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ABSTRACT

Spatial competition is a phenomenon which exists in numerous situations throughout nature. Examples of *objects* in competition for space can be cited for biological, economic, social, and environmental processes. In many of these processes, the competition is for resources distributed in space, rather than simply the space itself. When two or more objects compete for the same space, it is possible to model the process such that we may objectively define the resulting space occupied by the objects. In this paper, I develop a model for the competitive process in order to define the region of space occupied. The model is incorporated into a methodology which utilizes a coordinate transformation function to determine the space the objects occupy. An application of the methodology to groundwater protection is included in which water wells are the objects and groundwater is the resource being competed for. The study was conducted using a geographic information system to transform spatial coordinates and generate figures defining the occupied space. 101 pp.

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THE FLORIDA STATE UNIVERSITY

COLLEGE OF SOCIAL SCIENCES

A COORDINATE TRANSFORMATION MODEL FOR OVERLAP DISTRIBUTION: AN APPLICATION TO GROUNDWATER PROTECTION

by

TODD GERALD ROBINSON

A Thesis submitted to the
Department of Geography
in partial fulfillment of the
requirements for the degree of
Master of Science

Approved:

Professor Directing Thesis

Summer Semester, 1988

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CHAPTER ONE

INTRODUCTION

Water is viewed by most people as one of nature's most valuable resources. Without it life cannot be sustained. Supplies of water are often mistakenly perceived as virtually unlimited, especially in relation to one's personal needs. It is crucial to note that the availability of an adequate water supply is dependent on the resource's distribution through space and time. Even when available, it can be made unusable if polluted.

Surface water and ground water are the major sources of public water supply in the United States. Both sources are susceptible to pollution. Surface supplies are readily contaminated due to their unconfined nature (lack of barriers between the supply and the environment). Ground water, because of its confined character, is polluted through more subtle processes. Contaminated supply wells must be condemned if the resource is determined unusable. The polluted groundwater can even contaminate surface water bodies fed by the associated aquifer (groundwater reservoir). Due to the relatively slow movement of ground water, aquifer contamination may not be detected until years after a pollutant release.

Groundwater Protection

Taylor (1977) suggests that source protection is the "first line of defense" in assuring drinking water quality. The intent of protective measures is to reduce or eliminate human activities which utilize substances that pose a potential contamination threat to the water source. Criteria for defining such substances are as follows (van Wageningh and van Duijvenbooden, 1979):

dangerous substances are substances that

- are harmful to health
- impair taste, aroma, or color of water
- lead to lack of subsoil aeration
- increase the corrosiveness or hardness of the water
- affect the water temperature

Water pollution can be classified by contaminant type, biological or chemical. The primary aim of the water supply industry has been to ensure that the consumer is provided with water which is free from pathogenic microorganisms. Yet, the single most prominent cause of waterborne disease in the U.S. is the presence of pathogens due to inadequate disinfecting procedures (Toft, 1985). In spite of these incidences of bacteriological contamination, the major public concern with drinking water has been possible contribution to cancer risks due to chemical pollutants.

To date, over 8,000 wells have been closed or substantially affected by toxic contaminants (Bachman, 1986) with more than 200 chemical substances detected in the groundwater (Office of Technology Assessment, 1985). This number is expected to increase dramatically. The expected increase is due to potential exposure of ground water to the more than 60,000 known chemicals involved in manufacturing (Shackelford and Cline, 1986). Of this huge number of potential chemical contaminants, only 250 are regulated under the Resource Conservation and Recovery Act, and even these few have no proven methods or standards for quality assurance or quality control (Dowd, 1985).

A more reasonable and flexible approach to protection measures is to list those activities which risk release of dangerous substances. Groundwater contamination processes can be divided into two categories based on the activity which resulted in the pollution. Those activities which can be located precisely are known as point source contamination. Surface impoundments, landfills, spills, and leaks are examples of point polluting activities. Diffuse activities, such as agricultural pesticide and fertilizer application, and residential septic tank seepage spread contaminants over large areas. These activities are known as nonpoint pollution sources. Both catagories of contaminating activities are equally hazardous to

groundwater supplies, but the latter is much more difficult to isolate and identify.

Florida's Groundwater Problems

The State of Florida, which has more ground water than any other state (McGuinness, 1963), supplies 88 percent of the public water consuming households from groundwater sources (Heath and Conover, 1981). Although the aquifers containing Florida's groundwater supply extend to relatively great depths, the shallow zones tapped for public supply are vulnerable to contamination. The overlying materials don't impede the movement of surface contaminants into the groundwater supply. Considering these factors and the state's intense growth and development trends, one can easily see the critical importance of protecting the quality of Florida's groundwater resources. The increasing demands on a vulnerable groundwater supply necessitate regulatory measures to assure the public an adequate quantity of potable water.

Recognizing the importance of regulatory protection for the state's groundwater resources, the Florida Department of Environmental Regulation (FDER) developed specifications for delineating "protection zones" around vulnerable public supply wells (Vecchioli et al., 1987). Within these protection zones, certain activities which entail contamination risks to the ground water are prohibited or restricted by Florida statutes. As a

consequence of the legislation, the state is required to map the protection zones around existing public supply wells. The FDER solicited the assistance of the U.S. Geological Survey Water Resources Division to define and map the zones.

Protection Zone Definition

Fried and Zampetti (1979, p.292) defined a groundwater protection zone as "a geographically circumscribed area where certain activities are banned, controlled, or subject to authorization, and the use and ownership of which are subject to certain obligations in order to safeguard the underground waters against the risk of pollution." These zones are restrictive areas situated about supply wells (Figure 1) with the intent of limiting surface land use activities to preserve the quality of the underlying water reserves contained in the aquifer. The protection of an aquifer is a popular notion, but it is a much more complex problem than is initially apparent. Difficulties arise when an attempt is made to precisely define what surface area affects the groundwater supply. The major problem is a lack of scientific understanding of the movement of water and the attenuation of contaminants in the ground. Site specific studies to determine the geohydrologic characteristics of an area are few in number. Research of this nature is expensive and frequently beyond the means of local agencies. This leads to a general problem often confronted when one wishes to impose environmental safeguards: the

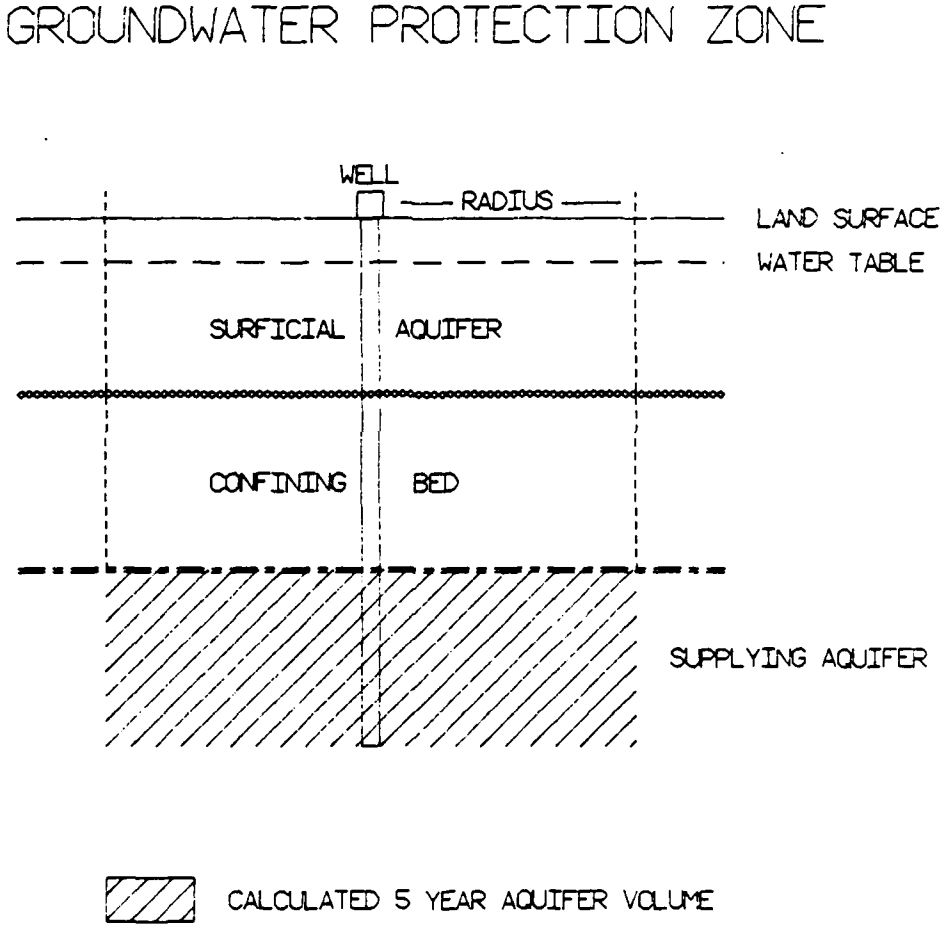

Figure 1: Cross-Section Of A Groundwater Protection Zone

cause-and-effect relationship may not be easily defined. In the case of ground water, this is especially true since the water, soil, and pollutant are all hidden from view. Therefore, as Goldrosen (1977, p.57) has stated, standards and rules for groundwater protection are "still a matter of guesswork."

When attempting to regulate activities near a withdrawal point, the uncertainties associated with the groundwater pollution process tend to complicate matters. Initially, one might assume that the protective measures should cover the entire catchment area. This seems reasonable since a polluting activity located within an aquifer intake area could potentially contaminate any well drawing from that aquifer. However, these aquifers can cover vast areas. Protective measures require that limitations be placed on land use, resulting in reductions in land value. The individual landowners whose property values may be diminished will certainly be reluctant to support such legislation. Despite the fact that the principle of protecting the entire intake area is theoretically correct, deviations from it are necessary for practicality. The protection zones need to be as large as required for health and safety purposes, but as small as possible for socio-economic reasons. Only when a fair compromise is reached between these two contradictory factors can protective legislation be enacted.

CHAPTER TWO

PROBLEM STATEMENT

Groundwater protection zone delineation is a problem which can easily be recognized at the practical level. To get a greater understanding of the problem, one must consider it at the conceptual level as well. Additional insight and scientific utility are derived from a fundamental theoretical approach. For this reason, this investigation addresses both the conceptual and the applied aspects of this spatial delineation problem.

Description of the problem in an abstract manner is somewhat awkward and undoubtedly confusing without mention of its practical application. The perception of the spatial concepts involved becomes more concrete when one first understands the circumstances which initially pose the problem. The protection zone delineation problem is described first. This should facilitate greater comprehension of the description and implications of the fundamental theoretical concepts.

Practical Problem

FDER rule docket number 85-23R specifies the requirements for delineation of protection zones in the State of Florida (Vecchioli et al., 1987). The size of the zone for an individual well is calculated using a radial

plug-flow displacement model based on a five-year permitted-rate withdrawal. The FDER formula used to determine the zone size is:

$$r = [\ Q*t/\pi*h*n\ ]_{0.5}$$

where

r = radius of the individual protection zone

t = time, 5 years or 1825 days

n = effective porosity of the associated aquifer

π = 3.14

Q = permitted withdrawal rate (ft^3/day) ,and

h = thickness of the aquifer interval penetrated (ft)

The result of the calculation is the radius of a circle. When circumscribed about the supply well, this circle defines the zone of protection for that well.

In some instances, the protection zones of neighboring wells overlap. This is very evident in areas where a number of wells are concentrated in space, known as wellfields. The formula for determining the size of the protection zones is based on a volumetric displacement concept. The volume of the water to be protected is proportional to the area of the protection zone. Thus, a condition of overlapping zones results in underestimation of the area requiring protective measures. The amount of area by which the overlapping zones are deficient for groundwater protection is equivalent to the area of overlap.

The FDER regulation stipulates that for wells whose zones overlap:

"...the area on the surface overlying the aquifer equal to the sum of the areas of the five year zones of protection of the individual wells, shall be used to define the area which encircles the perimeter of the wellfield. In cases where a zone of protection of a single well protrudes beyond the calculated perimeter or when the configuration of the wellfield is irregular, the perimeter will be shaped to accommodate the configuration. The surface area encircling the perimeter of the wellfield shall not exceed the total surface areas of the overlapping zones of protection for individual wells" (Vecchioli et al., 1987, p.60).

The U.S. Geological Survey procedure for delineating the zones for the overlap condition requires extending the area defined by the union of the overlapping individual protection zones (Figure 2) to an enlarged area which approximates the shape of the well configuration. Through successive approximations the area is expanded until it is within five percent of the summed areas of the individual zones. If upon expansion of the overlapping zones, the boundary of the enlarged area contacts a previously non-overlapping protection zone, the contacted zone is added to the union and the total areal requirement recomputed. Successive expansions produce a figure of correct area whose shape is representative of the well configuration (Figure 3). This expanded region is delineated on its respective quadrangle sheet. The resultant area mapped is designated a composite protection zone.

As is evident from the above description, the U.S. Geological Survey's manual cartographic procedure for

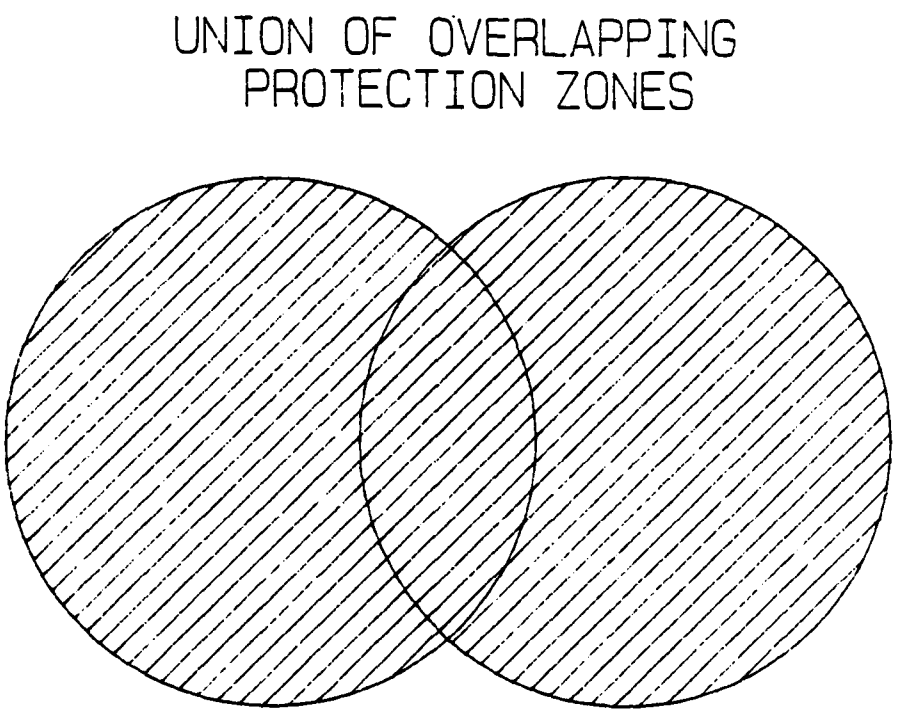

Figure 2: Union Of Overlapping Protection Zones

EXPANDED CONFIGURATION FOR
COMPOSITE PROTECTION ZONE

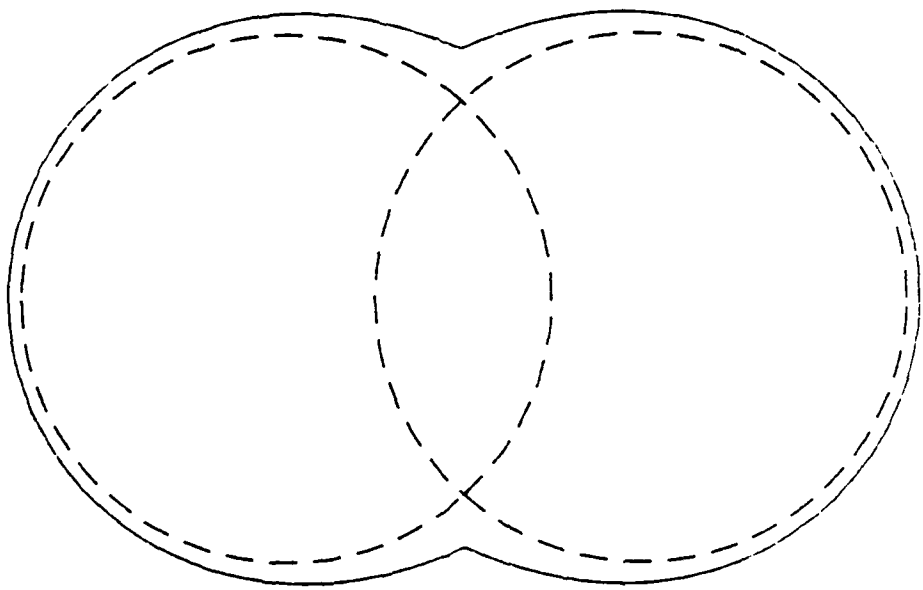

Figure 3: Expanded Figure For Composite Protection Zone

defining composite protection zones is subjective. The process relies on an individual's judgement to delineate a region shaped like the well field configuration. Different analysts could arrive at dissimilar composite protection zones. Since the purpose of protection zone mapping is to define land area upon which land use restrictions will be applied, this subjectivity poses problems to the legal aspects of enforcement. Owners of use-restricted land could certainly challenge the "arbitrary" method by which the areas were defined.

Conceptual Aspects

At the conceptual level, the problem equates to the modeling of a spatial delineation process. This, like most other spatial processes, is characterized using a general model framework employing points, lines, and/or areas. Patterns of these three feature types can be generated by the model according to various rules. These rules represent assumptions inherent to the spatial process and thus define the spatial process model.

The patterns of concern here are area patterns resulting from the spread of influence away from a set of initial point sources. This type of spatial process model is commonly termed a *growing space model*. The growing space model employs two basic concepts of importance, *competition* and *space*.

Cormack (1979, p.152) defines competition as "any process-physical inhibition, direct interference, or overlapping of niches-which has a negative influence on an individual's location, viability, or strength." He further describes space as "the two-dimensional physical area required by an organism for development." The natural representation of space occupied by an organism is assumed to be a circle centered on the organism. If the environment is uniform, the space occupied can also represent the resources available.

Obviously, the terms used by Cormack are indicative of biological processes, but the concepts involved are evidently appropriate to the present modeling problem. Competition for space/resources can result in two distinct interactions. First, the "growing" circles continue to grow after contact with neighboring circles. Thus, overlap occurs. The amount of overlap reflects the competition pressure imposed by one organism on another. Alternatively, the growing circles are not allowed to overlap, but distorted into polygons which represent the space available to the organism for development.

Getis and Boots (1978) describe the growth model in more general terms and refer to spatial processes of this type as *area generating point processes*. Those processes which prohibit overlap generate patterns denoted as *contiguous*. This type of process leads to a pattern which

is space-exhaustive (Figure 4). The process type which permits overlap generates patterns designated as overlap patterns, and is not space-exhaustive.

The present study is concerned with a process which is a hybrid of the two types described previously. Initially, overlap is allowed as a means of identifying the amount of overlap present. After the size of the overlap area is determined, the alternate condition which prohibits overlap is imposed. An area equal to the overlap area then must be distributed about the overlap pattern generated. Modeling this allocation process is the primary focus of this study.

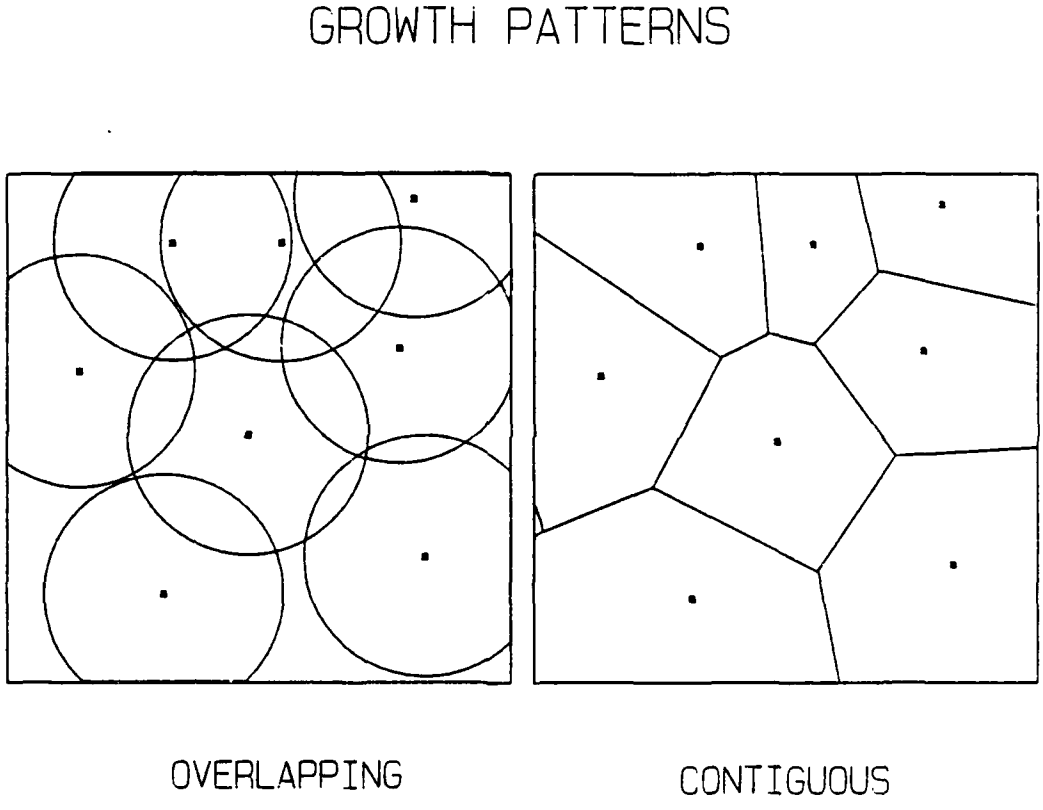

Figure 4: Growth Patterns

CHAPTER THREE

STUDY OBJECTIVES

The intent of this study is to develop a model for a process of spatial delineation based on the concepts of competition and space described earlier. From this model,a methodology is created for composite protection zone delineation which attempts to minimize scientific and cartographic subjectivity. As a means of satisfying this intent, the basic criteria defining the goals of the model must be stated. It seems most useful to outline the goals of the modeling process in the context of its application.

First, the model must meet the two requirements explicitly stated in the FDER rule. The composite protection zone must totally enclose all the circular zones of the individual wells. The area of the composite zone should be equal to the sum of the areas of the individual zones. Both requirements are met by the U.S. Geological Survey procedure, although the total area is to a lesser degree (5 percent tolerance level).

At the heart of the matter lies the objectivity of the process. The fundamental reason for the study is to develop a formal approach to the delineation problem. Such a procedure should yield a unique composite zone which can be reproduced during independent replication of the process.

Only when independent attempts result in identical protection zones, will the objectivity of the methodology be substantiated.

The underlying problem which introduces subjectivity into the manual procedure is that decisions concerning the extension of the protection zone boundaries are based on visual inspection of the overlapping well configuration. The key to solving this problem lies in the ability to define strict rules which dictate precisely how the overlap area of two individual protection zones is distributed when extending zone boundaries.

An attempt was made to quantify the decision process utilized during manual delineation. U.S. Geological Survey personnel were queried concerning cognitive guidelines which governed the distribution of the overlap while generating composite zones. Though difficult to define and more difficult to quantify, the discussion with USGS personnel resulted in one general conclusion: the overlapping zones were extended based on proximity to the center of the overlap area. The zone boundary was expanded more near the center of the overlap and to a lesser degree at more distant points. This is an inverse relationship between distance from overlap center and boundary extension. An inverse function based on distance from overlap center seemed to be the most plausible and reasonable approach to the problem, according to Geological Survey hydrologists. Central to

this study, the premise of an inverse distance relation is assumed to be accurate, based on U.S. Geological Survey expertise of groundwater movement.

The study results in a methodology developed from a model incorporating this inverse distance relationship. Testing requires the generation of composite protection zones in a format similar to those presented in the U.S.Geological Survey Report 88-4051 (Vecchioli et al., 1987). An analysis and evaluation is also conducted to establish the acceptability of the approach for application to groundwater protection as well as other spatial competition problems.

In summary, the objectives of this study are to develop and evaluate a methodology for generating composite protection zones based on a spatial distribution model. The proposed method is subject to the following constraints:

- the composite protection zone must totally enclose all individual protection zones of which it is comprised
- the area of the composite zone must equal the sum of the areas of the individual protection zones of which it is comprised
- the method must be formal and yield a unique composite protection zone of reproducible nature

- the central premise concerning overlap distribution (boundary extension) will incorporate an inverse relationship between distance from overlap center to boundary and boundary extension.

Utilizing a delineation methodology employing these constraints, objective composite protection zone delineation should be possible. In addition, the model may be applicable to similar space allocation problems.

CHAPTER FOUR

RELATED LITERATURE

A review of pertinent literature is included to address the present state of knowledge in collateral subject areas. The review includes references to groundwater protection as well as to relevant spatial modeling. Previous work which lends to the study effort are utilized to the greatest possible advantage toward problem solution.

Groundwater Issues

The increasing level of concern for the protection of ground water in the United States is apparent from the amount of legislation enacted to protect the resource. In addition to Florida, the states of Arizona, California, Colorado, Connecticut, Kansas, Massachusetts, New Jersey, New York, and Wisconsin have passed comprehensive groundwater protection statutes (Mosher, 1987). Still, the Florida program to protect zones around wells with land use controls is a unique approach.

The control of land use for groundwater protection is not without controversy. The lack of consistent, comprehensive data has made it difficult to establish direct relationships between human activities and groundwater contamination (Lee and Nielsen, 1987). The characteristics of groundwater movement are poorly understood by the public.

Frequently, the individual owning land with restrictions applied to its use will react negatively to such regulation. Libby and Kovan (1987) indicate that the lack of general awareness about connections between human activities and groundwater quality are responsible for such attitudes.

Land use controls are an essential means of groundwater protection, since discharges from nonpoint sources are not amenable to technological controls (Pye et al., 1983). Therefore, these sources of contamination must be controlled locally. The primary need in local land use planning is the definition of areas of influence for operating wells (Libby and Kovan, 1987). Once the areas are identified, land use patterns in a community can be guided in ways which enhance groundwater protection.

Land use controls are a means of segregating contaminative activities from the water supply. Pollution sources should be as remote as possible from the groundwater reservoir and, hence, withdrawal and catchment areas. This gives rise to protective areas or "zones" enclosing abstraction points and catchment areas.

Several zones are usually established (Fried and Zampetti, 1979). An inner zone of a relatively small area around the well is defined. In this inner zone all activities with contamination potential are banned. Normally the water authority is required to own land within this zone. An intermediate zone is specified which is

designed to protect against bacteriological contamination. Within this area, activities which might introduce biological toxins to the groundwater, such as cattle grazing or septic leaching, are prohibited. An outer zone is designated to cover the entire catchment area. Within this outer zone potential chemical polluters are banned. Controlling this larger area allows additional time for intervention, dilution, and breakdown of chemical contaminants.

The primary method for determining the size of protection zones is one based on delay times. Delay time refers to the time it takes a water droplet located at a given distance from a well to travel to the same well under forces of water withdrawal. Calculating zone size utilizing delay time, one can take into account the geohydrology of the subsoil, and size, form, and capacity of the well (van Wageningh and van Duijvenbooden, 1979).

Langeweg (1979) discusses a three-zone system used as a guideline in the Federal Republic of Germany. It consists of zones numbered I,II, and III, varying in size from 10 meters, 50-60 days delay time, and the entire intake area, respectively. The Netherlands also uses a three-protection-zone system for groundwater wells (van Dijk-Looijaard and de Kruijf, 1985). An inner 60-day zone is required to prevent bacteriological/chemical contamination and bans all activity within its boundary. A

10-year intermediate zone is specified whose delay time chosen to be adequate to control pollution after an accident or if necessary, replace the well. The outermost zone of 25-year delay time is based on the time required to replace a well and treatment plant without financial backlash (adequate write-off period). The restrictiveness of the Dutch regulation decreases from inner to outer zones, with the 10 and 25-year zones addressing potential chemical polluting activities only.

In the United States, legislation concerning groundwater protection zones has been much less ambitious. Many state regulations require only that water supply wells be located 100 feet or more from potential sources of pollution (USEPA, 1985). The leniency of the environmental regulations can in part be traced to the two major drawbacks to groundwater classification (zone delineation) posed by Duda and Johnson (1987). First, analyses of this nature require extensive hydrogeologic studies which may upon initial reflection seem too costly. Secondly, there exist a number of technical uncertainties in establishing boundaries of the classified units. Both shortcomings must be resolved if the states are to enact regulatory controls which will satisfy their objectives.

Admittedly, the method the FDER has chosen to calculate and delineate protection zones in Florida is not the most sophisticated available. Its limitations arise from the

lack of consideration of the natural slope of the potentiometric surface, recharge, natural boundaries, porosity variations, and incomplete knowledge of aquifer thickness. Data availability, combined with resource constraints for calculating and mapping the zones, dictated the method chosen. Nevertheless, the technique selected provides a major step toward ensuring Florida of an adequate drinking water supply.

Merchant et al. (1987) consider their approach to capture (protection) zone approximation to be a great improvement over the circular zone method. Taking into account regional flow, their method produces elliptical zones. By generalizing the aquifer to a homogeneous uniform-flow system, elliptical-shaped zones are generated whose eccentricity increases as the regional flow rate at the well increases. In order to use this method, more site-specific information would be required than for the FDER approach, including knowledge of the local flow direction and hydraulic gradient. Presently, this is a prohibitive factor when one considers zone determination for the large number of wells involved in Florida.

Spatial Concepts

The problem of protection zone determination has been addressed only in the context of groundwater application. At a more fundamental level, it can be viewed as a two-dimensional spatial problem. Essentially, two "objects"

located at specific sites are in competition for "resources" distributed in space. Whether the objects are bacteria, plants, or wells, and the resources are nutrients, light, or water, the goal is to define the region in space the competing objects require to fulfill their respective resource needs. For the purpose of this study, the solution is subject to the constraints previously listed. The resulting solution then provides the shape of the resource space required by the objects.

Johnson and Mehl (1939) studied surficial processes of the formation and growth of metallic nuclei. They described the crystallization of the nuclei as a radial growth process. In addition to their work concerning changes in growth rate of the crystal structure through time, they discuss what they call the *impingement factor*. This factor is so named because it describes the change in growth rate produced when a growing crystal contacts or impinges on neighboring crystals. Sometimes referred to as contact inhibition, this factor is calculated as the proportion of the total surface area outside the crystal considered which is not covered by other crystals. It is used to determine the fraction of a plane surface covered by growth with impingement through time.

In a similar study by Evans (1945), the covering of a surface by metallic films or layers of corrosion is examined. He describes the film or layer spreading out as

expanding circles from predetermined nuclei distributed randomly by a Poisson process. He also derives an equation for calculating the area of a surface not covered by the circles which is based on nuclei density, radial growth velocity, and time. The equation is then modified to consider nucleation rate, nucleation number, and three-dimensional growth. Evans further expands his idea to growths which avoid each other, such as is the case when a substance necessary for growth becomes exhausted as a result of growth. Unfortunately, he concludes discussion of this matter suggesting that this situation "often leads to dendritic structures" (p.368).

Studies with potential implications can also be found among the more conventional spatial analysis approaches. Nearest neighbor methods cover a variety of techniques which use distance measures to identify and analyze point patterns. The ultimate goal of these methods is to understand the process that generates the patterns. By definition, a point nearest to a randomly chosen point is its *nearest neighbor.* The distance between the two points is the nearest neighbor distance. It is this distance that is used in nearest neighbor studies.

A commonly used technique is the Clark and Evans nearest neighbor procedure (Ripley, 1981). This approach compares the average nearest neighbor distance with the expected average distance for randomly placed points. In

order to determine the expected distance, one must know the point density (number of points per unit area). Normally, ascertaining the number of points in consideration is not a significant problem. But how to define the area of the study region can be quite a different matter when dealing simply with a set of points. Numerous suggestions have been presented as possible approaches, but none are universally accepted. The area boundary/edge effect problem, as it is referred to, is the major difficulty encountered with all nearest neighbor techniques (Upton and Fingleton, 1985). The boundary effect associated with these techniques is a problem similar to the areal delineation problem of this study. However, the boundary solutions suggested for nearest neighbor methods, such as buffer zones or toroidal surfaces (Ripley, 1981), are inappropriate for the present investigation.

Simberloff (1979) modified the Clark and Evans technique to consider the data as a set of circles centered at the points identified, rather than simply as points. He was concerned with plant inhibition models which viewed plants as non-overlapping discs. His approach allows for calculation of the average radius of the discs based on nearest neighbor distances. Upton and Fingleton (1985) provide an example of Simberloff's modification in an application to the spatial distribution of beadlet anemones on the face of a boulder. Using the modification, they were

able to estimate the radius of a disc occupied by an anemone. A comparison of the organism's size with that of the estimated disc radius revealed interesting colonization characteristics. The aggressive little beasts occupied a territory over 12 times their own size. However interesting, this approach is inappropriate for this study, since the results are based solely on average interpoint distance.

The majority of inhibition models,such as Simberloff's, were principally concerned with ecological applications. However, regular patterns are also known to exist in human geography. Most of these seek deterministic rather than stochastic explanations for the resulting patterns.

A dominant theme in studies of this type is Christaller's *central place* model. His model concerns the optimum placement of supply points for goods and services required by a surrounding population. An inhibitory mechanism prescribes regularity in the locational pattern of central places. There are a number of levels of central places based on the number of locations required to supply the demand for any particular good or service.

Assuming a uniform environment, a reasonable consumer would travel the minimum distance to a central place to acquire goods or services supplied there. To achieve the distance minimization, the highest level centers are ideally arranged in a triangular lattice pattern with lower level

centers similarly interwoven. The resulting geometry suggests that each central place is located at the center of a hexagonal market area. Losch (1954) was able to show mathematically that hexagons provided "the best possible packing" of trade areas in a region for the mutual advantage of the consumer and producer. The regular subdivision of the region into a hexagonal tessellation pattern was the ideal structure according to the central place model.

Another tessellation which receives widespread use in spatial studies is known as a *Dirichlet* tessellation. This tessellation has been used in a number of contexts and goes by a variety of names, including Voronoi polygons, Thiessen polygons, the cell model, and the S-mosaic (Boots and Murdoch, 1983). The polygons which comprise the tessellation are formed about a set of points in a planar region. Each polygon is formed about a single point and has the property that every location in that polygon is nearer to that point than any other point in the region. This results in subdivision of the region into polygons in a space-exhaustive manner (Figure 5).

Crain (1972) posed that stochastic processes in metallurgy, cell biology, astrophysics, and geology could all be modeled using the Dirichlet tessellation. He described an example concerning two-dimensional crystal growth about randomly distributed nuclei. The crystals grow uniformly over the plane until mutual contact prevents

DIRICHLET TESSELLATION

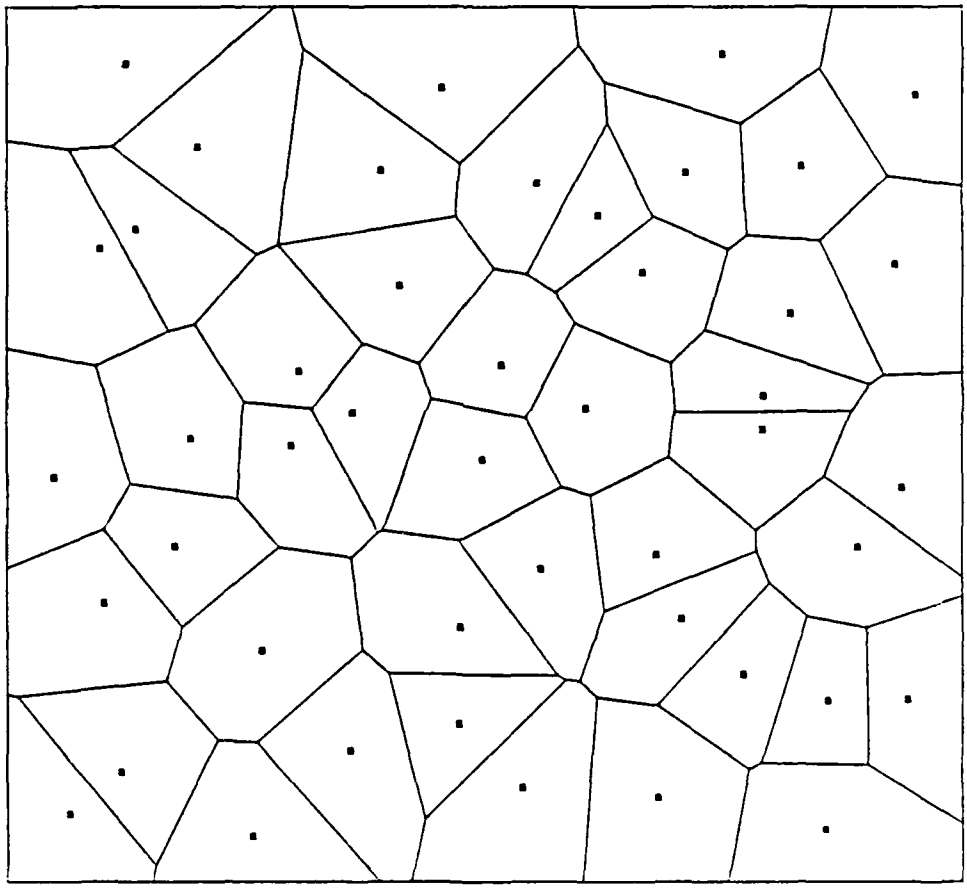

Figure 5: Dirichlet Tessellation

further growth. The process results in coverage of the plane with non-overlapping polygons (Dirichlet cells). He cited as the primary interest of his model the frequency distributions of such polygon parameters as the number of sides, perimeter, and area. Expected values were also derived for each of these parameters.

The basic characteristics of the polygons formed by a Dirichlet tessellation are given by Getis and Boots (1978): (1) all polygons have straight line edges, (2) all polygons are convex (i.e., it is possible to link any two points within the polygon without traversing another cell), and (3) the minimum number of edges is three.

If Crain's crystal model is modified to incorporate different rates of growth between individual crystals or to allow crystal nuclei to be "born" at different times, the resulting pattern is described as a curved boundary tessellation (Figure 6). Such a process of crystal growth was described previously by Johnson and Mehl (1939). The polygon characteristics for this model differ from Dirichlet cells in that: (1) they have curvilinear and straight edges, (2) the polygons are not necessarily convex, (3) the minimum number of edges is two, and (4) the common edge between two polygons can be discontinuous.

Other than the above characteristics, very little is known about properties of models of this type (Upton and Fingleton, 1985). Recent investigations into the geographic

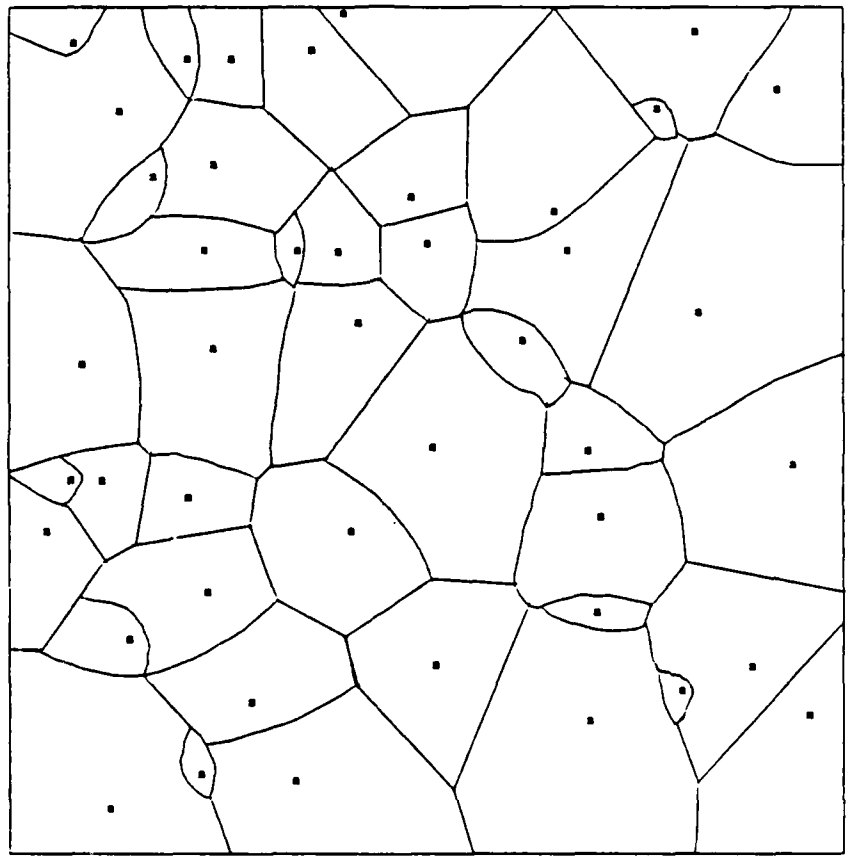

Figure 6: Curved Boundary Tessellation

application of this tessellation have yielded somewhat inconclusive results. Getis and Boots (1978, p.147) purport that "because of its potential value to geographers, it is unfortunate that it is difficult to derive analytically the properties of patterns produced by such a model".

Geographical research involved with the description of shape also has potential implications to this study. An infinite number of shapes can be delineated in the spatial competition problem. But within the constraints defined, is there a unique shape which delineates the protection zone? Lee and Sallee (1970) suggest that a finite number of parameters is not sufficient to produce a unique shape description. Frolov (1974) indicates that these parameters fail to adequately account for characteristics of shape variation which he denotes as compactness, dissection, and indentation. The parameters referred to in their research are single value types such as area and perimeter. Within the constraints employed in this study, there is a single value parameter (area), as well as conditional statements about minimal boundaries and overlap distribution. Since the conditions imposed here are shape-definitive in nature, the author contends that unique shapes can be generated satisfying all constraints.

In reviewing other approaches to similar spatial problems for potential application here, the works by Tobler and Rushton were discovered. Tobler (1963) described

Hagerstrand's problem of depicting migratory exchange. Hagerstrand suggested that migration was based on a distance decay function with decreasing migratory exchange at increasing distance from the population center. To illustrate this he used a logarithmic cartogram derived from the distance function resulting in radial scale distortion. Application of this illustration technique to the groundwater problem was considered, but subsequently rejected after further investigation. It was discovered that the radial scale distortion using a logarithmic function extended points located near the center point more than those further from the center. However, those points located farthest from the center could potentially be drawn in toward the center, a fact which one cannot ignore considering the minimal boundary constraint. However, Tobler does indicate that projections similar to Hagerstrand's can be obtained by using suspected functions of radial scale distortion for any distance model employed by geographers.

Rushton (1972) dealt with a spatial problem as a variation of the central place model. As previously stated, Christaller assumed environmental conditions to be uniform. Therefore, he suggested that ideally located central places would be distributed in a regular pattern. Rushton argues that if environmental conditions were spatially variable, the central place patterns would then be

distorted to account for that variability. Drawing from the work of Tobler, Rushton sought to develop a method for deriving expected patterns based on the spatially varying conditions. Specifically, he wished to determine the location and number of supply points, such that the proximal area equates to the area of threshold demand, while simultaneously minimizing patron travel distance. His approach utilizes a distance minimizing concept for boundary definition. He suggests several possible extensions of his method. One is for the definition of tributary regions with population and distance constraints. For example, define the regions so that they have equal populations and that no individual would have to travel further than some critical distance to a service point. He calls another extension revised boundary definition. In cases where people have free choice of which facility to patronize, a space-preference function could be included so as to locate service points which draw equal populations.

CHAPTER FIVE

MODEL SPECIFICATION

No existing spatial model adequately represents the process of generating composite protection zones. Using the practical problem of protection zone delineation and existing spatial models generated as a basis, the assumptions and arguments for a proposed model are defined. A fully specified model is incorporated into a methodology for solving the groundwater protection zone problem. It is hoped that the model improves the method for definition of composite protection zones, as well as yields insights into the spatial concepts underlying its application.

The process to be modeled can be classified as an area-generating point process. The growth model concept of Johnson and Mehl (1939) serves as the foundation for the proposed model. This model generates areal patterns or configurations resulting from the spread of influence across an area, outward from a set of points. In this application, the set of points is defined by well locations and the composite protection zone constitutes the areal pattern.

Assumptions and Arguments

There are a number of assumptions which will be included in the proposed model which are similar to those of the growth model. The natural representation of the

two-dimensional growth pattern for a single point is assumed to be a circle centered at that same point. The pattern is produced by uniform growth in all directions from the point. The process is assumed to be competitive for required resources which are distributed in two-dimensional space. The environment comprising this space is presumed to be uniform. Unlike the growth model, an assumption is included which restricts the number of points considered to two. This supposition is expanded to accept multiple point processes in later discussion.

As growth about a single point results exclusively in circles, the arguments specified are applicable to two-point patterns whose circles contact or overlap. Initially, the circles defining the space required by each point are allowed to overlap. From this configuration, three pieces of information concerning the process are extracted for later use in the model. The total area of the final configuration is the sum of the areas of the individual circles. The area by which the initial figure is "deficient" is equal to the overlap area or the area of intersection between the two circles. The initial configuration boundary is used as the figure to be distorted in the growth process.

Boundary Distortion

Next, a condition prohibiting overlap is imposed on the process. This necessitates expansion of the initial

configuration to include an area equivalent in size to the overlap area. The distorted figure must totally enclose the initial figure. Therefore, if the configuration boundary is distorted, it must be extended outward from the interior of the figure.

The determination of the boundary distortion technique is the focal point of this study. Drawing from the previously described works of Rushton (1972) and Tobler (1963), a unique approach is posed. Rushton suggested that a space-preference function could be incorporated into map transformations which utilize distance-minimizing concepts for boundary definition. The space-preference function of interest here is one which extends the boundary nearer the overlap region more than it does at distances farther from the overlap. A function of this type is compatible with the inverse distance relationship alluded to in the discussion of the study objectives.

The distance minimization can be easily understood if one views the expansion process as occurring about a single point or origin. The aggregate distance from the origin to all points on the boundary can be minimized. Tobler (1963) describes map transformations which are analogous to processes of this type. He indicates that the patterns generated exhibit radial scale distortion from the origin. In Tobler's work, the origin is the point from which

migration is assumed to begin, whereas Rushton's origin was the location of the central place under consideration.

As the application of a radial scale distortion transformation to the study model requires an origin, one must be selected. However, in the conceptualization of the present model, there are two circle center points surrounded by the overlap configuration. How the transformation origin is selected has a definite impact on the transformed figure.

On first inspection, one might assume that the weighted mean center (using circle radius as weight) of the two circle centers is the appropriate distortion origin. But for a pair of circles of very dissimilar size, the weighted mean center lies closer to the center of the larger circle. Radial distortion from this point would not reflect the spatial competition *pressure* present in the overlap area. The distortion would be almost uniform about the larger circle center with a slight deviation toward the small circle.

Utilization of the geographic center of the two circle centers as the transform origin provides a slight improvement over the weighted mean center. Nevertheless, dissimilar circle sizes still result in distortion with exaggerated influence from the larger circle. For this reason, the distortion origin selected is the centroid (geometric center) of the overlap region. It serves to distort the boundary (*relieve competition pressure*) relative

to the distance from the overlap. Use of the overlap centroid then seems the most appropriate alternative for the distortion transformation.

Using the overlap centroid for the transformation, how is the distorted figure to be generated? Given that the distorted figure must totally enclose the configuration, a fundamental concept of the model can be derived. For each point on the transformed boundary, the distance to the overlap centroid is always greater than or equal to the colinear distance from the initial boundary to the same centroid (Figure 7). This means that the distortion transformation may add to, but never subtract from the boundary/centroid interpoint distance.

Determining the distance to add to this interpoint distance is the key to modeling this spatial process. An inverse distance relation has been discussed several times, but never specified. The interpoint distance (d) could be extended by a factor proportional to 1/d or for that matter any polynomial function in d.

Transformation Function

The function selected for use in this study is one which extends interpoint distance by a factor of $1/d^2$. The function was not chosen arbitrarily, but selected after contemplation of its use in existing models. For example, Newton's Principle of Universal Gravitation and Coulomb's Principle of Electrostatic Attraction both calculate forces

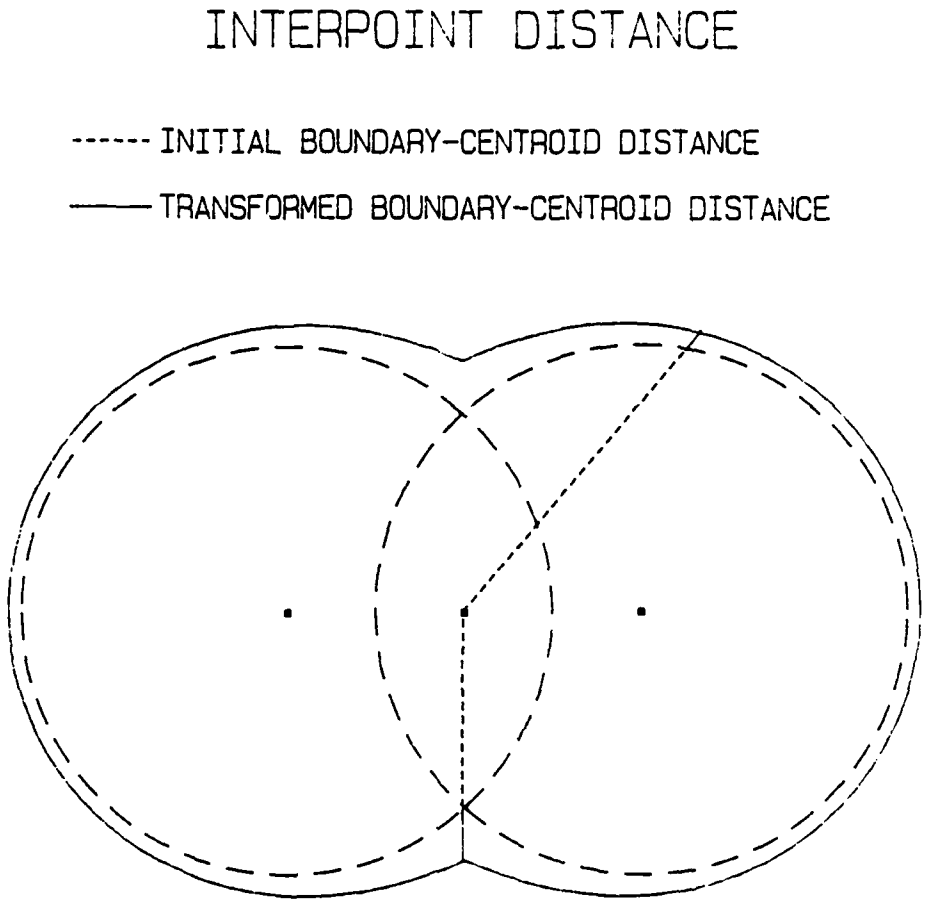

Figure 7: Boundary/Centroid Interpoint Distance

as inversely proportional to the squared distance separating the objects under consideration. Incorporating this function into the distortion model seemed appropriate, especially if one envisions the *pressure* of spatial competition as a force. When this pressure is diffused through space the force diminishes in such a manner as to be inversely proportional to the square of the distance from the original location. The squared term arises from the increase in area available to dissipate the force as one moves away from a point of higher pressure. This increase is analogous to the effect of increasing the radius of a circle. The areal increase is proportional to the radial increase squared. The point from which the diffusion process takes place is specified as the overlap centroid for this study.

In order to control the degree of distortion introduced by a transformation, a scaling factor must be incorporated into the model. This factor will limit the maximum distance extension increment to a desired value. Combining the scaling factor and the distance function the transformation function takes the following form:

$$d' = d + K/d^2$$

where

d' = transformed distance from the centroid to the boundary

d = initial distance from the centroid to the boundary

K = scaling factor to limit maximum extension increment

The value of K is determined by inserting the shortest boundary/interpoint distance for a given configuration into the above equation as d. The maximum desired increment is added to d to get a value for d'. K can then be determined algebraically.

The transformation function is applied to each point which defines the initial configuration boundary. This procedure has the effect of expanding the configuration boundary. The areal increase attributable to the distortion process is dependent on the value of K, as well as the initial overlap configuration. Since a single transformation may not increase the figure area to the total area required, multiple transformations may be necessary.

Using an iterative process, the transformation can be repeated until the distorted figure boundary encompasses an area equal to (or vary within a selected tolerance of) the total area requirement. Each repetition requires recalculation of K and utilization of the most recently transformed boundary points. The distortion process is complete when the area requirement is met.

The distortion model is designed to accommodate three possible structural overlap configurations (Figure 8). Lateral overlap is the simplest case and involves two circles overlapping side-to-side. The distortion process described to this point considered a lateral overlap structure only.

Embedded overlap occurs when one circle lies entirely within another. For this two-circle structure, a slight modification of the distortion model is necessary. The centroid of overlap is now defined as the center of the embedded circle. The initial configuration boundary is the outer circle. The minimum interpoint distance used to determine K is the shortest distance from the centroid to the outer circle.

The most complex structures are those involving multiple overlap. They consist of three or more circles involving any combination of lateral and/or embedded overlap. Model modification is also required for multiple overlap cases. Each overlapping pair of circles is treated as a separate overlap case of its respective simple type (lateral or embedded). The outer configuration boundary (union) of the multiple overlap is used for all scaling calculations and transformations. The distortion process is conducted by rotating through a sequence of transformation origins, one for each overlap pair. A single transformation is completed for one origin, then the areal increase is

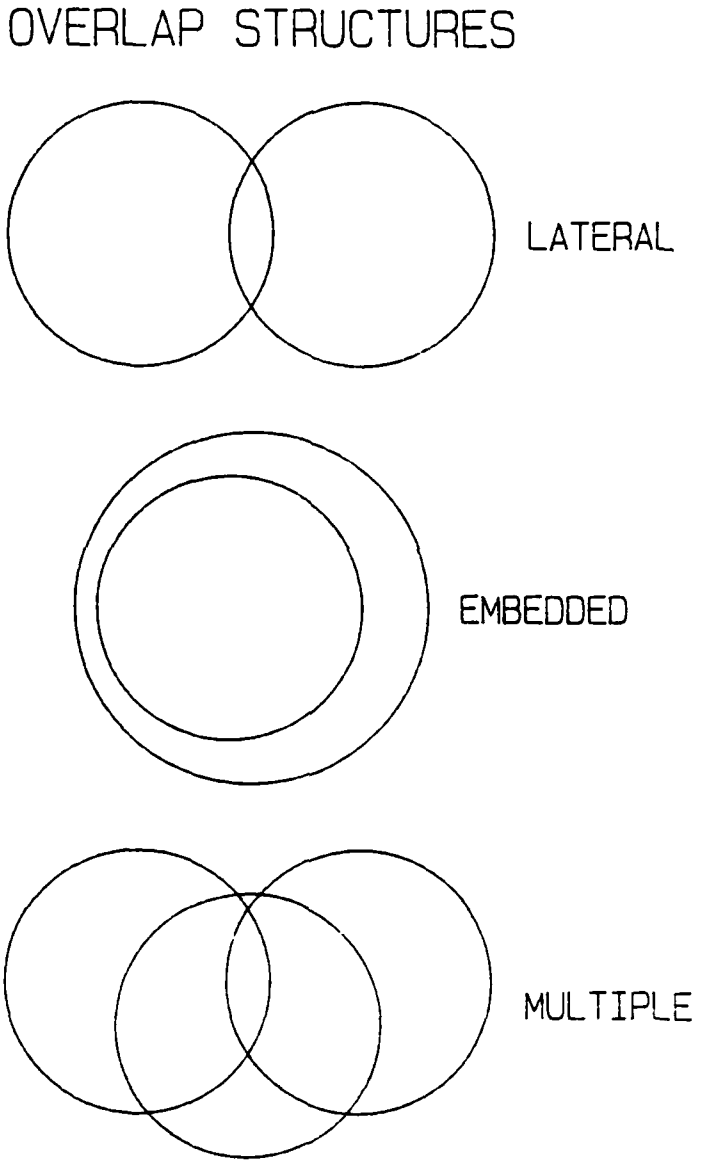

Figure 8: Overlap Structures

compared with the respective origin's overlap area. If the area requirement is met, the origin is dropped from the sequence. Irrespective of whether the origin is dropped, the transformation origin is advanced to the next overlap centroid in sequence and the transformation process is repeated. The procedure is continued iteratively until all origins are dropped from the sequence, indicating that the total area requirement has been met. This transform - rotate - transform - rotate sequence allows for uniform influence of all overlap pairs in the distortion process.

CHAPTER SIX

MODEL APPLICATION

The goal to produce an objective method for defining groundwater protection zones is of primary concern in this study. The manual cartographic procedure previously described falls well short of meeting that goal. Kaplan et al. (1986) indicate that a great deal of aquifer mapping is presently done by hand using similar labor-intensive, subjective procedures. They suggest that utilizing a geographic information system (GIS) would "allow faster, more reliable, and scientifically credible results."

Broten et al. (1986) also support the use of a GIS for spatial analyses related to groundwater contamination investigations. They cite a number of GIS characteristics which make such systems desirable for groundwater research. The efficiency and accuracy of a GIS allows for simple automation of many procedures. Routine functions necessary for spatial modeling are also included in these systems. Data management and map preparation are greatly enhanced by the use of a GIS. The advantages offered by these systems are not strictly confined to groundwater research, but rather to any field involving spatial analysis.

To capitalize on these advantages, a GIS was used in this study. The software employed in the research was the

ARC/INFO, Revision 4.0 (Environmental Systems Research Institute) geographic information system. The host computer was a Prime 750 with a Fortran 77 compiler. An Altek 9000 digitizing table was used as the data input device. A Hewlett Packard 7586B pen plotter was used for graphics output. The hardware and software are the property of the Tallahassee District Office of the U.S. Geological Survey, Tallahassee, Florida.

In the following discussion the term "system" is used to refer to the components listed above. The system is used in any way possible when it simplifies or enhances the modeling process. While describing the procedures of the process, the specific system commands and sequences are omitted and only the general descriptions of each step are discussed. As the system itself does not have all the functional capabilities required to implement the model, additional routines had to be developed. These routines are Fortran programs written to perform the transformation process. The transformation procedures are discussed in greater detail than the system functions as they comprise the essence of the study.

The entire modeling process consists of three basic steps to produce a composite groundwater protection zone. First, utilizing the GIS, input data for the transformation program are generated. These data are entered into the program during execution. The transformation output is then

used as input into the system for generation of graphic output. A discussion of each of these steps follows. First however, a description of the transformation algorithm is presented as a preview to understanding the required inputs.

Transformation Algorithm

Rushton (1972) describes the use of locational coordinate transformations for processes requiring revised boundary definition. He suggests that by imposing constraints based on areal size and/or space preference functions, a transformation can be used to define a new boundary from the set of coordinates describing an existing boundary. The solution is an iterative process which maps each boundary point to a new trial point. The amount and direction of each move is dependent on the constraints imposed. This type of transformation procedure was used as the foundation for the composite protection zone generation process.

In Chapter Five, Model Specification, a number of the conceptual aspects of the coordinate transformation are discussed. The transformation origin was selected to be the geometric center of the overlap region. The space preference function chosen was one which transforms each boundary coordinate to a new point, based on a factor inversely proportional to the squared distance from the original boundary point to the overlap centroid. The areal

constraint imposed was the sum of the areas of the individual protection zones involved.

The transformation algorithm was derived through algebraic manipulation of the general linear equation and distance formula. Using the coordinates of the centroid (Xc,Yc) and a boundary point (X,Y) to be transformed, the equation (slope and intercept) of a line through the two points can be determined in the form:

$$Y = a + bX$$

Using the distance formula, the distance (d) between the same two points can be calculated from:

$$d = [(X-Xc)^2 + (Y-Yc)^2]^{\frac{1}{2}}$$

As discussed in Chapter Five, the transformation serves to extend distance d to a new distance d' by the function:

$$d' = d + K/d^2$$

The distance each point is extended from the origin is then equal to K/d^2, with K being the previously described scaling factor.

K is inserted to control the maximum distance extension possible for a single transformation. Its value is determined by setting K/d^2 equal to the maximum extension desired when d is equal to the shortest initial centroid-boundary distance (see Figure 7). For this reason, the shortest distance must be determined prior to the transformation and be included as input to the process. This value remains the same through one complete

transformation iteration, which processes each coordinate pair once. The maximum extension desired for the protection zone application is ten feet. This figure is based on the U.S. Geological Survey requirement to round all protection zone radius calculations to the nearest ten feet. The ten-foot increment also seems reasonable in order that iterative expansion of the protection zone boundary fall within the five-percent areal tolerance. A larger increment might cause the transformation to overshoot the areal requirement beyond the tolerance level.

Once the extended distance d' is calculated for a boundary point, the transformed point coordinates (X',Y') can be determined by the following derived equations:

$$X' = \pm\, d'/(b^2+1)^{\frac{1}{2}} + Xc$$

$$Y' = a + b\, X'$$

where

d' = extended distance from centroid to boundary

a = intercept of line through centroid and boundary point

b = slope of same line

Xc = X coordinate of origin (centroid)

The $\pm$ for the X' term arises from the distance calculation which by definition results in only positive values. Since some boundary coordinates will have smaller X values for the boundary points than for the origin (negative

X distance), the direction of distance extension must be considered. Thus, for all boundary points with an X coordinate value less than Xc, the negative value of d is used to calculate the transformed coordinate X'. One step in the derivation of the transformed coordinate equations required translation of the centroid coordinates to the zero, zero origin (0,0). The addition of Xc in the derived equation for X' is required to retranslate the values back into the original coordinate system. Neither the $\pm$ term, nor the retranslation term appear in the equation for the transformed Y' value. The Y' coordinate is determined from the general linear equation using X'. Therefore, the direction of the distance extension and origin translation are already accounted for.

The transformed coordinates X' and Y' then replace the original input coordinates X and Y. The transformation process is repeated for the next X, Y input pair until all boundary points have been extended. This cycle of processing each boundary point one time constitutes one iteration of the transformation. After one iteration, the value of the shortest distance from the origin to the new boundary is saved for further iterations if necessary. The new value is simply the smallest extended distance (d') calculated during the previous iteration. Additional iterations are required if the areal increase due to the

transformation is less than the overlap area. Then overlap area is also required as an input.

Preparation of Inputs

Of the three basic steps to the delineation of a composite protection zone, the input preparation is the only one which varies and is dependent on the overlap structure under consideration (Figure 8). Initially, preparation of the data for a two-well lateral overlap structure is described. The modifications for embedded and multiple structures is presented later in this section.

The source for all inputs to the transformation program is USGS 1:24,000 topographic quadrangles on which well locations and individual protection zones are plotted. Also plotted on the quadrangles are the manually created composite protection zones. No verification of either well locations or protection zone radii was attempted, since a comparison of the manual and transformed composite zones was intended. Correction of well locations and/or individual zone sizes would certainly alter the resulting transformed composite protection zone and therefore make comparisons meaningless.

The well locations are digitized into the system and circular polygons are generated to represent the individual protection zones. The areas of the two circular polygons as determined by the system are summed to provide the total areal requirement for the composite protection zone. The

system is then used to determine the intersection of the individual protection zones. The area of the lens-shaped intersection polygon is that area which must be accounted for by the transformation. This intersection area (denoted as overlap) is another input required by the transformation.

The GIS is also used to determine the coordinates of the centroid of the overlap area which serves as the transformation origin. A system function that generates label points for unlabeled polygons is used for this purpose. According to the ARC/INFO documentation, the label point generated for each polygon would be located at its calculated geometric center. Visual inspection of the label locations for the lens-shaped overlap polygons indicated that the algorithm for centroid calculation is satisfactory for these particular figures. However, additional tests of the centroid calculation routine for irregular-shaped polygons yielded some unpredictable and incorrect geometric center locations. The generated centroids are used for the lens-shaped polygons since they are the only shape possible for the overlap polygons in the study. The system's centroid determination algorithm may be inappropriate if the model is modified to include overlap polygons which are not symmetrical.

The two circular polygons representing the individual protection zones are overlaid using the system to obtain the union of the figures. The area of the union is recorded for

input into the transformation as the initial figure area. Using the boundary of the union polygon and the calculated overlap centroid, a distance measuring function is invoked. Its purpose is to determine the shortest distance from the centroid to the boundary of the polygon, another required input. Finally, a system function is utilized to generate a file consisting of X,Y coordinates which define the union polygon's boundary. This is the initial set of coordinates transformed in the composite protection zone generation.

At this point, all data inputs are known, but they still must be put into proper input format. An input parameter file is created which includes: the X and Y coordinates of the centroid, the shortest distance from the centroid to the union boundary, and the size of the overlap area, respectively. One final parameter included in this file is the maximum distance extension increment, which is previously specified as ten feet. Since all coordinates and distances are measured in digitizer inches on a 1:24,000 scale map, the figure for the maximum increment is 0.005 inches, the equivalent of ten feet on the earth's surface.

For overlap structures other than the lateral type, modifications of the input preparation procedure are required. Embedded structures actually require less work for gathering inputs than does the lateral overlap case. No intersection process is necessary as the embedded circle is the intersection polygon. It follows that the area and

center of this circle are the area and centroid of the overlapping polygon. The union polygon area and boundary are simply that of the larger individual protection zone in the embedded structure. All other inputs are obtained in the same manner described for the lateral overlap case.

The multiple overlap structure requires additional input data and, therefore, additional work in pretransformation data processing. The individual protection zones are considered for all possible pairs of intersection. For purposes of the study, a visual determination of overlap occurrence was made. If a large number of wells is involved, a GIS analysis may be required to identify all existing overlap situations. For each overlap condition which does exist, inputs are gathered by the methods described for the respective simple overlap structure (lateral or embedded). The resulting parameter file consists of one record for each paired overlap occurrence. Each record contains centroid coordinates, shortest distance to the union boundary, overlap area, and the maximum extension increment. The initial figure area, total required area, and union boundary are determined in a manner similar to that previously described using all wells and protection zones involved.

Transformation Program

With all of the inputs prepared and formatted, the data are ready for transformation processing. The transformation

software consists of a main program and two subroutines written in Fortran 77 code (see Appendix). An overview of each of the three program segments is presented in the following discussion.

The initial step of the main program requires interactive input of the parameter file, initial figure area, total required area, boundary coordinate file, and an output file for the transformed coordinates. Each variable for each record in the parameter file is read into an array to be used during the transformation processing. The number of centroids input (and therefore number of records) is counted and displayed as a check on the input process. Each centroid input serves as transformation origin for coordinate transformation. The overlap area associated with each centroid is summed to determine the amount of area which must be added to the union figure.

Adding the sum of the overlap area and the initial figure area, the result is equal to the summed areas of the individual protection zones in those cases where only two wells overlap the same area. As the approach used for the study considered pair-wise overlap only, occurrence of overlapping areas by three or more individual protection zones would yield an artificially high value for the sum of overlap areas and the initial figure area. Areas of three-zone intersection would be added one-too-many times, four-

zone intersection two-too-many, and so forth, in overlap summation.

If the transformation was executed using this improper value, the resulting composite protection zone would be larger than required. For this reason a compensation factor is introduced which reduces each value of overlap stored in the parameter array by a factor of:

(Total Area Required - Initial Area)/Overlap Sum

This correction produces a transformed figure with the desired area (sum of the area of individual protection zones).

The boundary coordinates for the union figure are read into another array and the number of vertices is counted and displayed. The main program then begins a loop to transform the coordinates using the first record (centroid) in the parameter file. A subroutine to do the transformation is called and executed as previously described. Next, an area-calculating subroutine is called to determine and display the area of the transformed figure. The area added to the previous figure is calculated and subtracted from the overlap area associated with the transformation centroid and stored back into the parameter array. This allows for flagging a centroid when its overlap area has been accounted for by transformation with the centroid as the origin.

The procedure continues with the next parameter record in sequence (if a multiple overlap structure). The same

processes are repeated as the transformed boundary is expanded from the second centroid. After a single transformation is completed for each centroid in the parameter file, one iteration of the process is complete. The processing continues from the first parameter record through the same sequence. Any time a parameter record is read and its overlap value is zero, the centroid is skipped in the transformation sequence. When all the overlap values in the parameter file are equal to zero, the transformation process is complete.

The final transformed coordinates contained in the coordinate array are written to the output file. The number of iterations which were required to generate the composite protection zone is displayed. This completes the execution of the transformation program.

Use of Output

The output file containing the transformed coordinates requires minor format modification prior to importation into the GIS. The import routine is followed by a system function invoked to build polygon structure. This function provides an area calculation for the composite protection zone which is used as a check for the transformation program calculation. Using the graphics capabilities of the system, the composite protection zone generated is viewed on the CRT. Hardcopy output is then produced using the system plotter.

Wells Selected for the Study

The wells selected for use in the study were chosen from those requiring composite zones presented in Vecchioli, et al., (1987). Those selected involved a combination of the three possible overlap structures. The number of wells involved in any single composite zone was restricted to five or less to reduce input preparation time. Table 1 lists the wells used in the study along with associated information about each, including: the quadrangle on which the well is found, well ID, latitude, longitude, individual protection zone radius, and the generated figure number.

TABLE 1

Wells Selected for Composite
Protection Zone Generation
(Source: Vecchioli et al., 1987)

Quad Sheet	Well	Lat	Long	Radius(ft)	Figure
Weekiwachee	95	28 32 27	82 34 00	1380	9
"	1585	28 32 39	82 34 01	1150	9
Crystal River	51	28 54 06	82 34 38	1950	11
"	52	28 54 04	82 34 38	1510	11
Chassahowitzka	#8	28 42 23	82 31 25	1570	13
"	#9	28 42 12	82 31 15	1610	13
"	#14	28 42 30	82 31 34	1650	13
"	#15	28 42 34	82 31 44	1650	13
Citrus Park	1525	28 06 12	82 31 53	1190	15
"	1526	28 06 19	82 31 57	1050	15
"	1529	28 05 45	82 32 17	990	15
"	1530	28 05 52	82 31 58	1360	15
"	1531	28 05 50	82 31 57	1330	15
Citrus Park	1537	28 03 49	82 33 17	2240	17
"	1538	28 03 40	82 32 33	2250	17
"	1539	28 03 32	82 32 40	2250	17
"	1540	28 03 21	82 31 54	2260	17
Port Richey	434	28 16 43	82 41 49	970	19
"	435	28 16 31	82 41 51	960	19
"	436	28 16 29	82 41 53	1140	19
"	437	28 16 27	82 41 29	1320	19

CHAPTER SEVEN

DISCUSSION OF RESULTS

The results of the study are discussed in the two following sections. The first section describes the program operation characteristics. The computer-related aspects of the composite protection zone generation procedure with respect to data processing time and resource requirements are addressed. A discussion of the generated composite zones with an analysis of each figure is also provided. Each composite protection zone generated is compared with its manually delineated equivalent and evaluated with respect to the defined study objectives.

Program Operation

The preparation of input data for the transformation program accounted for a substantial majority of the time required to generate a composite protection zone. Preparation time varied from one to four hours depending on the particular situation. The time increased with an increasing number of wells, but depended particularly on the number of paired overlap occurrences. The more overlap involved, the greater the time required to obtain inputs. This owes to the fact that each paired overlap occurrence required determination of its centroid coordinates, shortest distance to the boundary, and overlap area for program input.

The size of the boundary file used as input for the transformation program varied according to the well configuration involved. The minimum possible number of vertices is 360. A simple embedded structure with a circular union figure would have this number of vertices. This is a system-induced minimum based on the number of points used to define a polygon produced by using a circle-generating function. The Crystal River configuration is an example consisting of the minimum possible vertex count. The largest number of vertices contained in a study configuration input file was 859 for Citrus Park 1. It should also be noted that the vertex count of the composite protection zone created is identical to the number input. The transformation merely modifies each point location: no new vertices are generated.

Like vertex count, the number of transformation iterations required to produce the composite zones varied according to well configuration. The total area of overlap was not in itself the sole factor in determining the required number of iterations. Rather, total overlap relative to the initial figure area gave a better indication of how many transformation cycles were necessary. The transformation for the Weekiwachee Springs composite zone required 35 iterations, the fewest of any of the study figures. Needing 160 iterations, the Citrus Park 1

configuration took the greatest number to complete the transformation.

The computer time required to generate the composite protection zones was not a significant factor for any of the study configurations. With all processing times of less than one minute, the computer resources utilized during transformation were negligible in comparison with those necessary for input preparation. This vast difference in time required for input preparation and transformation processing suggests that modifications to the transformation program might be feasible. Program changes which incorporate input preparation steps into the transformation software may prove beneficial with respect to time savings. Such modifications are discussed in the following chapter.

Use of the computer for modeling the spatial allocation process did serve to meet a primary objective of the research. The objective of developing a formal method for the generation of unique composite protection zones was satisfied. The method's ability to consistently reproduce results was also verified. A thorough examination of output files produced by separate executions of the program revealed identical coordinate sets. Additional checks were made on the number of iterations required and generated protection zone area to ensure that by repeating the procedure, the same values were obtained.

Generated Composite Protection Zones

Each of the configurations used for composite protection zone generation is discussed in this section. The figures depicting the generated composite zones are included. Also depicted on the figures are the well locations and individual overlapping protection zones for which the composite zone was produced. All the figures are 1:24,000 scale portrayals. The composite zones generated were visually compared with the U.S. Geological Survey's manually created equivalents. The USGS composite protection zone figures presented are extracted portions of figures found in Vecchioli et al. (1987).

Figure 9 represents the Weekiwachee Springs composite protection zone. This case was selected as an example of a simple lateral overlap structure. The resulting composite zone compares favorably with the USGS version (Figure 10) and exhibits only minor differences. The USGS delineation does not differentiate the degree of extension about the dissimilar-sized individual zones as the transformed figure does. Based on the specified distance function in the model, the transformed protection zone appears as expected. The function could be modified to become more distance-sensitive by inserting d^3 or d^4 in place of d^2. Such a change would produce a composite protection zone similar to Figure 9, but display even greater differentiation in boundary extension from bottom to top of the protection

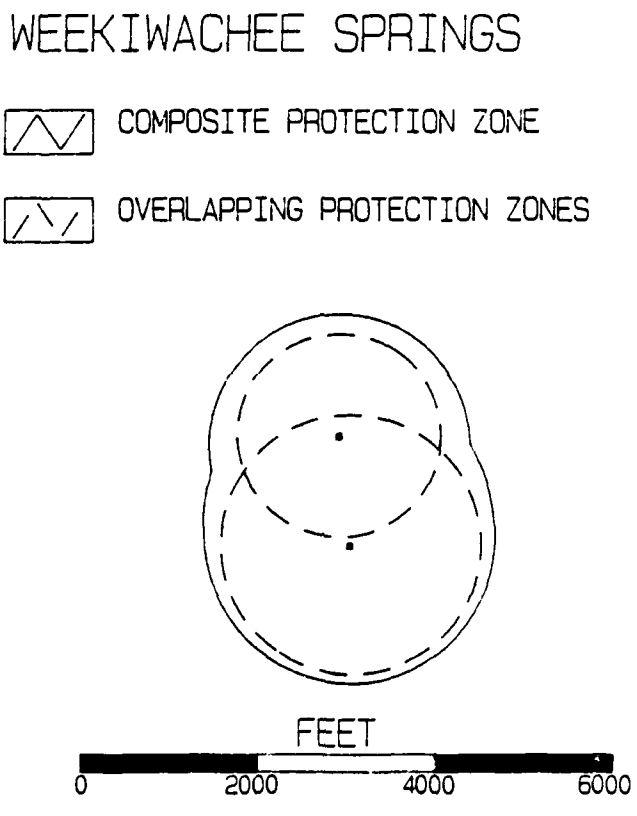

Figure 9: Weekiwachee Springs Composite Zone

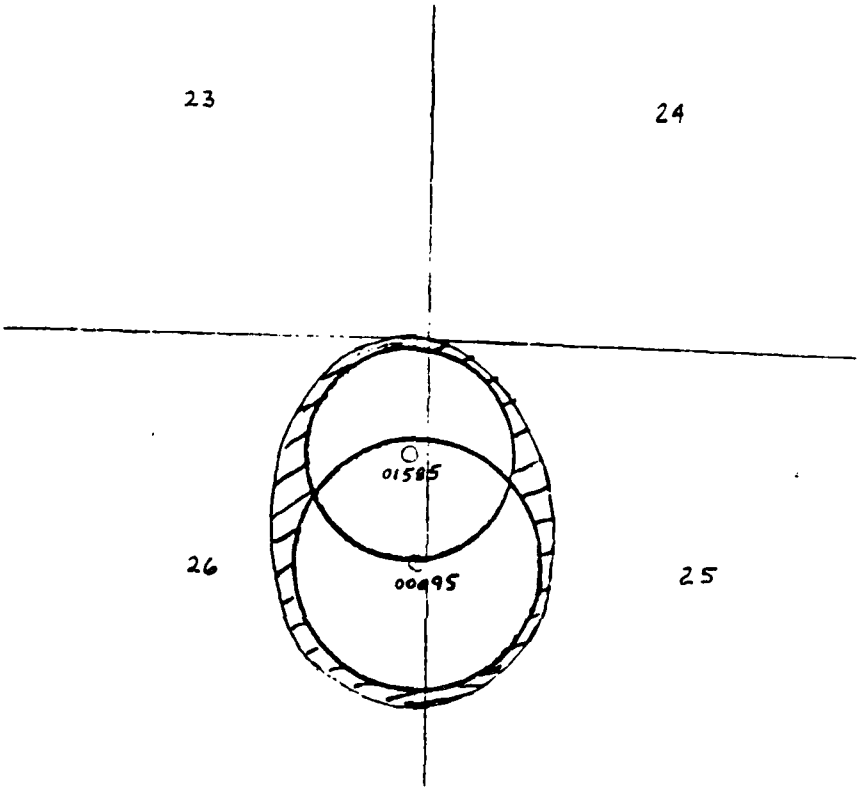

Figure 10: USGS Weekiwachee Springs Composite Zone

zone. For the Weekiwachee Springs example, all of the study objectives as defined appear to have been met.

The Crystal River example (Figure 11) was selected because of its embedded overlap structure. From this particular case, an interesting though not readily apparent aspect of the spatial model is demonstrated. Due to differential extension of the boundary points based on the distance function, the transformed distances from centroid to all vertices converge to the same value. Ultimately, if significant overlap exists, successive transformations produce a boundary comprised of points equally distant from the centroid. By definition then, the resulting composite protection zone is a circle centered on the overlap centroid. Convergence to a circle is evident in the Crystal River example. The manual (Figure 12) and computer-generated protection zones are almost indistinguishable for this particular situation. The resulting figure also meets the stated research objectives.

Figure 13 depicts a multiple overlap structure of wells located on the Chassahowitzka map sheet. During efforts to generate this particular composite protection zone, two shortcomings of the methodology were revealed. The problems encountered concerned the shortest distance value and total area requirement used for multiple overlap transformations.

A shortest distance (SDIST) value is determined for each centroid in the multiple overlap structure and input

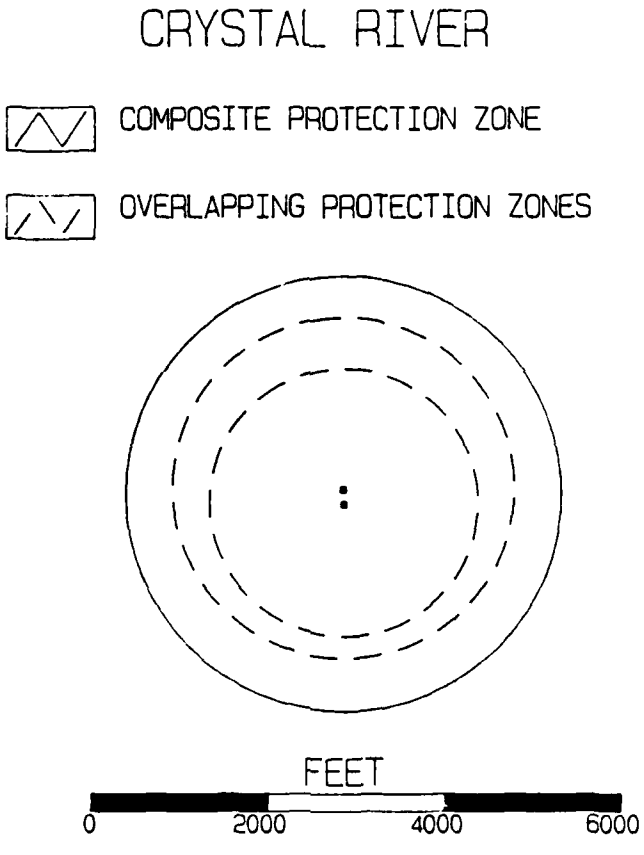

Figure 11: Crystal River Composite Zone

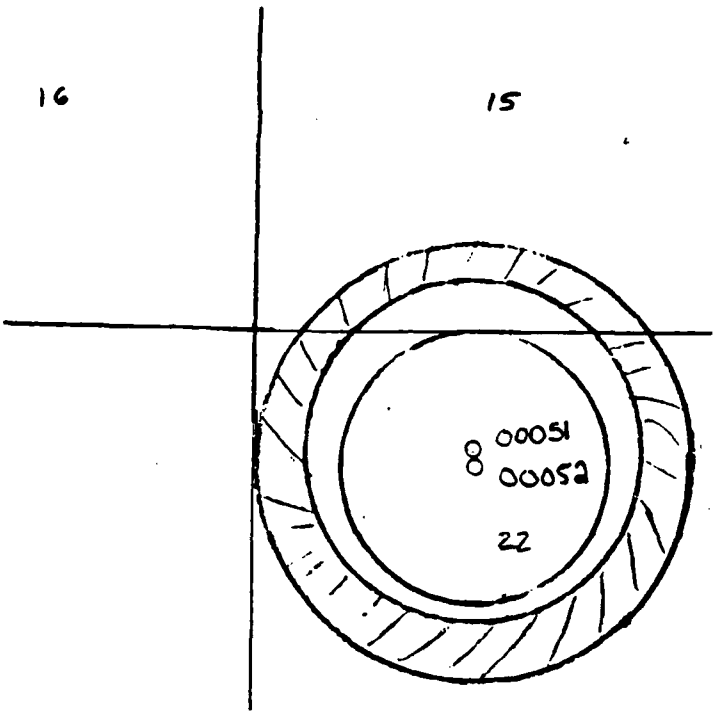

Figure 12: USGS Crystal River Composite Zone

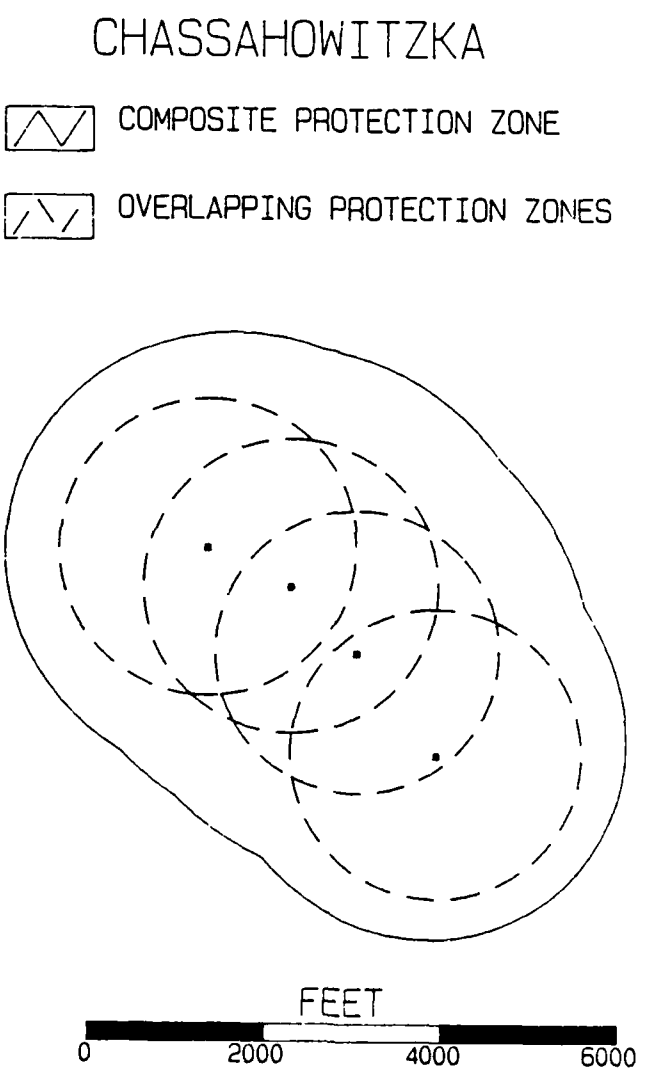

Figure 13: Chassahowitzka Composite Zone

via the parameter file. On the initial iteration from the first centroid in the parameter array, the system-determined shortest distance is properly used for the transformation. An updated SDIST is then calculated with respect to the new boundary and substituted into the parameter array. When the program advances to the second centroid, the transformation proceeds using the system-determined SDIST value obtained prior to any boundary extension. This results in a smaller than desired boundary extension increment for all coordinates, since the scaling factor (K) is calculated with an erroneously low SDIST value.

Even though the shortest distance is recalculated after transformation from its associated centroid, its value is not updated to reflect boundary changes effected by prior transformations. This is true for all coordinate processing which follows the initial transformation in a multiple overlap situation. The net result is a less than desired boundary extension for all but the first coordinate transformation.

The severity of this methodological error is difficult to determine with respect to effect on the resulting composite protection zone. Analysis of the problem seemed to suggest that the flaw was not overly critical. The worst-case possibility of any of the study figures is one in which five prior transformations extend the actual shortest

distance by a total of 50 feet (10 foot maximum increment times 5 transformations). The scaling factor calculated using 710 feet (the smallest system-determined SDIST), rather than 760 feet, would produce a maximum extension increment of 8.7 feet.

This worst-case scenario assumes that all of the transformations had the same centroid location. That is the only way possible for five boundary extensions to result in a 50-foot addition to the shortest distance of a sixth point. Although a single centroid location is a possibility, it seems very unlikely that such a situation might exist. Even if the centroid locations are slightly offset in a more realistic situation, the effect on the composite zone is believed to be minor. The expansion from several closely located origins results in a figure very similar to one generated based on transformation from any one of the individual centroids. The number of iterations will be increased because of the decreased maximum extension increment, but the final result will be nearly identical.

As the centroid locations become more distant from one another, the influence of prior transformations has less effect on the shortest distance values. Therefore, based on this analysis, the problem associated with the shortest distance values was not deemed to be a significant shortcoming of the study. Corrective actions for the problem are suggested in the following chapter.

The second problem, which surfaced during generation of the Chassahowitzka composite zone, was one previously described involving overlapping areas common to more than two individual protection zones. The method for summation of the paired overlap area with the union area resulted in a figure larger than the total area requirement. It was this problem that necessitated introduction of the compensation factor described in Chapter Six.

Once both obstacles to multiple overlap transformation were either dismissed as inconsequential or remedied, the Chassahowitzka figure was created. The composite zone generated was slightly more bulbous near the centroids than U.S. Geological Survey version (Figure 14). This seems plausible based on the distance function incorporated into the model. Even with that variation, the two composite zones were remarkably similar. The generated Chassahowitzka protection zone was also acceptable with respect to the study objectives.

Citrus Park 1 was another multiple overlap structure selected for protection zone generation (Figure 15). In this example, the well configuration is more complex than that in the previous case. Because of the additional complexity, the manual delineation technique would presumably be more difficult. Evidence of this is demonstrated by the significant differences found in the generated and manually created versions of the composite

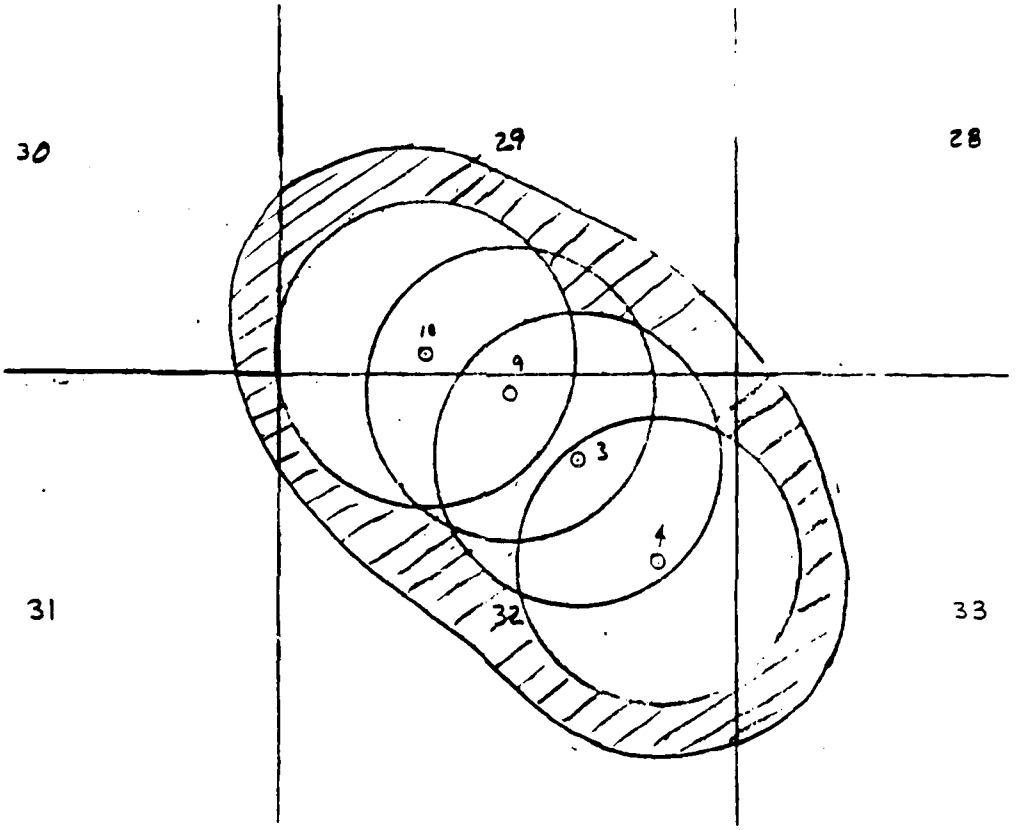

Figure 14: USGS Chassahowitzka Composite Zone

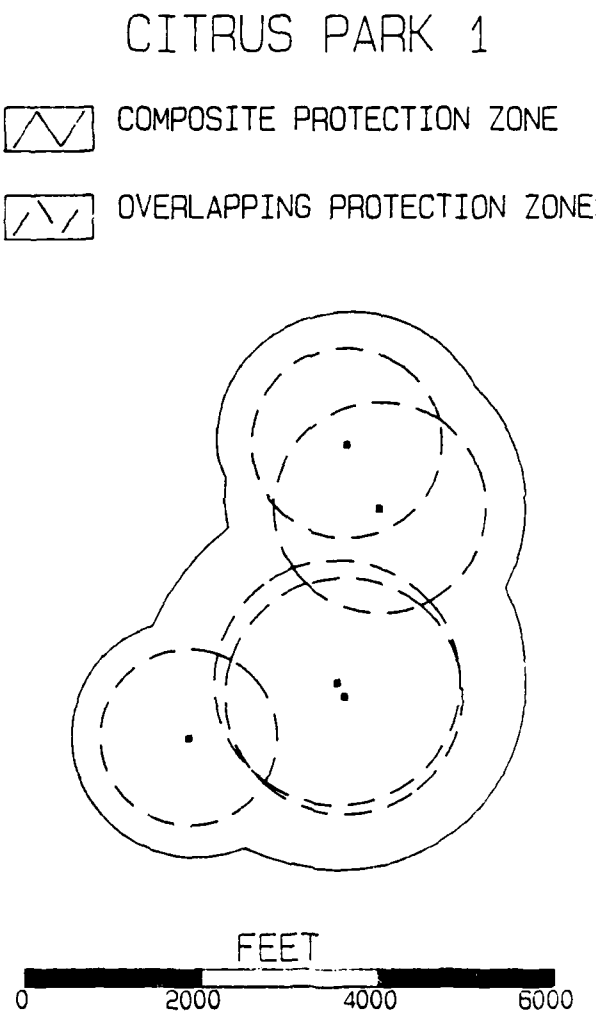

Figure 15: Citrus Park 1 Composite Zone

protection zones. The Geological Survey's composite zone (Figure 16) seemed to be constructed to yield a symmetrical figure. The transformed protection zone exhibits a more even distribution of overlap about the entire union figure. The tendency toward circular convergence is also evident in Figure 15, because of to the large areas of paired overlap involved. Like all previously discussed figures, the generated Citrus Park 1 composite protection zone adheres to the standards set in the study objectives.

Figure 17, Citrus Park 2, was selected as another unique multiple overlap example. Although the transformation-produced protection zone again displayed more even overlap distribution about the union figure, it greatly resembled its USGS counterpart (Figure 18).

Close examination of Figure 17 reveals the most serious flaw identified in the composite protection zone generation process. A point on the composite zone boundary was transformed to a location inside the union figure of the individual zones. This occurrence violates the fundamental study objective that the generated protection zone totally enclose all individual zones from which it is created. The flaw does not appear to cause drastic problems for the Citrus Park 2 configuration, but suggests the potential for more serious consequences in other situations.

The total enclosure problem was a completely unanticipated result of the research. This unforeseen

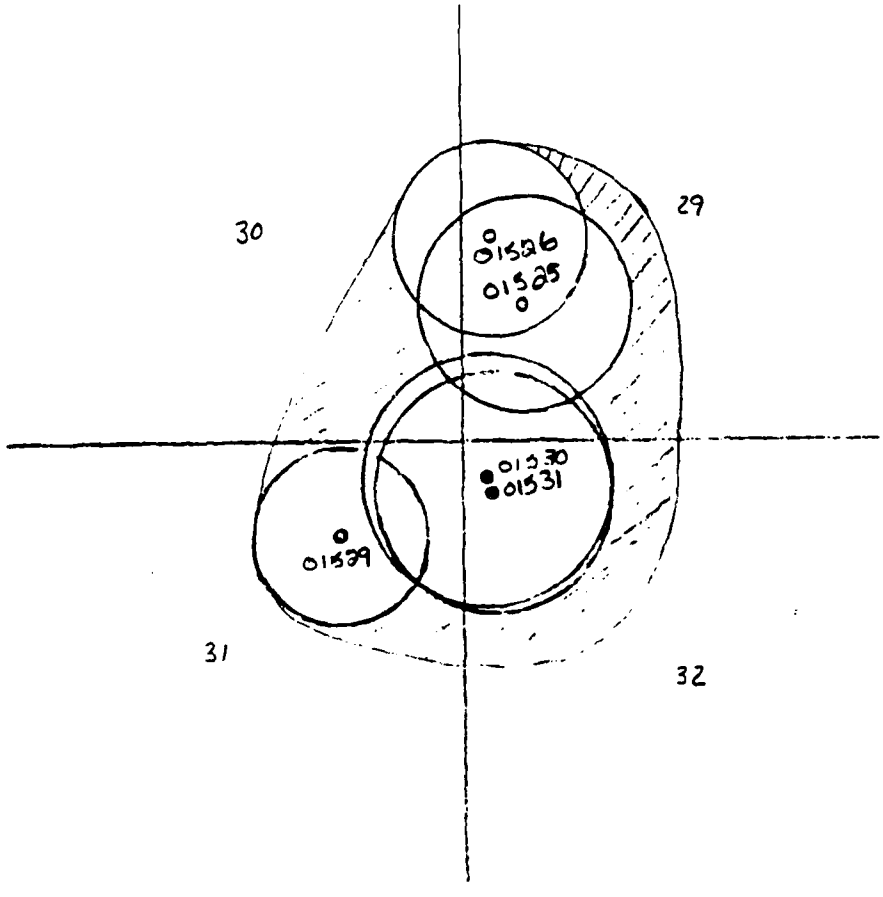

Figure 16: USGS Citrus Park 1 Composite Zone

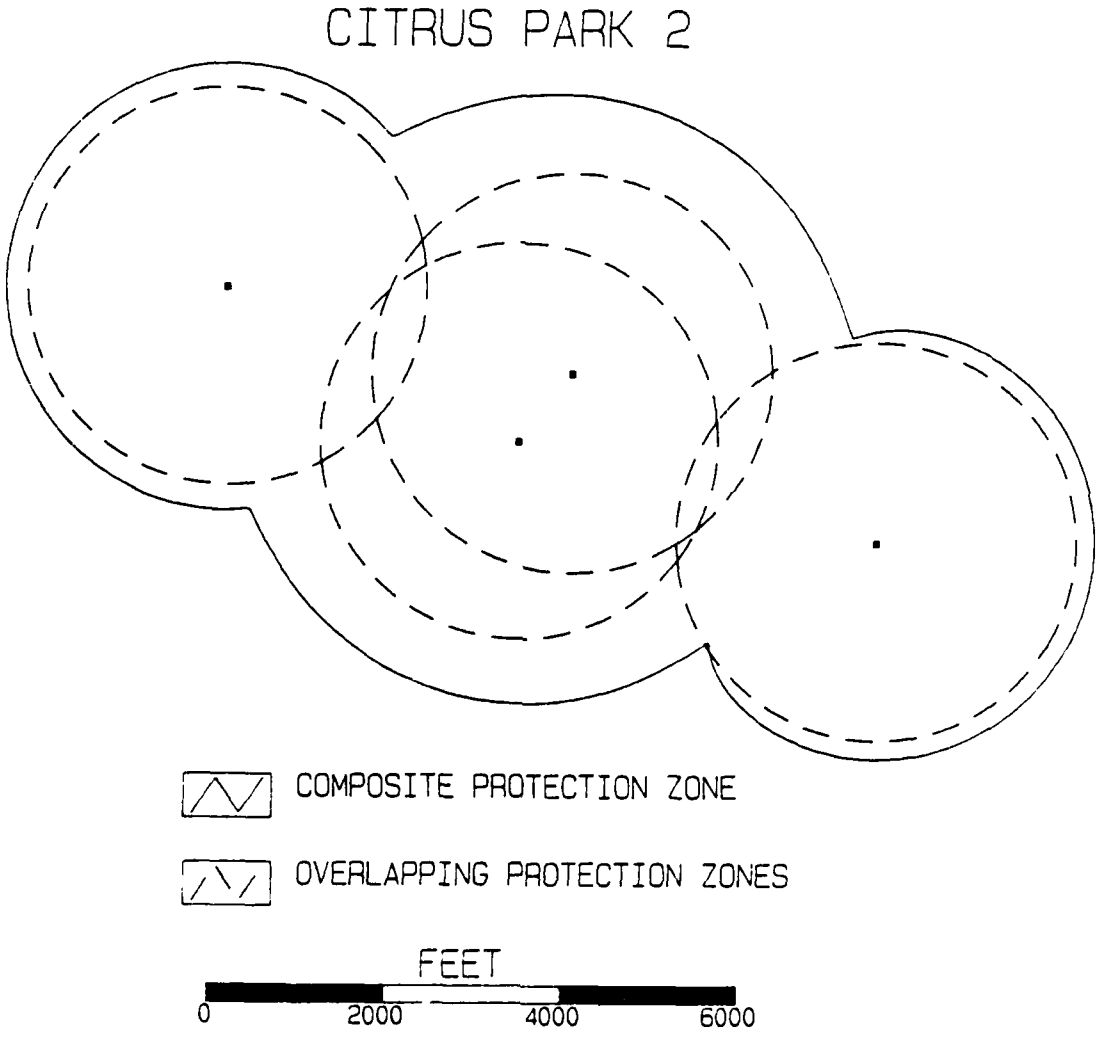

Figure 17: Citrus Park 2 Composite Zone

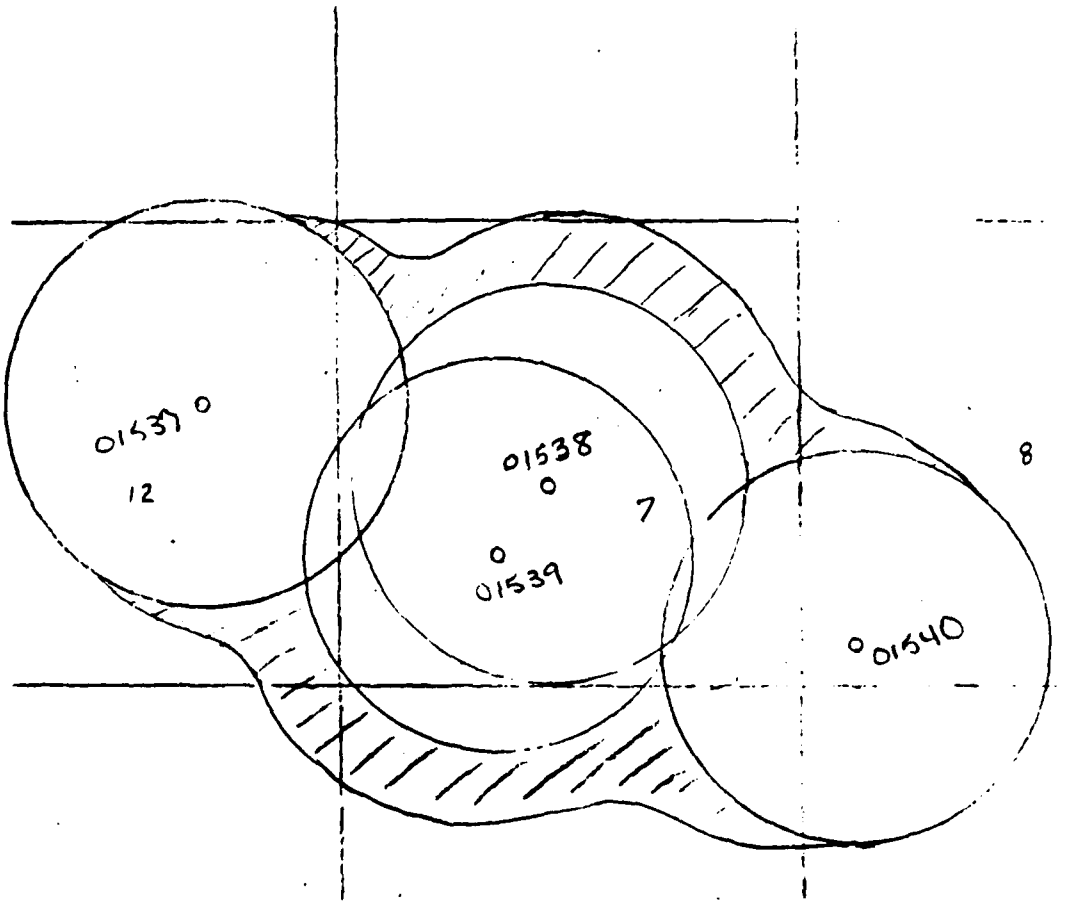

Figure 18: USGS Citrus Park 2 Composite Zone

possibility escaped detection as a result of the model development process. The model initially considered addressed a two-circle overlap condition. Boundary extension from the overlap centroid in the two-circle case would always result in a totally enclosed union figure. This fact was accepted as a given argument in the basic model. When expanded to consider multiple overlap structures, the argument was applied to the modified model and assumed valid for all configurations. A more in-depth review of the argument's applicability to multiple structures might have ascertained its lack of validity.

The problem depicted in Figure 17 seems to have been produced by transformation from the centroid located at the figure center. This particular centroid has a large associated overlap area requiring many transformations. Convergence to circular boundary expansion is demonstrated for the configuration. The numerous transformations effectively "force" the composite zone boundary inside of an individual protection zone.

The Port Richey example (Figure 19) was selected because of its perceived potential for producing a similar enclosure problem. The configuration did contain two relatively large overlap areas in close proximity with each other. Numerous expansions from the two centroids could possibly introduce the boundary enclosure problem.

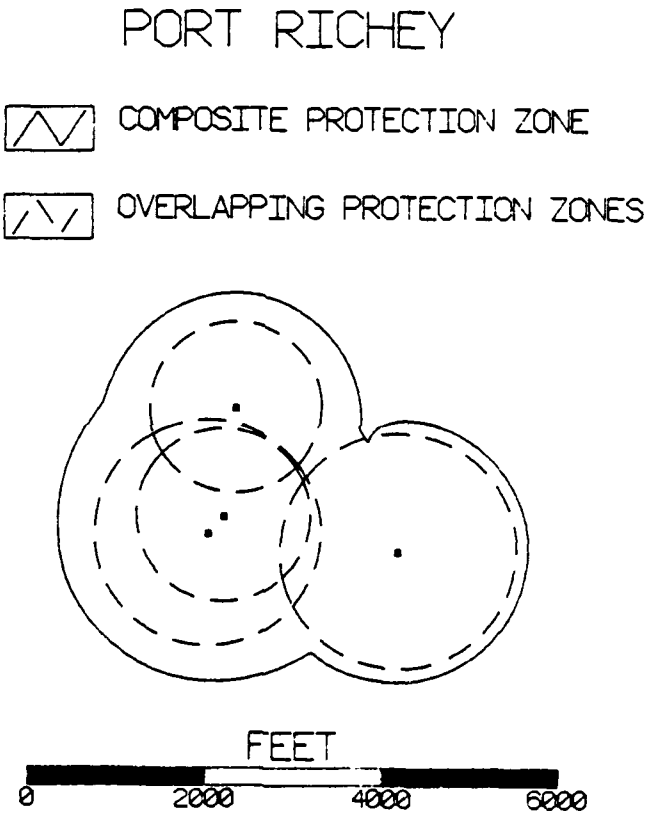

Figure 19: Port Richey Composite Zone

Even though the generated composite zone was very similar to the U.S. Geological Survey's version (Figure 20), the transformation did indeed locate composite boundary points inside an individual protection zone. The distance within the individual zone was small, but it resulted in a figure which fails to meet all of the study objectives. In addition, the problems associated with the last two generated figures discussed raise concerns about the applicability of the methodology to a number of multiple overlap structures.

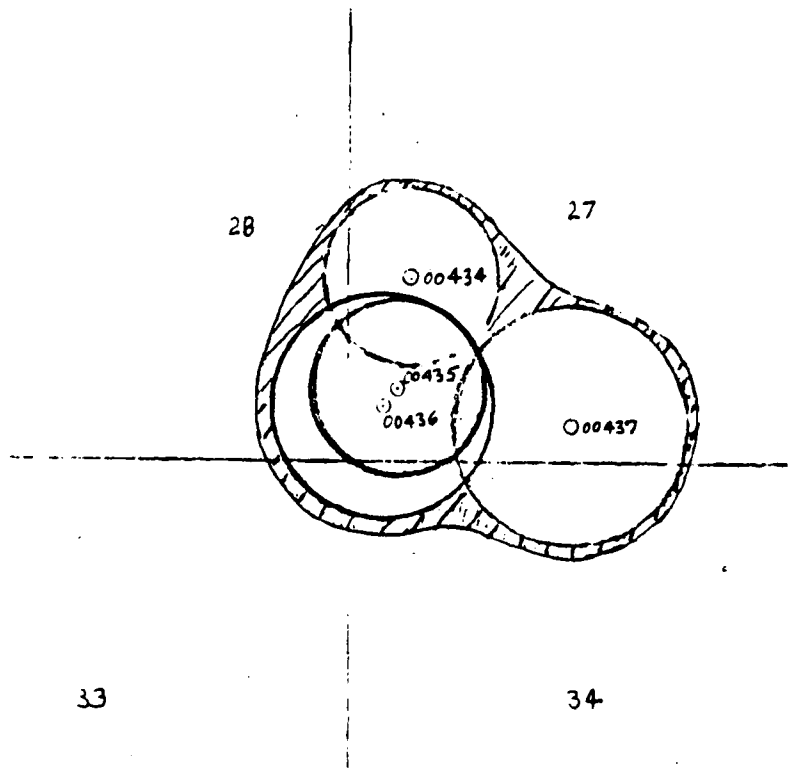

Figure 20: USGS Port Richey Composite Zone

CHAPTER EIGHT

CONCLUSIONS

The conclusions drawn from this study are presented in the two following sections. The first section is a discussion of the model's applicability to the problem of groundwater protection as well as other potential uses. Possible modifications of the methodology are also introduced. The second section provides a summary of the conclusions.

Applicability of the Model

For composite protection zone generation, the modeling process produced results which satisfied all of the objectives in four of the six examples. The simple cases involving only two wells with either lateral or embedded structures, provided pleasing results when compared with their manually created equivalents. In those cases where the figures differed, the computer-generated form is deemed to be a more reasonable representation of the composite zone, if only because of the formality of the generation procedure. It is believed that for any two-well overlap structure, the transformed composite zone is preferable to its manually delineated equivalent.

The boundary enclosure problem described earlier clouds the issue of the model's applicability for multiple overlap

structures. In two of the four multiple overlap examples, the resulting composite zone was totally acceptable in terms of the study objectives and figure appearance. Two other multiple overlap structures produced composite zones which did not totally enclose all individual protection zones involved in the configuration. Thus, the model's applicability requires verification on a case-by-case basis. Since an unspecified intention of the study was to develop a universally applicable model, additional research involving the model's modification is suggested.

Other potential areas exist for application of model. In any situation where *objects* are in *competition* for space, the model may have utility. Whether the spatial competition process involves biological, environmental, or economic phenomena, the proposed model may provide an acceptable research tool. As with the groundwater applications, consideration should be given to model modification when the process concerns more than two objects.

Possible Modifications

A number of modifications to the composite protection zone generation process are possible. The changes discussed are ones which would alleviate those problems which are considered to be merely annoyances as well as major flaws. Several alterations in the transformation program would result in extensive reduction in the time required to prepare the data inputs. Insertion of a subroutine to

calculate the intersection (overlap) area of the individual protection zones would eliminate a tedious portion of input preparation. The algorithm for the subroutine is not simple (Rosewell, 1986), but could easily be incorporated into the program.

A centroid determination subroutine might also be included in the program. Any one of a number of existing algorithms could be used. The result would be removal of the GIS centroid determination step from the input preparation procedures.

Another modification to the program concerns the shortest distance (SDIST) determination. As mentioned in Chapter Seven, the value of SDIST used during multiple overlap transformation is correct only for the first transformation. Since the subroutine for shortest distance calculation already exists in the transformation software, the problem can easily be corrected. Changing the order of the program's SDIST calculation to a point immediately prior to transformation processing, rather than following it, would eliminate the problem. The reordering of processing steps also reduces input preparation time, as a system-determined shortest distance value would no longer be required as input.

Each of the changes suggested to this point would have desirable effects on input preparation time and program operation. In fact, it is estimated that the maximum input

data preparation time required for any of the configurations addressed in this study, could be reduced from four hours to less than one. At the same time, program execution is not expected to exceed three minutes, a two-minute increase over the unmodified execution time. The modifications do decrease reliance on GIS-supplied capabilities, since they would be written into the program. This contradicts the previously stated intention to utilize routine spatial functions available within the system. However, the cumbersome, time-consuming nature of GIS function use dictates that the modifications be incorporated into the program and that system reliance be reduced.

Another modification should be included to enhance the program integrity concerning the compensation factor. Recall that the factor is applied to each paired overlap area when a configuration contains three or more individual protection zones which intersect the same area. It serves as a correction to the total area requirement determined by adding the summed overlap areas tc the area of the union. It is the intersection areas common to more than two individual zones which produce the summation problem. Therefore, areas comprised exclusively of two-zone overlap should not be reduced by the compensation factor.

It is unclear as to which is the best method of handling the problem. One possibility is to consider each overlap occurrence based on the number of individual zones

which intersect to form an overlap area. This would eliminate the lens-shaped polygon of paired overlap as the only possibility considered. The multiple intersection polygons could have very irregular shapes. As noted, experience with the system indicates that the GIS centroid calculation routine may not prove satisfactory for such configurations. Since an improved centroid calculation routine was suggested for an earlier modification, the system's shortcoming is not viewed as a problem.

The result of this change is that each polygon formed by overlaying all individual zones is treated as a separate transformation entity. Knowledge of the location of its centroid, its area, and the number of individual zones which intersect to form it is required for transformation. The area added from a particular centroid during transformation would be based on the number of zones which intersected to form the associated overlap polygon. An area equivalent to that of the polygon is added for two-zone intersection. The intersection of three, four, or five individual protection zones requires addition of two, three, and four times the intersection polygon area respectively. Comparison of figures generated using a program incorporating this modification with those produced by the existing transformation would provide for interesting research.

One additional modeling error also mandates program modification. The boundary enclosure problem, considered to

be a major program flaw, necessitates refinement of the model to accommodate all possible structures. Unfortunately, an acceptable approach to solving the enclosure dilemma has not been devised. Extended research into the problem is required. It is believed that with such efforts, the program could potentially be made applicable to any and all overlap structures.

Summary

The spatial model and its associated transformation program appear to provide an acceptable approach to defining composite groundwater protection zones for simpler overlap structures. In addition, application of the model to analogous spatial processes is entirely feasible. Two-object competition for space can be modeled using the program if the competitive process adheres to the assumptions and arguments specified.

A number of modifications are also possible for the program. Several of the changes would greatly reduce the time required to prepare the inputs for the transformation process. Other program alterations are recommended to increase transformation integrity and applicability. The changes in the shortest distance determination and compensation factor application would result in a program which is more consistent with study objectives.

The most severe flaw associated with the model is the boundary enclosure problem. The problem affected the

applicability of the model to some multiple overlap structures. Although program modifications are suggested, the specific changes required to produce universal applicability in multiple overlap situations are absent. Additional research concerning the model and transformation process is necessary before specific changes can be cited. However, acceptability of the existing program for use on multiple structures can be evaluated on an individual basis.

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APPENDIX A

```
C *** PROGRAM TO GENERATE COMPOSITE PROTECTION ZONES ***
C
C ***VARIABLE DECLARATION ***
C
      CHARACTER PARMF*20,INBND*20,OUTBND*20
      INTEGER NVERT,NEXT(50),J,ITER
      DOUBLE PRECISION XCENT(50),YCENT(50),SDIST(50),OVRLAP(50)
      DOUBLE PRECISION TAREA,AREA,SUBTRT,XIN(2000),YIN(2000)
      DOUBLE PRECISION ADDIST(50),RQAREA,OVRSUM
C
C *** INTERACTIVE  INPUTS ***
C
      WRITE(1,*) 'ENTER PARAMETER FILE'
      READ(1,30) PARMF
      WRITE(1,*) 'ENTER INITIAL FIGURE AREA'
      READ(1,25) TAREA
      WRITE(1,*) 'ENTER TOTAL AREA REQUIRED'
      READ(1,25) RQAREA
      WRITE(1,*) 'ENTER BOUNDARY FILE'
      READ(1,30) INBND
      WRITE(1,*) 'ENTER OUTPUT FILE'
      READ(1,30) OUTBND
C
C *** OPENS INPUT FILES ***
C
      OPEN(8,FILE=PARMF,STATUS='OLD',ERR=999)
      OPEN(9,FILE=INBND,STATUS='OLD',ERR=999)
      OPEN(10,FILE=OUTBND,STATUS='NEW',ERR=777)
C
C  *** READ PARAMETER FILE INTO ARRAY ***
C
      DO 10 K = 1,50
        READ (8,70,END=15) XCENT(K),YCENT(K),SDIST(K),OVRLAP(K),
     $     ADDIST(K)
        NEXT(K) = 1
10    CONTINUE
C
15    NCENT = K - 1
      WRITE (1,*) 'NCENT =',NCENT
C
C*** LOOP TO SUM OVERLAP AREAS ***
      OVRSUM = 0.0
      DO 90 K = 1,NCENT
         OVRSUM = OVRSUM + OVRLAP(K)
90    CONTINUE
C
```

APPENDIX A

```
C *** MULTIPLE OVERLAP COMPENSATION FACTOR ***
      DO 75 K = 1,NCENT
         OVRLAP(K) = OVRLAP(K) *(RQAREA - TAREA) / OVRSUM
75    CONTINUE
C
C *** READ INPUT COORDS INTO ARRAY ***
C
      DO 40 I = 1,2000
        READ (9,20,END=45) XIN(I),YIN(I)
40    CONTINUE
C
C *** CALCULATE NUMBER OF COORD PAIRS ***
45    NVERT = I - 1
      WRITE (1,*) 'EXIT COORDS ARRAY, NVERT =',NVERT
C
C ***  LOOP TO TRANSFORM FROM EACH CENTROID WITH OVERLAP REMAINING
***
C
      ITER = 0
100   DO 55 J = 1,NCENT
        IF (NEXT(J) .EQ. 0) THEN
           GOTO 55
        ENDIF
C
      ITER = ITER + 1
C
C *** CALL COORDINATE TRANSFORMATION SUBROUTINE ***
C
      CALL TRANS(ADDIST,SDIST,NVERT,XIN,YIN,XCENT,YCENT,J)
C
C *** CALL AREA CALCULATING SUBROUTINE ***
C
      CALL CALCAR(XIN,YIN,NVERT,AREA)
C
C *** UPDATE OVERLAP REMAINING AFTER TRANSFORMATION ***
      SUBTRT = AREA - TAREA
      WRITE (1,*) 'AREA =',AREA
      OVRLAP(J) = OVRLAP(J) - SUBTRT
      TAREA = AREA
C
C *** SET FLAG TO SKIP CENTROID WHEN OVERLAP ACCOUNTED FOR ***
C
      IF (OVRLAP(J) .LE. 0) THEN
         NEXT(J) = 0
          WRITE (1,*) 'OVERLAP',J,'= ZERO'
      ENDIF
```

APPENDIX A

```
55      CONTINUE
C
C *** LOOP TO CHECK IF ALL OVERLAP IS ACCOUNTED FOR AT ALL
CENTROIDS
C
        DO 60 L = 1,NCENT
           IF (NEXT(L) .EQ. 1) THEN
              GOTO 100
           ENDIF
60      CONTINUE
C
C *** WRITE FINAL TRANSFORMED COORDS FROM ARRAY TO OUTPUT FILE ***
        DO 80 I = 1,NVERT
           WRITE (10,20) XIN(I),YIN(I)
80      CONTINUE
C
        WRITE (1,*) 'NUMBER OF ITERATIONS',ITER
C
C *** FORMAT FOR PARAMETER FILE ***
70      FORMAT (5(2X,F6.3))
C
C *** FORMAT FOR INITIAL FIGURE AREA ***
25      FORMAT (F6.3)
C
C *** FORMAT FOR INPUT AND OUTPUT COORDS FILES ***
20      FORMAT (2(6X,F9.6))
C
C *** FORMAT FOR INTERACTIVE INPUT FILE NAMES ***
30      FORMAT (A20)
C
C *** CLOSE ALL FILES ***
        CLOSE (8)
        CLOSE (9)
        CLOSE (10)
C
        GOTO 1000
C
C *** FILE OPENING MESSAGES ***
999     WRITE (6,*) 'ERROR IN OPENING INPUT FILES'
777     WRITE (6,*) 'ERROR IN OPENING OUTPUT FILE'
1000    STOP
        END
C
C
C *** SUBROUTINE TO TRANSFORM COORDINATES ***
C
```

APPENDIX A

```
      SUBROUTINE TRANS (ADDIST,SDIST,NVERT,XIN,YIN,XCENT,YCENT,J)
C
      DOUBLE PRECISION
KFACT,SHORT,SLOPE,INTERC,A,B,NEWDIS,XOUT,YOUT
      DOUBLE PRECISION ADDIST(50),SDIST(50),XCENT(50),YCENT(50)
      DOUBLE PRECISION XIN(2000),YIN(2000)
      INTEGER NVERT,J
C
C *** CALCULATES EXPANSION FACTOR ***
C
      KFACT=ADDIST(J)*SDIST(J)**2
C
C *** INITIALIZE SHORT TO A LARGE VALUE ***
C
      SHORT=100.0
C
C *** EXECUTE COORDINATE TRANSFORMATION LOOP ***
C
      DO 50 M=1,NVERT
C
C *** CALCULATE SLOPE OF LINE BETWEEN INPUT COORD AND CENTROID ***
      SLOPE=(YIN(M)-YCENT(J))/(XIN(M)-XCENT(J))
C
C *** CALCULATE INTERCEPT OF LINE ***
      INTERC=YCENT(J)-SLOPE*XCENT(J)
C
C *** CALCULATE DISTANCE**2 BETWEEN INPUT COORD AND CENTROID ***
      A=(XIN(M)-XCENT(J))**2+(YIN(M)-YCENT(J))**2
C
C *** CALCULATE EXTENDED DISTANCE ***
      NEWDIS=SQRT(A)+KFACT/A
C
C *** SAVES SMALLEST NEWDIST INTO SHORT TO UPDATE PARAMETERS ***
      IF (NEWDIS .LT. SHORT) THEN
         SHORT=NEWDIS
      ENDIF
C
C *** MAKES NEWDIS NEGATIVE FOR XIN VALUE TO LEFT OF XCENT ***
      IF (XCENT(J) .GT. XIN(M)) THEN
         NEWDIS=-1.0*NEWDIS
      ENDIF
C
C *** CALCULATES DERIVED TRANSFORM FACTOR ***
      B = SLOPE**2 + 1.0
C
```

APPENDIX A

```
C *** CALCULATES OUTPUT COORDS FROM TRANSFORMATION ***
      XOUT=NEWDIS / SQRT(B)+XCENT(J)
      YOUT=INTERC+SLOPE*XOUT
C
C *** WRITE OUTPUT COORDS TO COORD ARRAY ***
      XIN(M) = XOUT
      YIN(M) = YOUT
C
50    CONTINUE
C
C *** SETS SDIST TO SMALLEST NEWDIST AND UPDATES PARAMETER ARRAY
***
25    SDIST(J)=SHORT
C
      RETURN
      END
C
C *** SUBROUTINE TO CALCULATE AREA ***
C
      SUBROUTINE CALCAR (XIN,YIN,NVERT,AREA)
C
C *** VARIABLE DECLARATION AND INTIALIZATION ***
      DOUBLE PRECISION XIN(2000),YIN(2000),AREA
      REAL XOLD,YOLD,YORIG,X,Y
      AREA=0.0
      XOLD=XIN(NVERT)
      YORIG=YIN(NVERT)
      YOLD=0.0
C
C *** LOOP TO REPEAT FOR EACH COORD PAIR ***
      DO 60 N=1,NVERT
        X=XIN(N)
        Y=YIN(N)-YORIG
        AREA=AREA+(XOLD-X)*(YOLD+Y)
        XOLD=X
        YOLD=Y
60    CONTINUE
C
      AREA=ABS(0.5*AREA)
      RETURN
      END
```