHP areas decline from 1.14 sq. mi. to 0.765 sq. mi. to 0.464 sq. mi.



Figur 25. Summary of the WHP/6 defined with low k',
e Long run (31/16 years), 10 years, 5 years.
Areas - 2.47 sq. ml., 1J9 sq. ml., and 1.14 sq. ml.

if Run 1, 31/16 Y!1
>, - 4, 10 yrs
... Run 7, .S yn;.

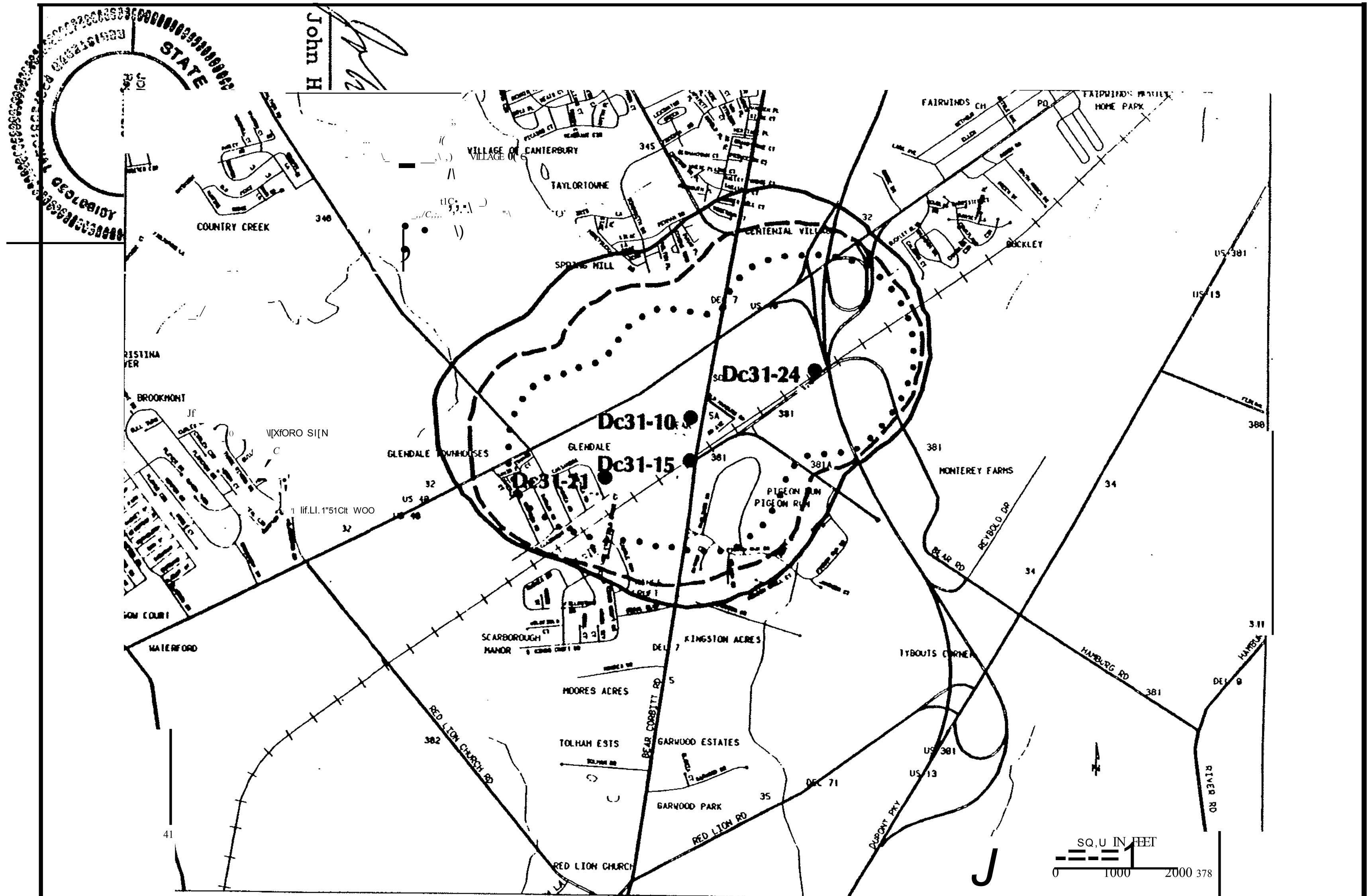


Figure 26 Summary of the WHPh defined with average k',
Long run (31/16 years), 10 years, 5 years.
he.!6 - 138 sq. mi., 1.09 sq. mi., and 0.765 sq. mi.

Ji Run 2, 31/16 *yrs.*
lf . Run 5, 10 *yrs.*
: Run 8, 5 yrs.

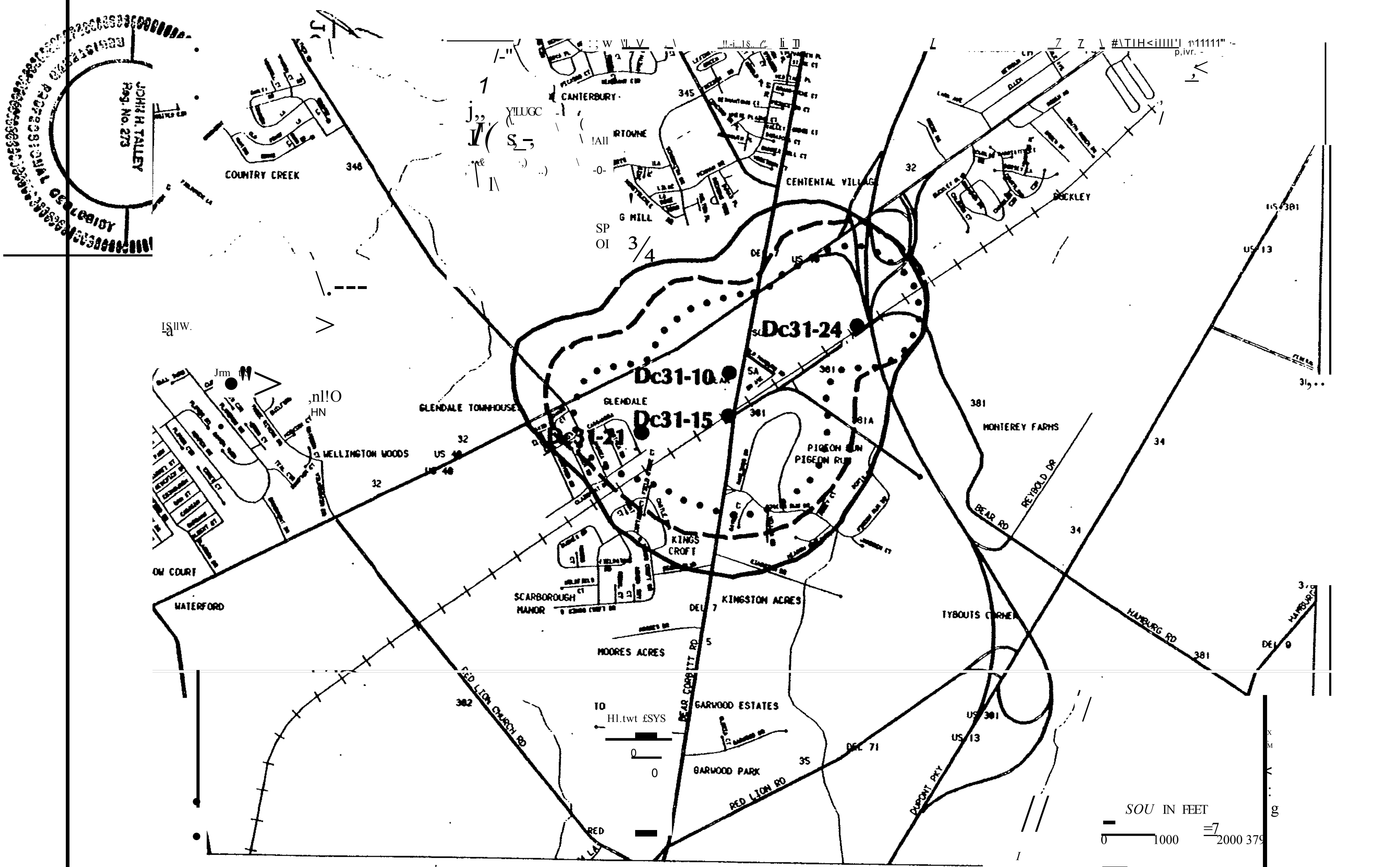


Figure 27. Summary of the WHP/6 defined with hig k',
Long run (31/16 years), 10 years, 5 years.
heas - 0.96 sq. mi., o.706 sq. mi., and 0.464 sq. mi.

Run 3, 31/16 yrs.
Ru 10 yrs.
Run 9, 5 yrs.

travel for water to reach-the aquifer from the ground surface. Thus, surface water less than 30 years old is present in the aquifer indicating that the aquifer system is leaky.

As mentioned previously, in 1987 a preliminary wellhead protection area was drawn in the Glendale wellfield. This area was compared to areas delineated using the EPA modules for the period of record (Figure 28). In this comparison, the area mapped in 1987 coincides most closely with the results of run 2 (long run, average k'). It thus appears that module runs using the average k' value, assuming all other inputs are valid, is applicable for use in module runs with a selected time of travel period.

Application of the EPA modules appear to have been useful in refining the wellhead protection area at the Glendale wellfield. It must be emphasized, however, that in a complex hydrogeologic environment such as exists at Glendale, the modules should be used in conjunction with an understanding of the hydrogeologic framework, and review and application of all hydrologic data, both general and site specific, that are available.

Wellhead protection area delineations using five and ten year times of travel are presented in Figure 26. Either one can be used for regulatory purposes depending upon the time of travel selected.

EASTERN STATES WELLFIELD

The Eastern States wellfield is located near the intersection of U.S. Route 40 and the Delaware-Maryland state line (Figure 4). There are three significant production wells in the Eastern States wellfield, Da44-06 (Artesian Well# 1), Da43-03 (Artesian Well# 2), and Ce-Bf-59 (Elkton Well # 3) (Figure 29). All three wells are screened in the lower Potomac aquifer, which had initially been considered confined in this area.

Hydrogeologic Framework

The hydrologic framework is relatively complex in that the area is overlain by a relatively thin veneer of sediments belonging to the Columbia Formation. Because the Columbia does not have the thickness or hydraulic characteristics to provide appreciable quantities of water to wells, very few wells have been completed in it. The underlying Potomac Formation is complex in that individual beds of sand, silt, and clay are discontinuous and cannot be traced laterally or vertically with any degree of precision. Several test wells have been drilled in the area. Some warranted conversion to production wells while most did not. Correlation of sandy beds cannot be completed with any degree of accuracy even though it has been determined that the sandy zones in which the wells are screened are hydraulically connected. Only two of the test wells in Delaware have yielded positive results with respect to obtaining appreciable quantities of water.

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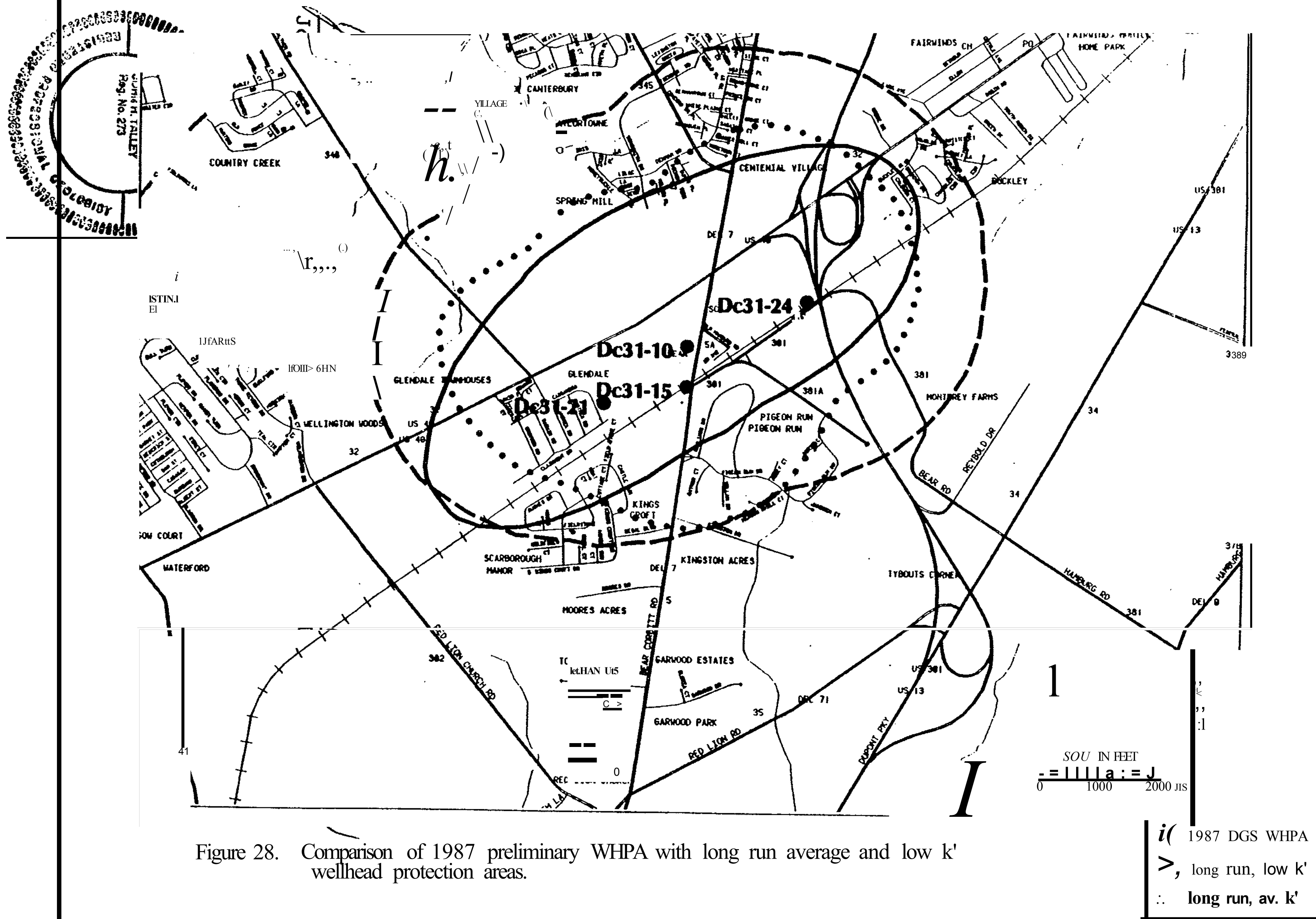

Figure 28. Comparison of 1987 preliminary WHPA with long run average and low k' wellhead protection areas.

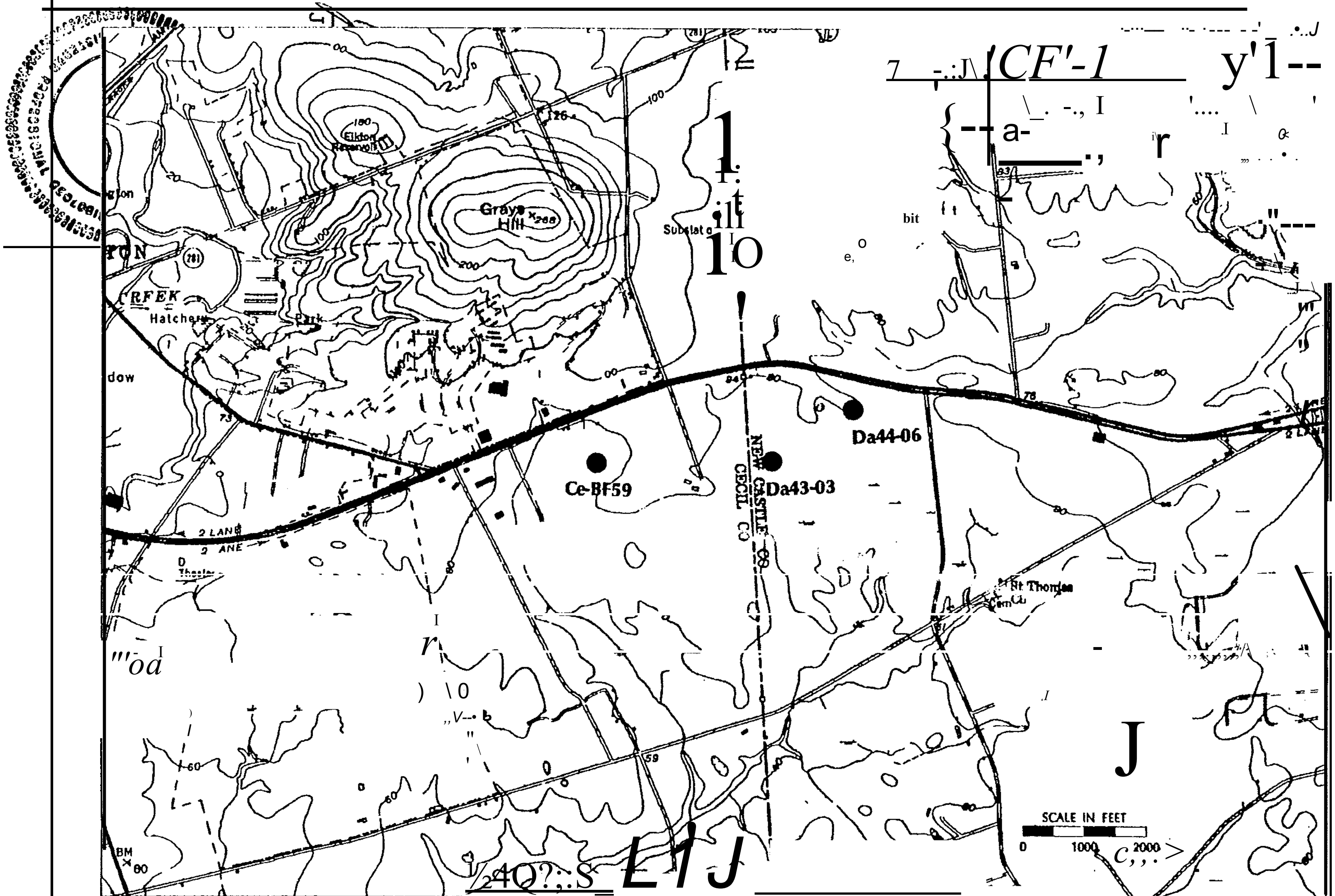

Figure 29. locations of production wells in the Eastern States wellfield. Ce-Bf59 (Elkton #3), Da43-03 (Artesian #2), Da44--06 (Artesian #1).

Analysis of descr ?tive logs from eight test holes drilled by Artesian Water Company as part of a ground-water exploration program and analysis of geophysical logs from twc of those holes reveals that sands in the lower portion of the Potomac ar-" overlain by fine-grained sediments (silt and clay) that appear to function a::: confining beds. Predominately clayey zones were encountered in all of the est holes between about 20 and 90 ft. This indicates that recharge in areas adjacent to the production wells probably occurs at very slow rates end water levels in shallow wells are probably not significantly affected by pnnping. However, this has not been documented as efforts to locate shallow wElls and water-levels in the vicinity of the wellfield were not made as p rt of this project. Descriptive logs are presented for wells Da44-06 ,-.nd Da43-03, respectively in Figures 30 and 31.

The Maryland Water Reso. ·rces Administration (1989, p. 46) reported that in the Eastern States wellfie}:l area that "A preliminary investigation revealed that ground water lev ls were falling and that a number of 40 to 60 ft deep wells had, in fact, gene dry." They report that the area in which water levels were affected was iounded on the north by the base of Grays Hill, on the west by White Hall Road .n nearby Maryland, on the south by a line that runs roughly parallel to and 3,()0 ft south of U. S. Route 40, and on the east by a north-south trending line a·proximately 5,000 ft east of the Delaware Maryland State boundary.

Two conclusions reached by r.':leMaryland Water Resources Administration (1989, p. 67) are: (1) "The Middle Potomac confining unit, severely limits recharge to the underlying Lower Pc omac south of U. S. Rte. 40, where it consists of thick, impermeable non-·.:ransmissive clay," and (2) "The Middle Potomac is more sandy, allowing rec arge to reach the Lower Potomac north of U. S. Rte. 40 and south of U. S. Rte. 40 near Maloney Road."

Pumping Histor, and Allocations

Available pumpage records for the Eastern States wells are presented in Table 13. Pumpage has been increasing steadily, with the maximum daily pu. page of these three wells exceeding two mgd in 1987.

Well allocations were obtained from the Water Supply Branch of the Delaware DNREC. The Elkton well (Ce-Bf-5:') allocation of 0.8 mgd (555 gpm, 109,925 ft³/day) is based upon the 1987 maximum yearly pumpage of 0.798 mgd (Table 13). For the Artesian Water Company wells, current allocations of 600 gpm (115,500 ft³/day) for well Da44-06 and 300 gpm (57,750 ft³/day) for well Da43-03 have expired; however, proposed allccations (April, 1992) are the same as past rates.

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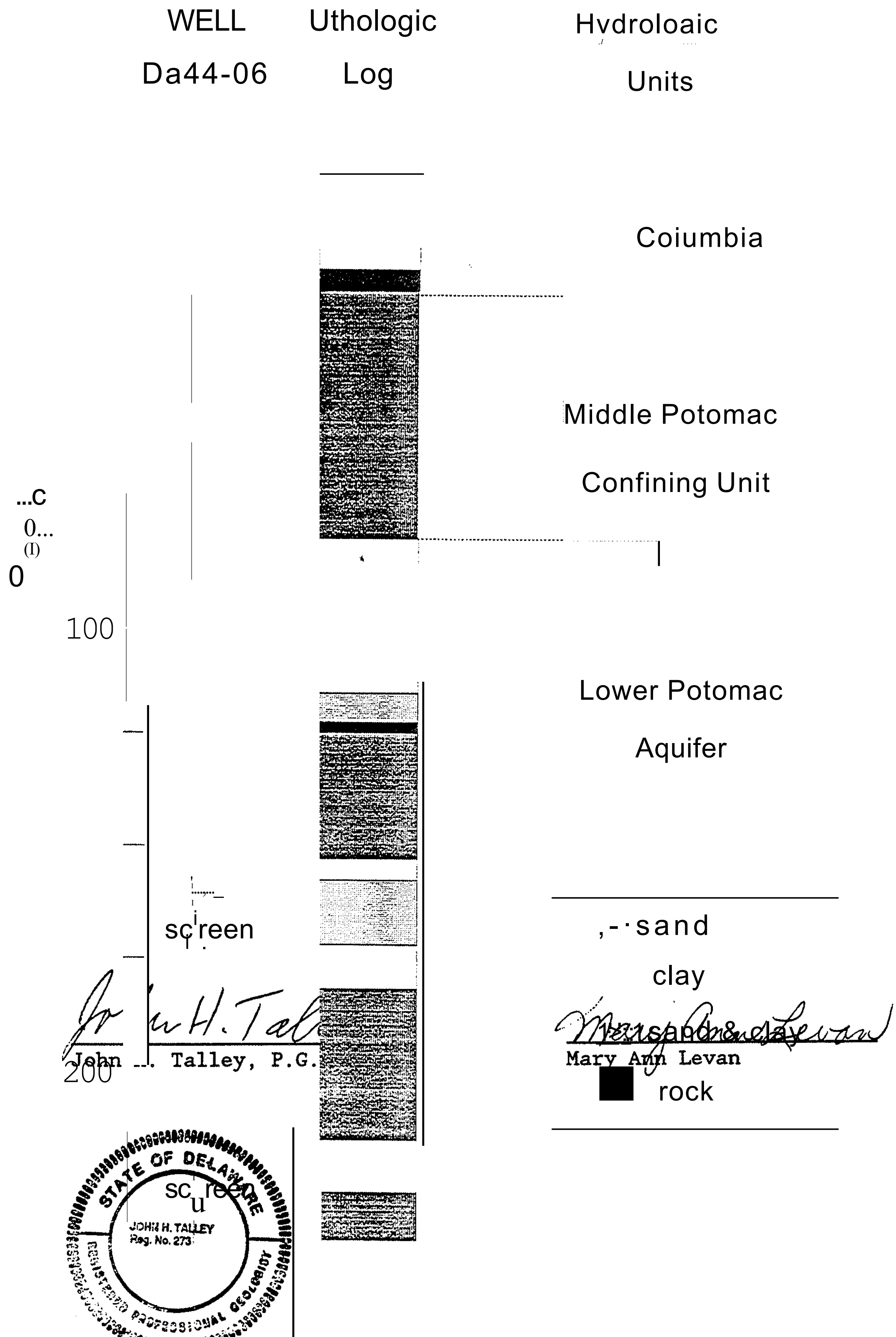

Figure 30. Lithologic log for Eastern States well Da44-06.

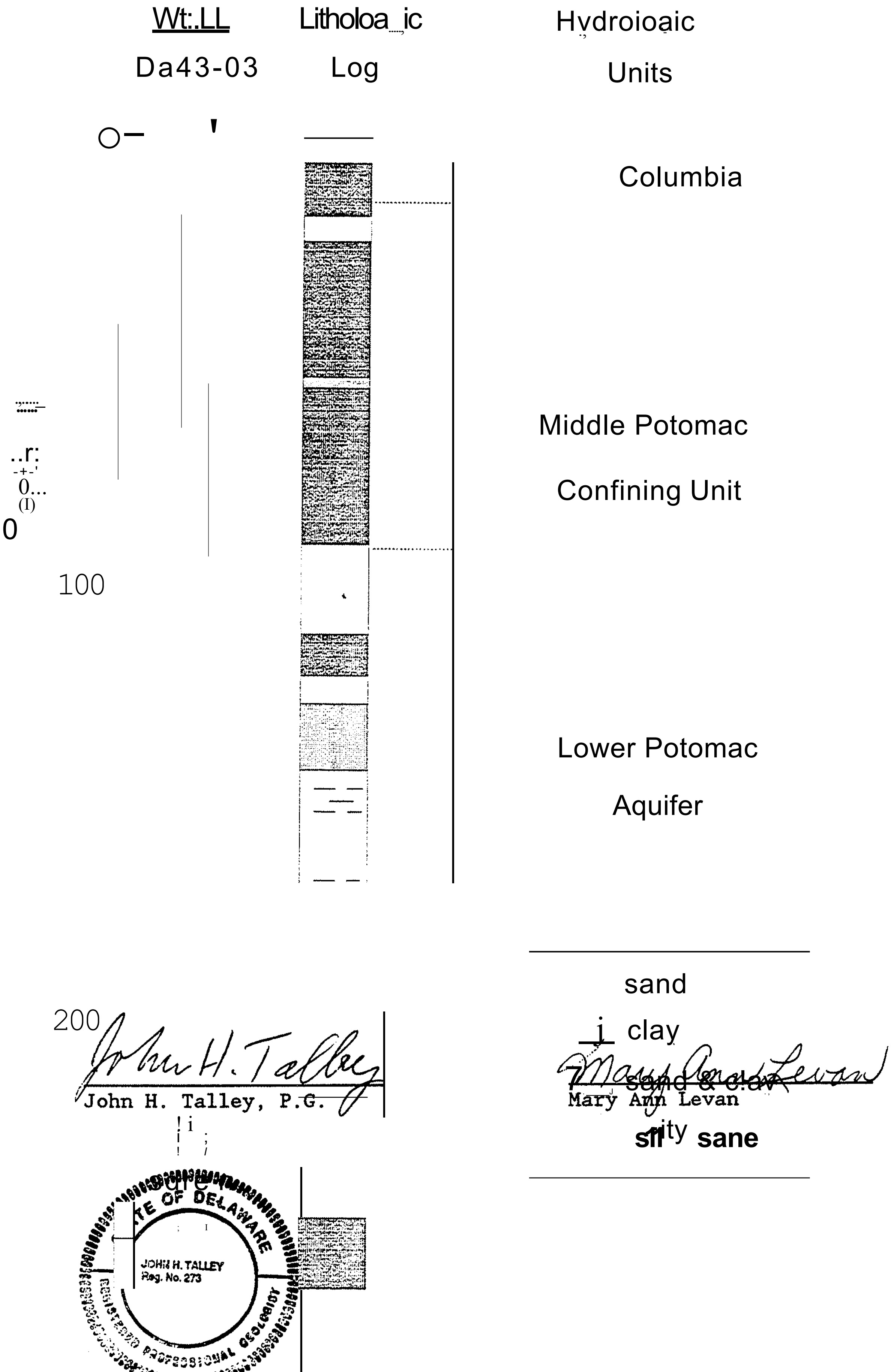

Figure 31. Lithologic log for Eastern States well Da43-03.

Table 13. Pumpage records for the Eastern States wellfield. (Artesian Water Co. and Maryland Water Resources Administration, 1989)

Maximum Yearly Pumpage -million gallons/day-				Maximum Yearly Pumpage -gallons per minute-			
Year	Town of Elkton	Artesian	Total	Year	Town of Elkton	Artesian	Total
1979	.305		.305	1979	212		212
1980	.264		.264	1980	183		183
1981	.586		.586	1981	407		407
1982	.710		.710	1982	493		493
1983	.659	.910	1.569	1983	457	631	1088
1984	.711	1.16	1.871	1984	494	806	1300
1985	.671	1.031	1.702	1985	466	716	1182
1986	.674	1.34	2.014	1986	468	931	1399
1987	.798	1.296	2.094	1987	555	900	1455

APPLICATION OF THE W'HPA MODEL AT EASTERN STATES

Because of the complexity of the geologic setting of the Eastern States wellfield, no one wellhead protection module was clearly best. The choice of a wellhead protection module depends upon the geology of the wellfield and availability of hydraulic characteristics. The RESSQC module is suitable only for fairly simple geologic settings and was not adequate for this wellfield. The MONTEC module is used as a tool for sensitivity analysis and was also not appropriate. The remaining two modules, GPTRAC and MW'CAP, were evaluated in detail. These two modules have different capabilities and require slightly different inputs (Tables 2 and 3).

Input Parameters

John H. Talley, P.G.

Mary Ann Levan

A data form used for W'HPA runs is shown in Table 8. The process of defining wellhead protection areas required many successive module runs, with refinements made according to the outcomes.

Following the sample data sheet in Table 8 for the Eastern States wellfield, the module ID was either GPTRAC or MW'CAP, with a time-related capture zone run type. For purposes of evaluating the modules, a simulation time of ten years was used. When the final approach was chosen for defining a recommended protection area, both five and ten year simulation times were run.

STATE OF DELAWARE
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Pumping Well Inputs

For each pumping well in the wellfield, both the GPTRAC and MWCAP modules require inputting the type of aquifer in which the well is screened (confined, semi-confined, or unconfined) and the well pumping rate.. The MWCAP module also requires a well radius.

Although wells are not pumped continuously at constant rates, the WHPA modules require input of a single (constant) pumping value for each well. As with the Glendale module runs, well allocations were used for the pumping rates. Since the allocations are the maximum allowed pumpage, this gives a conservative estimate of the wellhead protection areas if actual rates are less than the allocated rates. Pumping well inputs are summarized in Table 14.

Table 14. Pumping well input parameters for the Eastern States wellfield.

Pumping wells: 3

Well ID:	Ce-Bf-59	Da43-03	Da 44-06
Formation:	Lower Potomac	Lower Potomac	Lower Potomac
Aquifer Type:	Confined*	Confined*	Confined*
Pumping Rate (ft^3/day):	109,925	57,750	115,500
Well **Radius** (ft):	0.5	0.42	0.42

*In a single GPTRAC evaluation, an aquifer type of "semi-confined" was used.

Aquifer Properties

The modules used require input of transmissivity, thickness, porosity, ambient hydraulic gradient, and angle of flow. For aquifer transmissivity and thickness, MWCAP allows input of individual (discrete) values for each well, whereas for GPTRAC, an average value must be used.

Considerable aquifer test data were available for calculating transmissivity for all three production wells. Recovery and drawdown data were analyzed both graphically and through the use of an automated pump test analysis program which calculated transmissivity and coefficient of storage (Walton, 1960). Results are presented in Table 15. An average value of transmissivity of 1,588 ft^2/day was used for well Da43-03 while an average value of 1,445 ft^2/day was used for well Da44-06. A value of 3,900 ft^2/day for well Ce-Bf-59 was reported by the Maryland Water Resources Administration (1989). When GPTRAC was run, an arithmetic average transmissi ity of 2,311 ft^2/day was used for the entire wellfield.

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Aquifer thicknesses in the vicinity of each well and average aquifer thickness for the wellfield were determined through interpretation of lithologic and geophysical logs from production wells, test/-0bservation wells, and test holes (Figures 30 and 31). These logs show the lower Potomac aquifer

Table 15. Transmissivity and coefficient of storage values derived from aquifer test analyses for the Potomac Formation, Eastern States wellfield.

WELL ID	DATA TYPE	TRANSMISSIVITY (ft2/dav\	COEFFICIENT OF STORAGE	ESTIMATION TECHNIQUE
PRODUCTION WELL Da43-03 "Eastern States 112"	Drawdown	1470 1382		Graphical, Artesian Pump test program
	Recovery	1770		Graphical, semilog
5" Observation well 78feetfrom production well	Drawdown	1436	0.00014	Theis curve matching
	Recovery	1880		Graphical, semilog
PRODUCTION WELL Da44-06 "Eastern States #1"	Drawdown	1550 1616 1738		Graphical, semilog Pump test program Theis curve matching
	Recovery	1735		Graphical, semilog
2" Observation well 15 feet north of production well	Drawdown	1470 1380 1540	 0.0044 0.00316	Graphical, semilog Theis curve matching Pump test program
	Recovery	1580		Graphical, semilog
6" Observation well Eastern States Test Well #5, Da43-02 ·	Drawdown	1933		Theis curve matching

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underlying the middle Potomac confining unit; both the lower- and middle Potomac units consist of interbedded clays and sands. There is no distinct change from an aquitard or confining bed to an aquifer. In most instances a transition zone separates the aquifer from the confining unit.

In order to construct efficient wells and to obtain maximum yields, only those sands interpreted as being able to be developed and capable of yielding large quantities of water were screened. For each well, the aquifer thickness was considered equivalent to the screened interval. The thicknesses of the screened intervals were used as aquifer thicknesses for individual wells in the MWCAP module runs. Thus, for well Da44-06, an aquifer thickness of 36 ft was used, as the sum of the two screened intervals between 160-186 ft and 222-232 ft. Although some sandy zones were reported to be between 81 and 125 ft, they were not included in the aquifer thickness since they are separated from the screened interval by relatively thick intervals of fine-grained sediments. Similar judgments were made for the other wells; Da43-03 is screened between 222-250 ft (28 ft) and Ce-Bf-59 between 126-157 ft (31 ft). For the GPTRAC module, these numbers were averaged to give an aquifer thickness of 32 ft.

As indicated earlier, because of the complex depositional environment of the Potomac Formation, most, if not all of the assumptions on which analytical formula are based are violated to one degree or another. For example, the sands in the Potomac are not of uniform thickness, and the water-bearing formation is not uniform in character and permeability in both horizontal and vertical directions. This aquifer system clearly differs from the ideal uniform horizontal aquifer assumed by the WHPA modules and other hydrologic models. Accordingly, care must be taken in applying the WHPA modules to delineate a wellhead protection area at Eastern States.

There is little potentiometric surface information available for computing a pre-pumping gradient. Most reported water table readings are for domestic wells screened in the unconfined Columbia aquifer. The pre-pumping gradient and direction of flow were determined through interpretation of 1955 steady state potentiometric surface maps of the lower Potomac aquifer simulated by Martin (1984). The gradient was determined to be approximately 15 ft/2.5 miles or .001136 with a direction of flow of S15°E (285° for the model).

Aquifer property inputs are summarized in Table 16.

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Aquifer Boundaries

Both modules (**MWCAP** and GPTRAC) allow utilization of stream and barrier boup.daries. In the Eastern States wellfield, the Grays Hill bedrock outcrop north of the wellfield at approximately the 140 foot contour was considered as a barrier boundary. A straight line boundary can be used in the GPTRAC module and assigned to any side of the study area with the simple input of "top", "bottom", or east or west "side". In MWCAP, the boundary is located by measuring the perpendicular distance and direction of the boundary relative to each well. Measurements made from the three Eastern States wells to the 140 foot contour are shown in Figure 32 and numerical inputs are presented in Table 17.

STATE OF DELAWARE
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Reg. No. 273
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Table 16. Aquifer property inputs for the Eastern States wellfield.

Module Well ID	MWCAP T (ft^2/day)	 b (ft)	GPTRAC T (ft^2/day)	 b (ft)
Ce-Bf-59	3900	31	2311	31
Da-43-03	1588	28	2311	32
Da44-06	1445	36	2311	32
Aquifer Porosity	.25		.25	
Ambient Hydraulic Gradient	.001136		.001136	
Angle of Flow	285°		285°	

Table 17. Boundary inputs for the MWCAP and GPTRAC modules.

Module	MWCAP		GPTRAC
Boundary Type	Barrier		Barrier
Perpendicular Distance and Orientation	Ce-Bf-59	2916 ft, 288°	"top of study area"
	Da43-03	4019 ft, 310°	
	Da44-06	4492 ft, 327°	

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Recharge Inputs

The lower Potomac aquifer appears to be confined south of U. S. Route 40 and evidence presented by the Maryland Water Resources Administration (1989) suggests that it becomes semi-confined north of U.S. Route 40 where the middle Potomac unit becomes thinner, more sandy, and leaky. The area north of U.S. Route 40 is within the area of -influence of the three production wells and contributes recharge to the aquifer (Maryland Water Resources Administration, 1989). Because the MWCAP module does not accommodate recharge, all runs using MWCAP were made without recharge. GPTRAC does accommodate recharge and two approaches were used. The approaches are discussed and included in the following section.

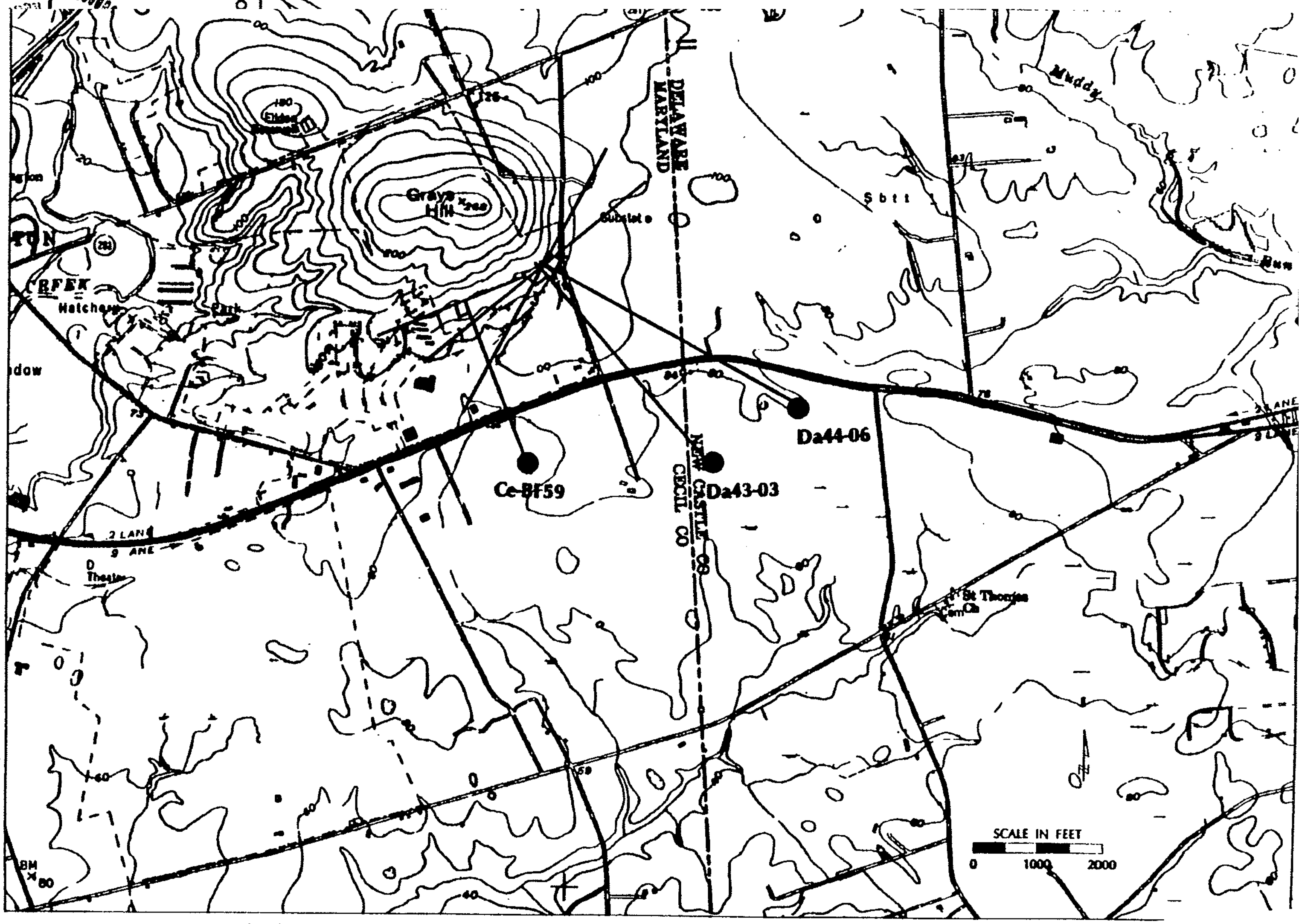

Figure 32. Method of measuring distance and direction for boundary orientation in MWCAP.

Recharge to the Potomac occurs by water percolating down from land surface. Interpretation of the geologic framework in the vicinity of the wellfield and review of conclusions reached in the investigation of the geology and hydrology of the wellfield by the Maryland Water Resources Administration (1989) suggests that *a* significant portion of recharge occurs in the updip portion of the aquifer system north of U. S. Route 40. Some recharge also reaches the aquifer from directly atop the wellfield from migration of water down through or around aquitards. As discussed earlier, individual beds of sediment (sand or clay) are laterally and vertically discontinuous and pumping from individual production wells results in interference with other production wells. As a result, calculation of rates of recharge from the surface in the immediate vicinity of the wells is difficult. Nevertheless, some recharge probably occurs.

A tritium analysis of water obtained from well Da44-06 indicates that at least some of the water being pumped from this well is relatively young (less than 30 years old). Relatively young water is migrating to the well either through near vertical leakage or from updip recharge areas north of U.S. Route 40, or both. Based on review of published data (Maryland Water Resources Administration, 1989) and interpretation of descriptive and geophysical logs, its appears that most of this relatively young water is probably coming from areas north of the wellfield.

MODULE RUNS AT EASTERN STATES

Four concerns arose and had to be addressed in response to the use of GPTRAC and MWCAP (Table 18).

The comparisons outlined in Table 19 are presented below in a series of computer module runs utilizing a 10-year time of travel.

As discussed above, both modules operate with the same pumping well inputs, with all wells pumping constantly at the allocated rate for the entire simulation time. The MWCAP module does not account for well interference. With the GPTRAC module, well interference is accounted for, and when pumping wells interfere, the shape of the capture zones reflect well interference. Since the Eastern States wells have high pumping rates, are screened in the same formation, and are closely spaced, it was expected that well interference would be significant. Module runs 1 and 2 (Table 19) were designed to evaluate the effects of well interference. The same values were input into each module.

John H. Talley, P.G. | Mary Ann Levan

The output of the MWCAP module with overlapping capture zones shows that well interference is significant in this wellfield (Figure 33). The effects of well interference have also been documented in aquifer tests. Pathlines in GPTRAC capture zones are elongate where well interference occurs, and the outlined WHPA is substantially larger (Figure 34) than that determined using MWCAP. Overlaying the two delineated WHPAs (Figure 35) shows the difference in size of the delineated areas. The area delineated using MWCAP area is 3.15 mi^2 while the area delineated using GPTRAC is 4.85 mi^2. Based on evidence that interference does occur, the GPTRAC module appears to be more applicable that MWCAP in simulating the capture zones in this wellfield.

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JOHN H. TALLEY
Reg. No. 273

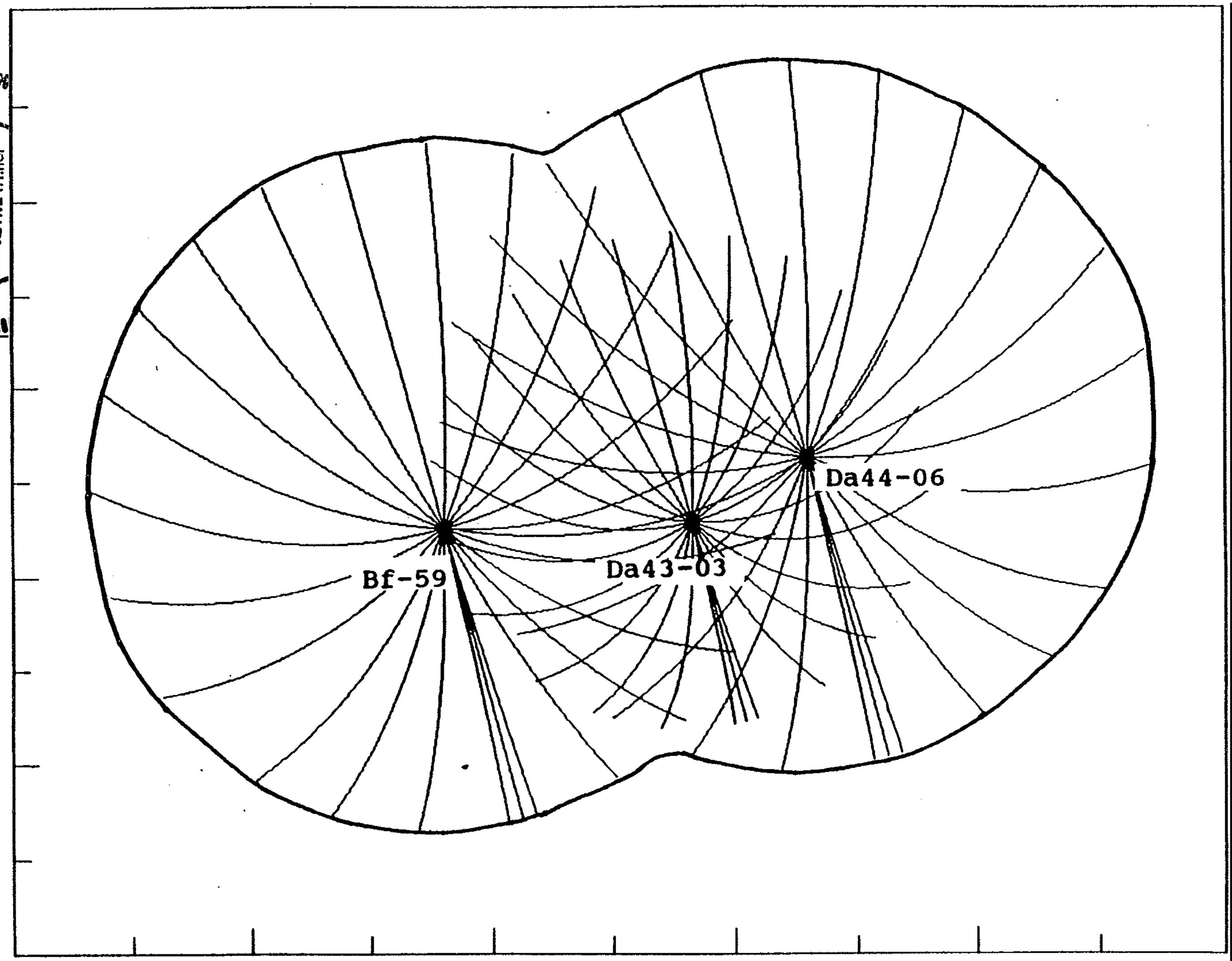

Figure 33. MWCAP capture zones for Eastern States run 1. The overlap indicates significant interference among the wells.

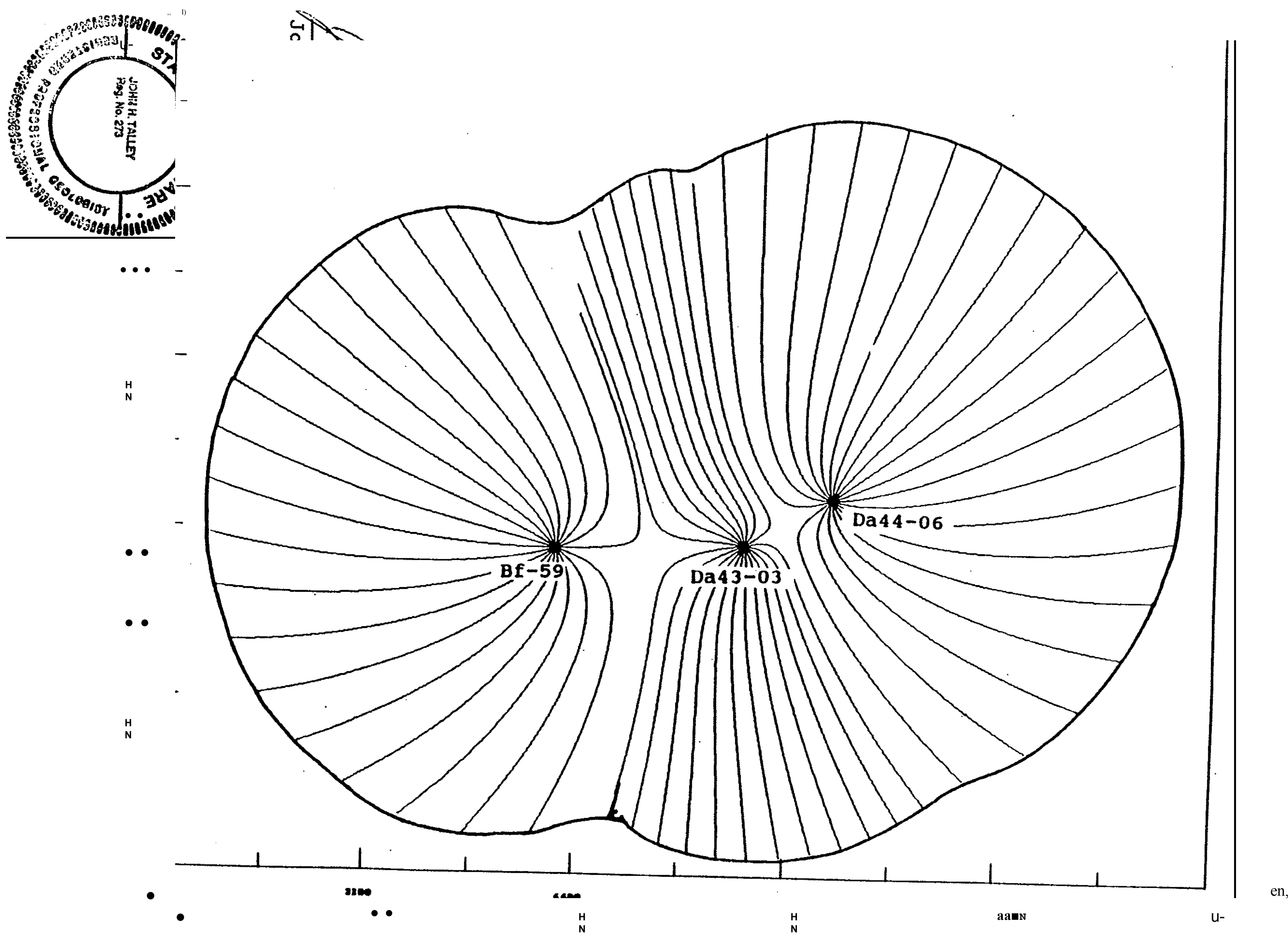

Figure 34. GPTRAC capture zones for Eastern States run 2. Since this module accounts for well interference, the capture zones are skewed and the WHPA is much larger than with MWCAP with the same input parameters.

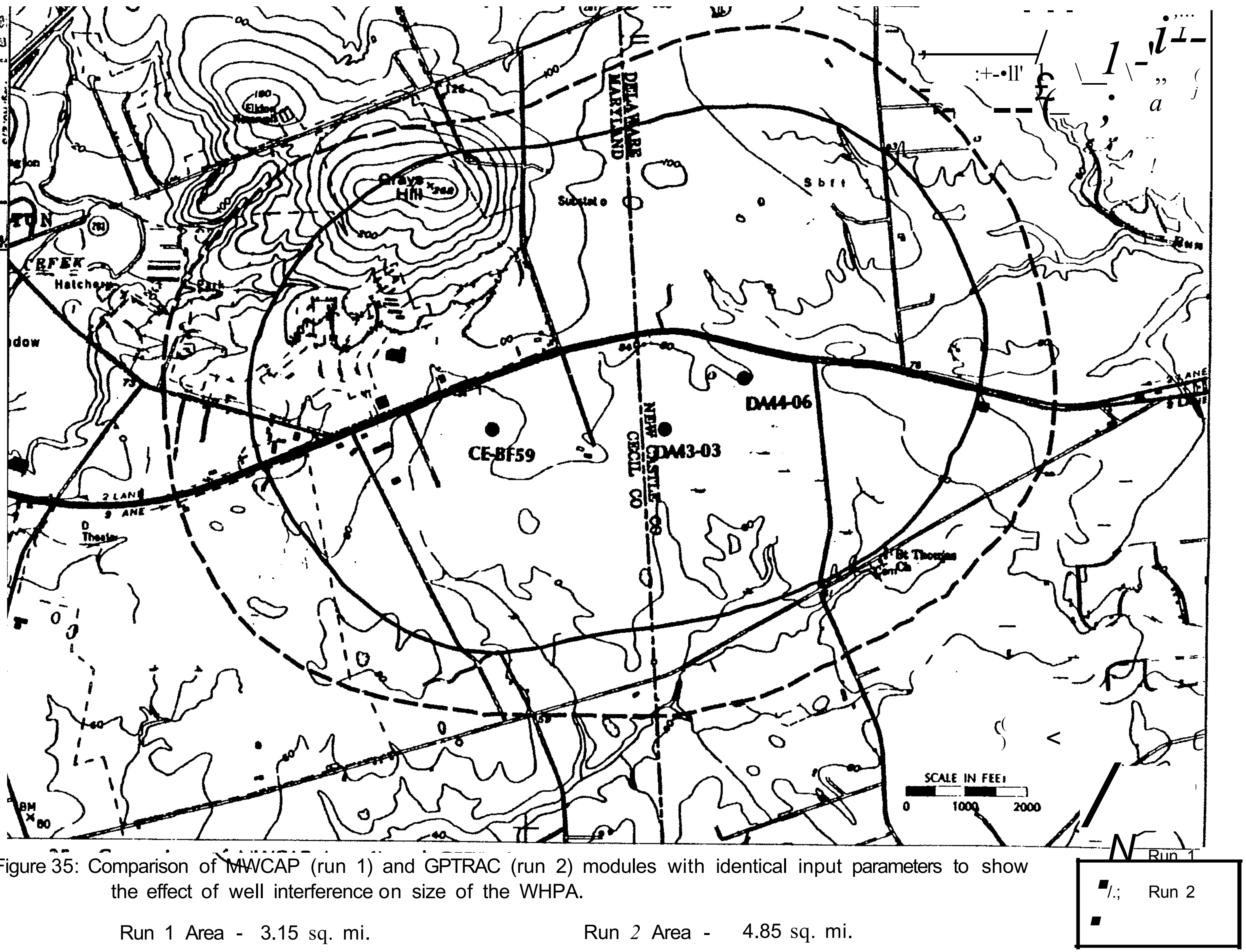

Figure 35: Comparison of MWCAP (run 1) and GPTRAC (run 2) modules with identical input parameters to show the effect of well interference on size of the WHPA.

Run 1 Area - 3.15 sq. mi. Run 2 Area - 4.85 sq. mi.

Table 18. Capabilities of the MW'CAP and GPTRAC modules in relation to the Eastern States wellfield.

	MODELING CONCERN	GPTRAC CAPABILITIES	MWCAP CAPABILITIES
1.	Well Interference	Accounts for interference	Ignores interference
2.	Highly variable hydraulic characteristics of aquifer	Requires average hydraulic inputs	Can input discrete values for each well
3.	Curvi-linear bedrock boundary forms barrier to flow to north/north west of wellfield	Treats as linear E/W boundary at top of study. study area	Treats as a series of linear boundaries to approximate a curve
4.	Part of wellfield is confined while other parts are probably semi-confined or unconfined	Can input recharge	No recharge

Unlike MWCAP, the GPTRAC module does not allow input of individual hydraulic parameters for each well; an overall aquifer average must be used. Because of the variability in hydraulic characteristics in the Potomac Formation, this was a major concern. This concern was evaluated by running MWCAP with discrete (run 3) and average (run 4) inputs for ransmissivity and thickness, holding all other input parameters constant (Table 19). The outlined capture zones show little difference between the runs (3.16. mi^2 vs 3.11 mi^2), indicating that little error is introduced by using average values in the GPTRAC module when the ranges in transmissivity and thickness are not very large (Figure 36).

John H. Talley, P.G.

Mary Ann Levan

Grays Hill northwest of the wellfield is composed of crystalline rock. Sediments of the Potomac Formation lap onto Grays Hill where they thin and form a featheredge. The Potomac is generally not present above the 140 ft contour. The crystalline rocks form a barrier boundary. Accordingly, it was appropriate to use a module that could account for such a boundaries. To compare module capabilities and results, the GPTRAC module was run without a boundary (run 2) and with a boundary (run 5). The results were then compared to a run made utilizing MWCAP with a boundary (run 6).

Table 19. Input parameters for module evaluations for the Eastern States wellfield. All runs were made with a 10-year time of travel.

COMPARISON	WELL INTERFERENCE		AVERAGING HYDRAULIC INPUTS		BOUNDARY DEFINITION		RECHARGE
RUN#		2	3	4	5	6	.7
MODULE	MWCAP	GPTAAC	**MWCAP**	MWCAP	GPTRAC	MWCAP	GPTRAC
AQUIFER TYPE	Confined	Confined	Confined	Confined	Confined	Confined	Confined
WELL ID	T,b	T,b	T,b	T,b	T,b	T,b	T,b
Bf-59	2311,32	2311,32	3900, 31	2311,32	2311,32	3900, 31	2311,32
Da43-03	2311,32	2311,32	**1588,** 28	2311,32	2311,32	1588,28	2311,32
Da44-06	2311,32	2311,32	1445,36	2311,32	2311,32	1445,36	2311,32
BOUNDARIES							
BOUNDARY TYPE	---	---	---	---	Barrier	Well ID Distance Orient.	---
ORIENTATION		---	---	---	E/W	Bf-59 2916 288	---
PERPENDICULAR DISTANCE		---	---	---	"top"	Da43-03 4019 310	---
						Da44-06 4492 327	---
RECHARGE							
#RECHARGE WELLS		---	---	---	---	---	19
RECHARGE		---	---	---	---	---	6745/well
CONFINING LAYER K	---	---	---	---	---	---	---
RATE	---	---	---	---	---	---	---

CONFINING LAYER b

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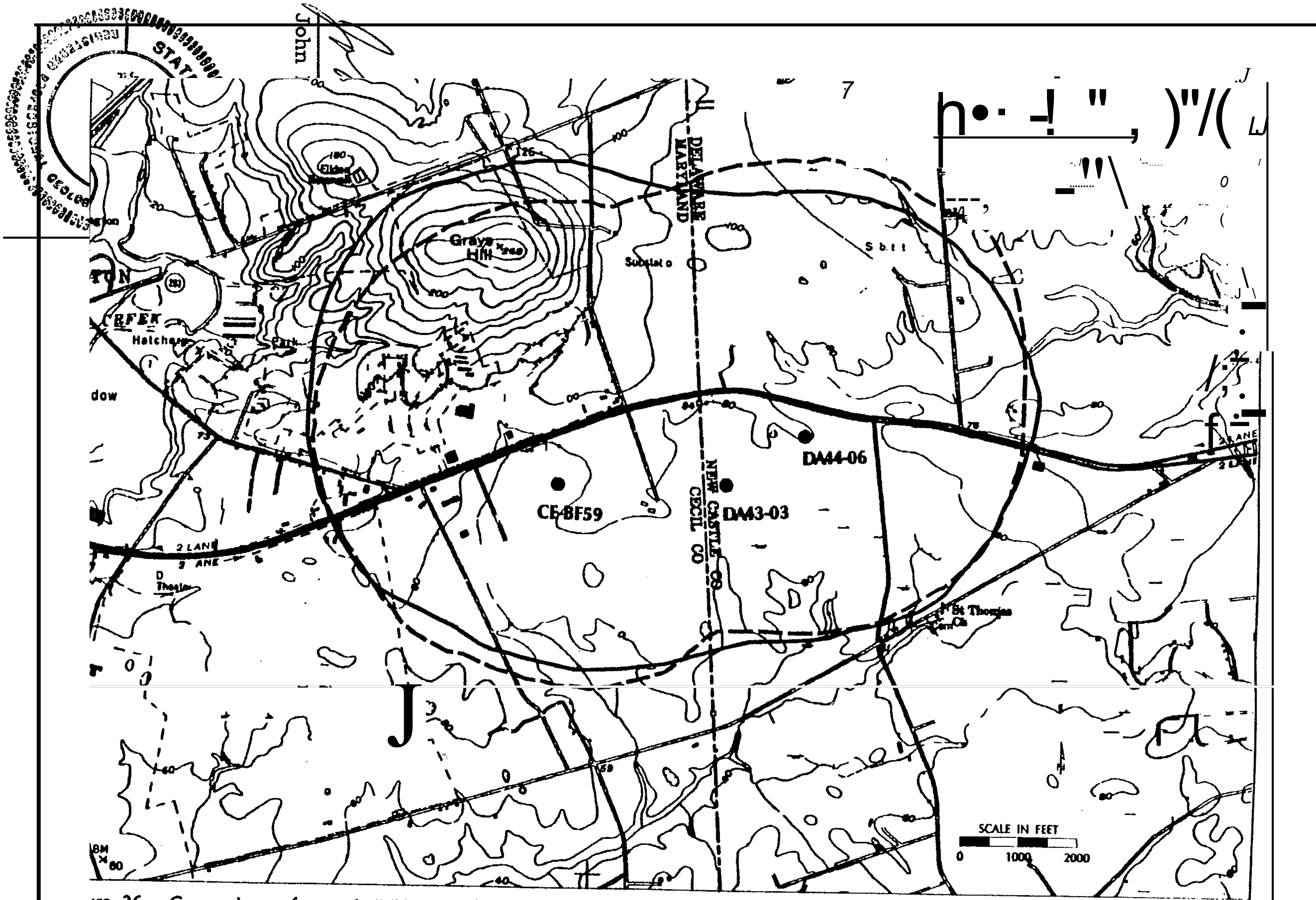

Figure 36: Comparison of runs 3 (MWCAP, discrete hydraulic parameters input for each well) and 4 (MWCAP, average hydraulic parameters input for each well).
In this case using average inputs caused an Insignificant change In the size and shape of the WHPA.

Run 3 Area - 3.16 sq. mi.   Run 4 Area - 3.11 sq. mi.

Run 3
Run 4

With GPTRAC, a boundary can be defined on any straight line edge of the study area. The effect of inputting a straight line boundary *at* the 140 foot contour was *to* eliminate from the wellhead protection area a portion of the area to the north of U. S. Route 40 where the confining bed becomes leaky and the sediments are more conducive *to* recharge (Figure 37). By contrast, the distance and direction measurements input for each well with the MWCAP module resulted in a series of linear boundaries associated with each well, which better approximates the curvilinear boundary (Figures 32 and 38) and allows the protection area *to* extend northward to the east of Grays Hill, an area underlain by sedimentary rock. The MWCAP module is more applicable because it can more realistically reflect actual boundary conditions.

It should be emphasized that all runs discussed so far have not accounted for any recharge to the aquifer over the course of the 10-year simulation; thus, the protection areas defined are relatively large.

The area in which we feel most recharge occurs is located north of U. S. Route 40 and east of Grays Hill and is within the area of influence of the wells as determined from previous module runs. For the purposes of this simulation, the WHPA area defined by run 6 of MWCAP was used to estimate the extent of the recharge area north of U. S. Route 40. Using a recharge value of 581,000 gpd/mi^2 (77,674 ft^3/day-mi^2) (Maryland Water Resources Administration, 1989) over this 1.65 mi^2 area resulted in a calculated recharge of 958,650 gpd (128,162 ft^3/day). Nineteen recharge wells were spaced uniformly throughout the defined area and the recharge distributed as 6,745 ft^3/day per well. Input of recharge through uniformly spaced recharge wells resulted in a reduction in the the size of the protection area from 4.85 mi^2 to 3.5 mi^2 (Figure 39), and seemed to present a reasonable approach to account for recharge. Since MWCAP does not have a semi-confined option or a recharge well option, GPTRAC is favored on this basis.

Module preferences based on comparison outcomes are summarized in Table 20. The GPTRAC module was strongly preferred on the bases of modeling well interference (Figure 35) and recharge (Figure 39). Input of average hydraulic characteristics required by the GPTRAC module appeared reasonable in this particular wellfield (Figure 36). However, based upon boundary definition, the MWCAP module was strongly preferred (Figure 38).

John H. Talley, P.G. **Mary Ann Levan**

Discussion

The **wellhead** protection area delineations that were generated using MWCAP and GPTRAC (10-year time of travel) were modified to account for limitations associated with each module. Three delineated areas are presented on Figure 40. The GPTRAC delineated area is from run 7: well interference is accounted for, average hydraulic parameters are used, the aquifer is considered confined with a grid of recharge wells, and there is no boundary. The MWCAP delineated area is from run 6: no well interference, discrete hydraulic parameters, confined aquifer with no recharge, and discharge boundaries. The combined discharge boundary follows the MWCAP defined boundary along the south side of Grays Hill then picks up the GPTRAC outline

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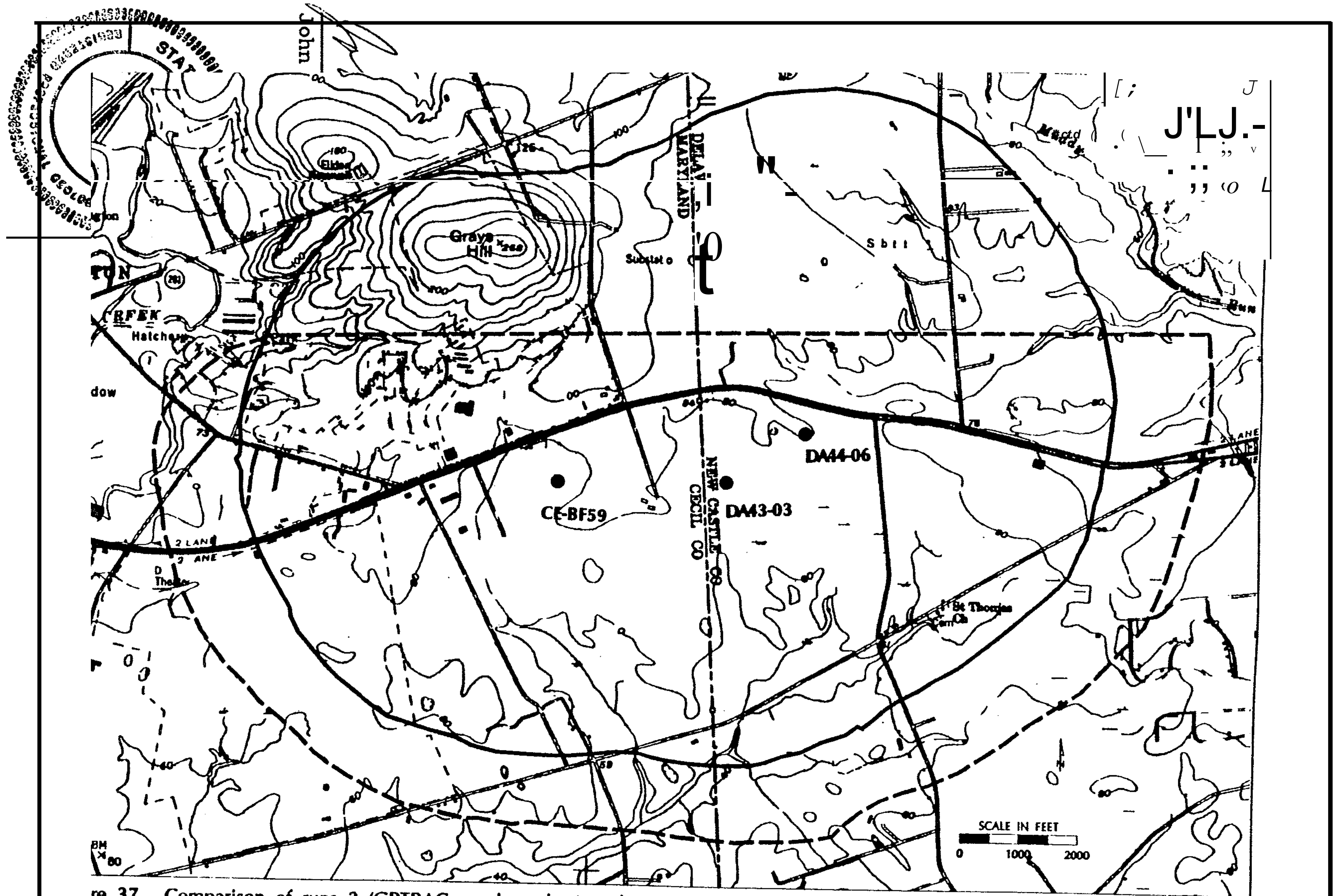

Figure 37. Comparison of runs 2 (GPTRAC, no boundary) and 5 (GPTRAC, with boundary) shows the straight line E/W boundary available with the GPTRAC module.

Run 2 Area - 4.85 sq. mi.

Run 5 Area - 4.8 sq. mi.

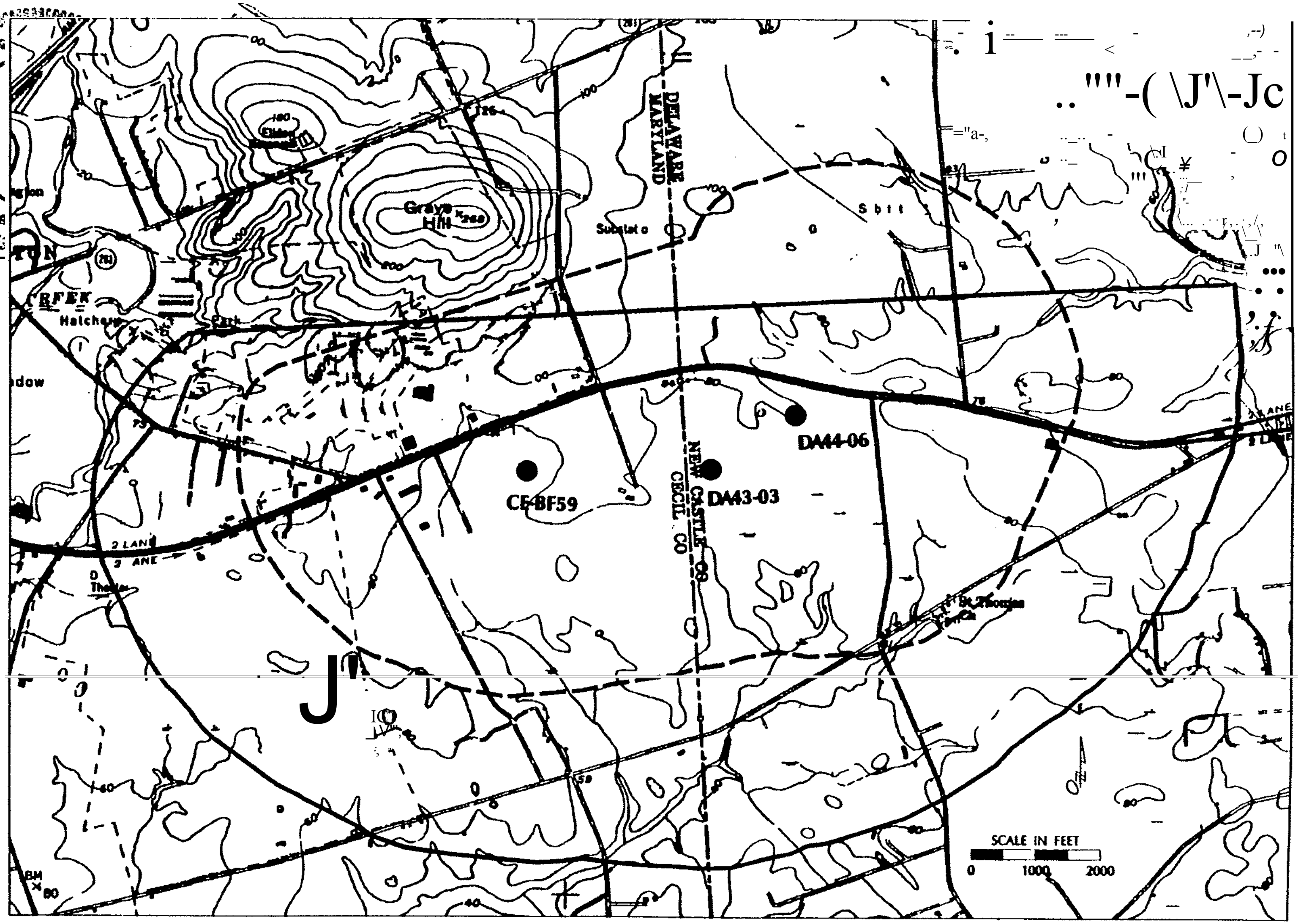

Figure 38. Comparison of runs 5 (GPTRAC, no boundary) and 6 (MWCAP, with boundary)_
The series of straight line boundaries used by the MWCAP module gives a better approximation of the actual boundary than does the straight line E/W boundary of GPTRAC.
Run 5 Area - 4.8 sq. mi. Run 6 Area - 2.85 sq. mi.

/./ Run S
/.j Run 6

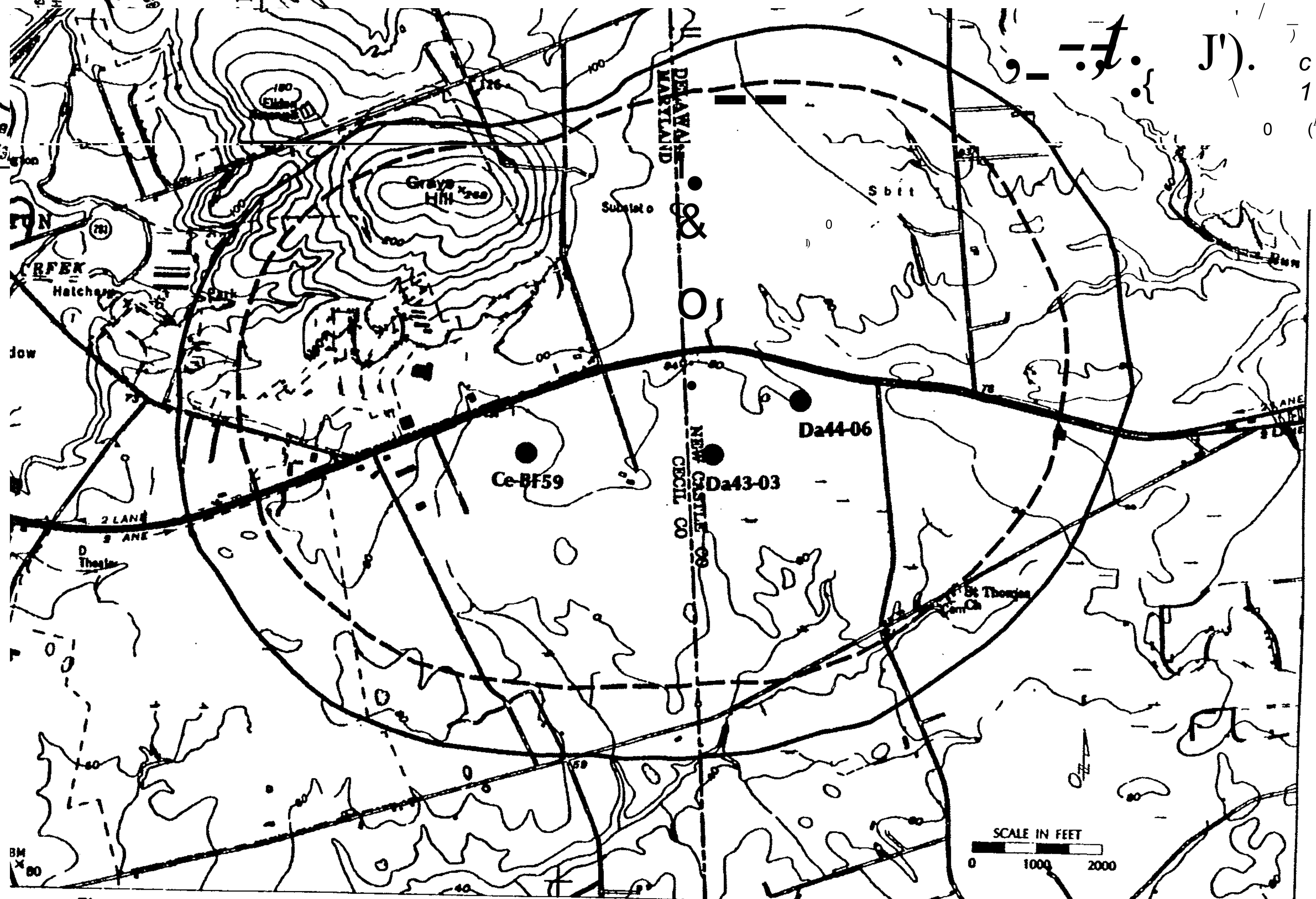

Figure 39: Comparison of runs 2 (GPTRAC, no [illegible]
and 7 (GPTRAC, no boundary, confined with recharge via recharge wells).
This method was effective at simulating recharge to the area south of Route 40.

Run 2 Area - 4.85 sq. mi. Run 7 Area - 3.5 sq. mi.

N
Run 2
Run 7

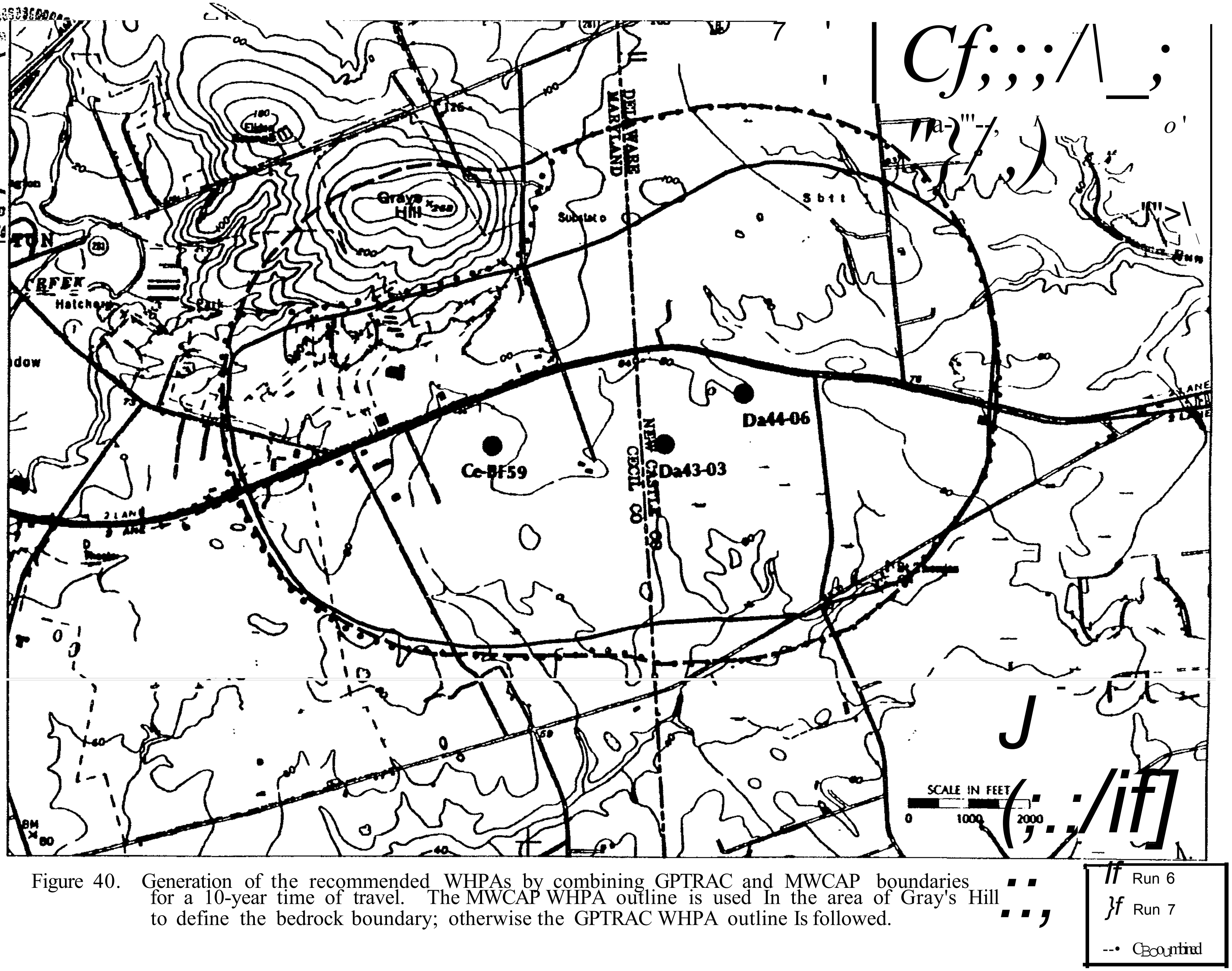

Figure 40. Generation of the recommended WHPAs by combining GPTRAC and MWCAP boundaries for a 10-year time of travel. The MWCAP WHPA outline is used In the area of Gray's Hill to define the bedrock boundary; otherwise the GPTRAC WHPA outline Is followed.

Table 20. Module recommendation based on comparison of module runs.

COMPARISON/FACTOR	IMPORTANCE	PREFERRED MODULE
1. Well Interference	Significant	GPTRAC
2. Discrete Inputs Hydraulic	Insignificant	GPTRAC or MWCAP
3. Boundary Definition	Significant	MWCAP
4. Recharge	Significant	GPTRAC

to the northeast. This 10-year combined wellhead protection area is shown in Figure 41 along with a 5-year protection area that was generated using the same approach. That portion of the wellhead protection area located north of U.S. Route 40 (Figure 41) is very similar in shape and size to that area determined to be a prime recharge area for the three production wells by the Maryland Water Resources Administration (1989, figure 3-12, page 69).

With this combined boundary, the 10-year wellhead protection area encompasses 3.16 mi^2 while the 5-year area encompasses 2.01 mi^2 in both Delaware and Maryland. The Delaware portion of the 10-year area encompasses 1.63 mi^2 while the 5-year area encompasses 0.99 mi^2.

Application of the EPA modules appear to have been useful in delineating the wellhead protection area at the Eastern States wellfield. It must be emphasized, however, that in a complex hydrogeologic environment such as exists at Eastern States, the modules should be used in conjunction with an understanding of the hydrogeologic framework, and review and application of all hydrologic data, both general and site specific, that are available.

As discussed in the section "Recharge Inputs," geologic conditions do not appear to be very conducive for rapid **recharge** to the lower Potomac aquifer system south of U. S. Route 40. In addition, water-level data were not available south of wells Da44-03 and Da44-06. Therefore, the potential effects that pumping may have on water levels in the water-table aquifer could not be evaluated. Because of the importance of this wellfield for water supplies in a developing area along U. S. Route 40 and lack of adequate geologic and hydrologic control in the southern portion of the wellfield, the areas within the 5- and 10-year time of travel **were** included in the recommended wellhead protection area as shown on Figure 41.

John H. Talley, P.G.

Mary Ann Levan

STATE OF DELAWARE
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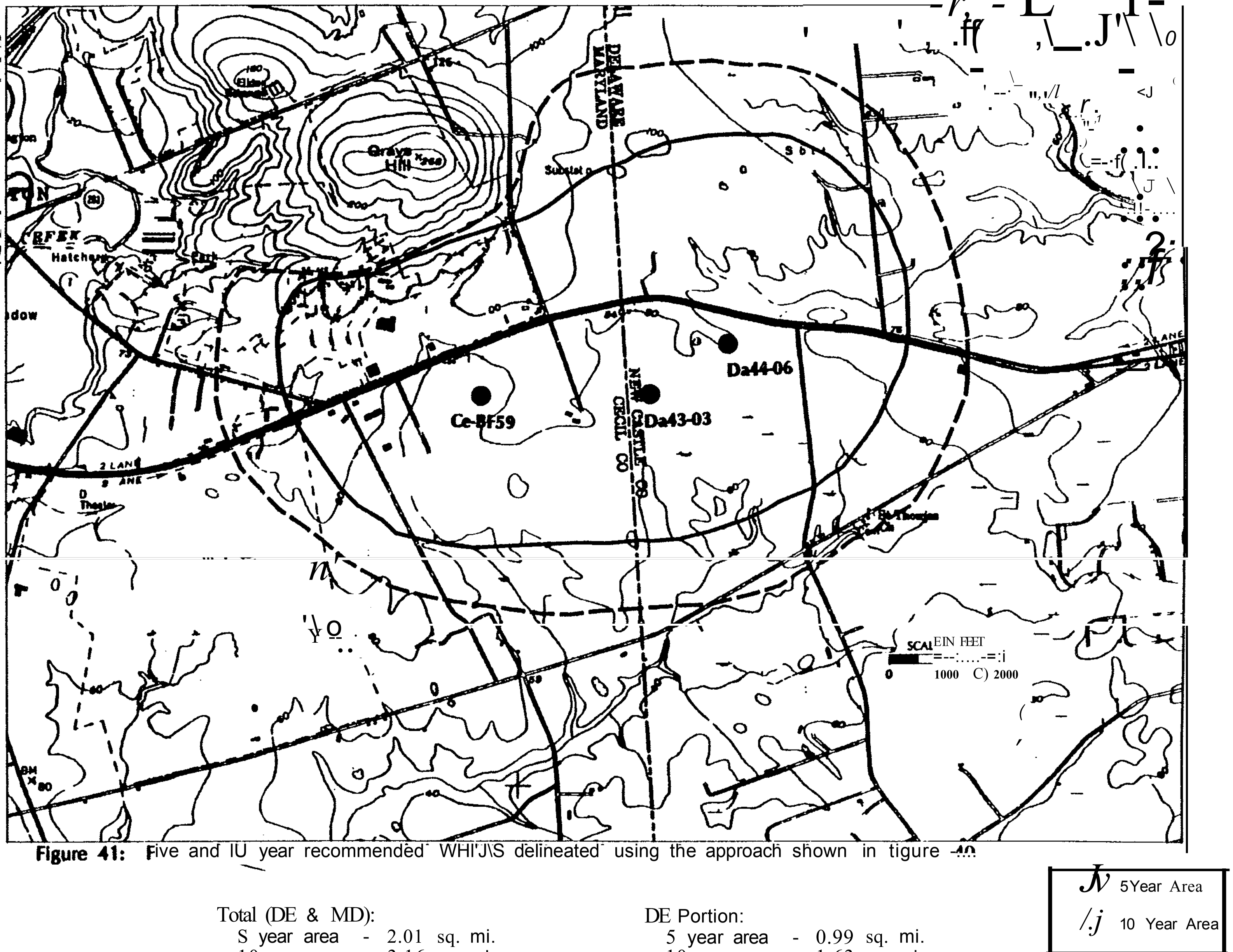

Figure 41: Five and 10 year recommended WHPAS delineated using the approach shown in figure 40

Total (DE & MD):
5 year area - 2.01 sq. mi.
10 year area - 3.16 sq. mi.

DE Portion:
5 year area - 0.99 sq. mi.
10 year area - 1.63 sq. mi.

SUMMARY AND CONCLUSIONS

The established EPA criteria and methods for delineating wellhead protection areas were reviewed for application to two wellfields in the Atlantic Coastal Plain province of New Castle County, Delaware. Time of travel was selected as the appropriate criterion to be used in support of wellhead delineation. This criterion is consistent with that being used in Delaware's WHPA program and is used in application of computer programs developed by the USEPA to support wellhead protection area delineation. Analytical methods and hydrogeologic mapping were used in conjunction with the USEPA modules MWCAP, GPTRAC, and MONTEC in this study.

Considerable effort was expended in researching and calculating numerical inputs for the models and evaluating the appropriateness of each EPA module for wellhead delineation at each wellfield. Information such as type of aquifer, aquifer thickness, transmissivity, storativity, porosity, hydraulic conductivity, hydraulic gradients, pumping history, details of well construction, etc. were obtained from existing data in the form of published and unpublished reports and maps, and data on file at the DGS, and from the Department of Natural Reources and Environmental Control, New Castle County Department of Planning, Water Resources Agency for New Castle County, Artesian Water Company, and the Maryland Water Resources Administration. A few aquifer test analyses were performed on data from aquifer tests performed at the Eastern States wellfield and tritium analyses were performed on samples from wells in the Glendale and Eastern States wellfields.

Both wellfields are located in complex geologic and hydrologic settings that do not allow for simple analysis. At Glendale, wells are developed in the water table aquifer which consists of sediments that range in thickness from about 30 to 70 ft and in underlying leaky aquifers in the Potomac Formation. Some of the sands comprising the water table aquifer may be part of the Potomac Formation. The wellfield has a complex pumping history, with eight wells operative at various times since development in 1959, and only four currently in operation. Well interfer nce has been documented.

The Glendale wellfield was modeled using the four active pumping wells, one in the Columbia and three in the Potomac Formation. The GPTRAC module, which accounts for well interference and allows for recharge, was run for the three Potomac wells and overlaid with a separate run for the Columbia well. Three travel times were selected, 5 and 10 years, and a "long run" time of 31 years (Columbia) and 16 years (Potomac) to simulate the time of operation of the presently operating wells in the wellfield. Based on review of available information, an intermediate value of k' (0.1 ft/day) was used in developing the recommended wellhead protection areas.

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STATE OF DELAWARE
JOHN H. TALLEY
Reg. No. 273
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Wells in the Eastern States wellfield are completed in aquifers in the Potomac Formation. The Potomac Formation is very complex in that it consists of interbedded clays, sands, and silts that are laterally and vertically discontinuous and therefore, difficult to trace over relatively short distances. The Potomac laps onto crystalline rocks underlying Grays Hill to the northwest that form a barrier boundary. Analysis of the hydrogeologic environment by the Maryland Water Resources Administration (1989) indicates that the Potomac confining beds north of U. S. Route 40 are leaky and the sediments are more conducive to recharge than to the south of U. S. Route 40 where they appear to be relatively tight. Declining water levels in some areas north of U. S. Route 40 have been attributed to pumpage in the Eastern States wellfield (Maryland- Water Resources Administration, 1989). The three public water supply wells are sufficiently close and productive that there is significant interference.

The Eastern States wellfield was modeled using three wells. Because of the number of variables that had to be addressed (highly variable hydraulic characteristics, well interference, variable recharge, and barrier boundaries), none of the available EPA modules was able to handle all of the variables. Seven separate module runs were made using GPTRAC and MWCAP to evaluate the variables. GPTRAC was preferred when the effects of well interference and recharge were taken into account. However, for boundary definition, MWCAP was preferred. The wellhead protection areas delineated at Eastern States were derived by incorporating the results of module runs using both GPTRAC and MWCAP with an understanding of the hydrogeologic framework.

Based on the results of this investigation, it appears that the "Modular Semi-Analytical Model for the Delineation of Wellhead Protection Areas, Version 2.0" (EPA, 1991) can be used in support of wellhead protection area delineation in portions of New Castle County, Delaware. However, because of the complex geologic and hydrologic environment, the degree of success or confidence in delineating areas and the integrity of the results also requires the application of principles of geology and hydrology, an understanding of the hydrogeologic systems, incorporation of as much available information as possible, and an appreciation for and understanding of the limitations of the modules.

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STATE OF DELAWARE
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