FEATURES

A Comparison of Wellhead Protection Area Delineation Methods for Public Drinking Water Systems in Whatcom County, Washington

Chris Miller, M.S., R.E.H.S.
Paul Chudek, R.S.
Scott Babcock, Ph.D.

Abstract

Groundwater protection is a critical issue on a global scale. A relatively recent strategy for reducing the potential for contamination has been to establish wellhead protection areas on the land surface above aquifers. One method of delineating groundwater flow around public supply wells is the calculated-fixed-radius (CFR) method. The purpose of this study was, with a geographic information system (GIS), to create spatial-data overlays based on CFRs and to compare the areas captured with the results of more complex methods (i.e., analytical methods, hydrogeologic mapping, and numerical flow/transport models).

The overlays showed that as distance from the well decreased, the areas captured by the CFRs became more similar to those captured by the noncircular (more complex) methods. In the one-year overlay, only 20 percent of the noncircular areas were not captured by the CFR method, while 42 percent were not captured in the 10-year overlay. The one-year CFR had a 57 percent overcapture area outside the noncircular area, while the 10-year overcapture was very high, at 75 percent.

Study results indicate that local health departments can successfully incorporate both existing formal wellhead protection areas and CFRs into various land use permitting processes, with emphasis placed on six-month and one-year time-of-travel areas. Where time, money, and personnel are limited, the CFR method is an effective starting point for improved protection of groundwater quality.

Introduction

Wellhead Protection Areas—Defined

A wellhead protection area (WHPA) is defined as the land surface that lies directly over and recharges the aquifer that contributes water to the well. Under normal pumping conditions, this area is also known as the zone of contribution. Recharge zones also are known as "capture areas." A capture area defines a surface beneath which infiltrated water will be "captured" by a well or well field. When a time-of-travel (TOT) criterion is applied to capture areas, a time-related capture area is defined. This capture area is delineated as an area surrounding the well (Hansen, 1991).

It has been found that "designating wellhead protection areas around public water supply wells provides one of the best ways to protect groundwater supply systems from possible contamination, because the emphasis has shifted toward the protection of groundwater supplies rather than the regulation of potential contamination threats" (Texas Water Commission and Texas Department of Health, 1990).

Governmental Agency Involvement and Public Health

For years, state agencies across the United States have been adopting wellhead protection programs. The focus of many of these programs has been to protect water supplies by delineating and recognizing the area contributing recharge to the water supply wells so that land use decisions can be made accordingly. Often, these programs are used locally to specify regulations in order to minimize contamination of the recharge water by various land surface activities (Reilly & Pollock, 1996).

Section 1428 of the 1986 Amendments to the Federal Safe Drinking Water Act states that all federally defined Group A public water systems using groundwater as their sources are required to complete a wellhead protection plan. A wellhead protection area is one component of such a plan.

Methods of Delineating Wellhead Protection Areas

Several methods of delineating wellhead protection areas around public supply wells can serve as the first step in safeguarding against chemical and microbial contamination of groundwater (Hansen, 1991). Those methods, from least to most costly and complex, are as follows:

1. calculated-fixed-radius (CFR) method,
2. analytical models,
3. hydrogeologic mapping methods, and
4. numerical flow/transport models.

Public water systems have employed each of the four methods. The numerical and analytical models more closely reflect actual hydrologic conditions than does the CFR method because they allow for water table and variations in hydraulic conductivity (Hansen, 1991). The numerical/transport model is the most credible method, but others can be more cost-efficient and yield similar results where flow rates are constant and flow paths are simple (Hansen, 1991).

Choosing the appropriate method requires specific procedures that take into account the amount of hydrogeologic data, the complexity of the hydrogeology, the funding available, and the required accuracy of the results (Rifai, Hendricks, Kilborn, & Bedient, 1993). Comparative research into the various flow models using the one-year capture areas for each method (Bogue, 1994) has shown that the numerical model most accurately represents the flow system. On the other hand, the semi-analytical and analytical models seem to perform adequately in delineating wellhead capture areas. It is important to remember that the analytical method requires less time, expense, and effort than the numerical method, but that the analytical methods cannot be upgraded and improved as additional data are gathered.

Studies show that the standard 100-foot area for well protection used by many local health departments often underestimates the up-gradient flow of groundwater to the pumped well (Landemeyer, 1994). An overestimation of the contributing land area could lead to the establishment of a wellhead protection plan that involves the management of excessive time-of-travel (TOT) boundaries, ultimately wasting important

FIGURE 1

Noncircular Wellhead Protection Areas (Numerical Model) for the City of Sumas, Washington

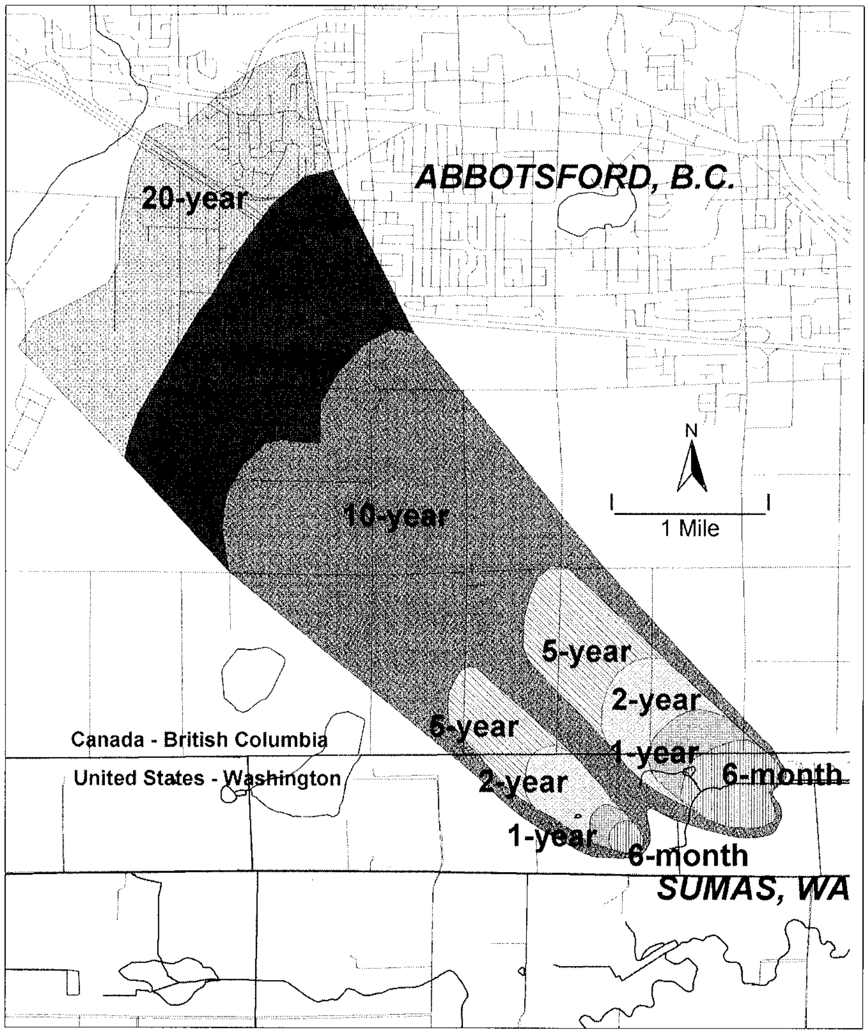


TABLE 1

Annual Pumped Volumes* and Time-of-Travel Radii

Annual Volume Pumped (gallons)	Time-of-Travel (feet) 6-Month Radius	1-Year Radius	5-Year Radius	10-Year Radius
≤5,000,000	220	310	700	980
10,000,000	310	440	980	1,390
20,000,000	440	620	1,390	1,970
50,000,000	700	980	2,200	3,110
100,000,000	980	1,390	3,110	4,400
250,000,000	1,550	2,200	4,920	6,950
500,000,000	2,200	3,110	6,950	9,830

* All calculations assumed a screened interval of 10 feet.

TABLE 2

Portion of Database Displaying Data for Water Systems

Public Water System	Group	Total Connections	Total Gallons per Year	Calculated Fixed Radius (in feet) 1-Year	5-Year	10-Year	GPS Point Location Data (in Decimal Degrees) Easting	Northing
Glenhaven Lakes	A	561	40,953,000	980	2,200	3,110	549707.9	389044.7
Gooseberry Point	A	134	9,782,000	440	980	1,390	524659.1	397901.1
Ridge Water Association	B	5	730,000	310	700	980	522847.4	395699.7
Grandview Beach	A	16	2,336,000	310	700	980	515796.0	414711.3
Vande Kamp Water	B	6	876,000	310	700	980	547354.0	412021.0

time and money in the identification and regulation of potential contaminants (Bogue, 1994).

Lack of a comprehensive wellhead protection program has led to critical problems for various states throughout the country. At one point, according to Noake (1989), "Over forty municipalities in Massachusetts had lost all or part of their municipal groundwater supplies to chemical and bacteriological contamination due to the citing of inappropriate land uses in the primary recharge areas of their public supply wells."

In Whatcom County, Washington, it was determined that it was important to conduct a comparative analysis of methods used for the delineation of wellhead areas before organizing a wellhead protection program. The comparative analysis would enable the county to note the differences between simple and sophisticated methods—potentially finding that the sophisticated methods are not worth the cost, as when the geology is homogeneous (Cleary & Cleary, 1991).

The operating hypothesis for this study was that as distance from the well decreases, the volumetric CFR method for delineating groundwater flow around a public supply well captures land areas increasingly similar to those found by more complex methods of groundwater mapping. This hypothesis was based on area-by-area GIS time-of-travel comparisons. In other words, the CFR method may provide protection similar to that provided by more complex groundwater mapping methods for wells in the land areas that are most likely to affect groundwater quality (i.e., land areas closer to the well). Confirmation of the hypothesis would validate the CFR method as a simple but valid method of delineating a wellhead protection area.

Paper maps have been the most common form of map delineation and representation for coordinate-based wellhead protection areas. The small amounts of data provided by maps and the inability to determine complex relationships have become a problem for recognition of wellhead protection areas (WHPAs) (Marble, 1987). Furthermore, these cumbersome maps are a time-consuming form of data maintenance and storage.

Previous WHPA comparison research indicates that it is important to see how well more complex delineation methods compare with the numerical-modeling method since the latter method is generally considered the most accurate way of delineating groundwater flow (Bogue, 1994). Land use, hydrologic, geologic, and contamination source data were required to assess the risk to groundwater quality in wellhead protection areas of Whatcom County. As has been noted in other studies, base maps do not provide these data with similar accuracy or at the same scale. Furthermore, the data may lack geographically similar attributes (Olimpio, Flynn, Tso, & Steeves, 1990).

Through the development of a geographic information system, these data have been linked with existing electronic land use planning and related spatial groundwater models. This organized electronic system will allow state and local health, planning, water resources, public water system, emergency response, and water utility managers to use the data layers for technically reliable groundwater-related programs (Moore, 1993). It will also allow local and state agencies to quickly retrieve and review wellhead protection areas when considering various land use and emergency decisions.

Methods

Initial Public Water System Data

The authors initiated data collection by obtaining a public water system database for Whatcom County (for June 1999). Since groundwater sources were the main focus of this study, all systems that were inactive, that used surface water, or that purchased water from another system were deleted from the database.

Initial fieldwork recorded the positions of all Whatcom County public water system sources (wellheads, springs, and surface-water sources) using a Trimble GeoExplorer II GPS. All positions were differentially corrected via Pathfinder Office software through local Internet base stations for ±10-foot accuracy. Over 410 (Group A and Group B) sources were located (some systems have multiple sources).

Following differential correction, the GPS point data were imported into a GIS (ArcView GIS, Version 3.2a), and a full county map was created. In order to work with existing county mapping data, the authors recorded GIS coverage on the Universal Transverse Mercator (UTM) grid, Zone 10 Projection with a –5,000,000 shift in the *y*-axis (North American Datum of 1927).

Initial Wellhead Protection Area Data

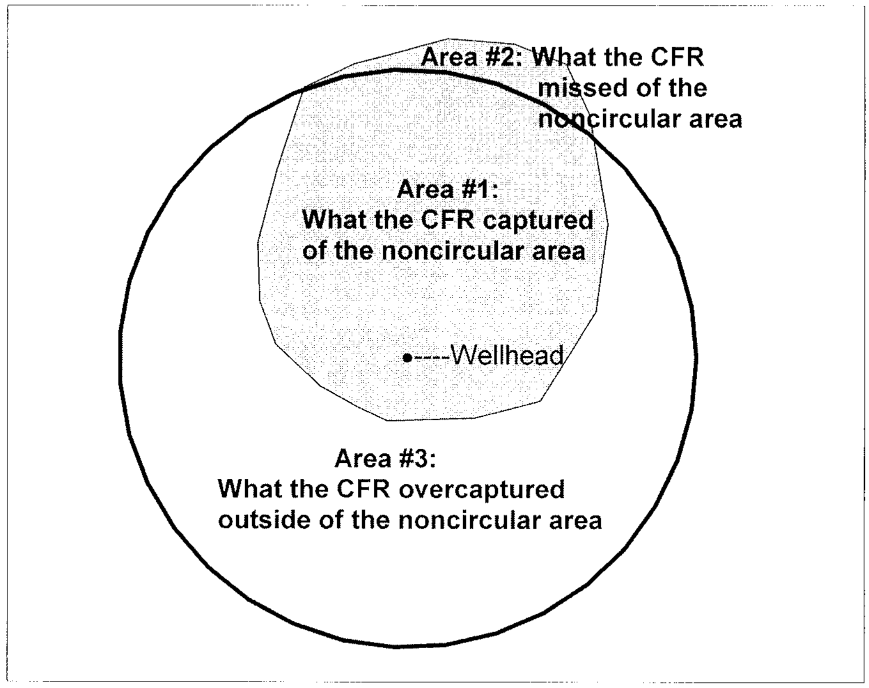
Current wellhead protection area data for Whatcom County, either in paper or electronic form, were not available in an organized fashion. A June 2000 database was obtained from the Washington State Department of Health listing the total service connections for each system. The system files were sorted to ascertain which systems might have an approved plan. Next, a database of the 50 largest public water systems (June 2000), based on total service connections, was created; again, the authors made sure to eliminate systems that did not have a groundwater source. Plans and maps were located and compiled for systems that had a wellhead protection area accepted by the Washington State Department of Health (WSDOH).

Map Digitizing and Current Electronic Wellhead Protection Area Data

Each engineer or hydrogeologist who had completed a wellhead protection plan was contacted for possible electronic data. The digitizing for all remaining WHPA paper maps (a majority of the maps) was accomplished by "heads-up" editing on the screen with a mouse using absolute coordinates via information such as source GPS points, section lines, hydrology, and street data. Figure 1 shows the multiple wellhead protection areas for the city of Sumas water system. This system is unique because the majority of its protection areas (six-month and one-, two-, five-, 10-, 15-, and 20-year areas) cover territory in a province of another country—British Columbia, Canada.

FIGURE 2

Example of a Graphical Display (One-Year Time of Travel only) of the Three Areas Used to Calculate the Effectiveness of the CFR Method



Area 1 + Area 2 = x; Area 1/x = percentage captured.
Area 1 + Area 2 = x; Area 2/x = percentage not captured.
Area 1 + Area 3 = x; Area 3/x = percentage overcaptured.
Note: The best CFR has the highest percentage captured, the lowest percentage not captured, and the lowest percentage overcaptured.

Calculating CFRs and Time-of-Travel Comparisons

For all sources countywide, the authors created wellhead protection areas by using the volumetric-flow equation of the calculated-fixed-radius model (U.S. Environmental Protection Agency, 1987). The CFR model used in this study is based on one-, five-, and 10-year time-of-travel criteria so as to determine the outer boundary of the contributing areas. Because of the simplicity of the CFR method, WSDOH recommends that it be used for moderate or smaller systems (Jennings, 1995). The majority of the water systems in Whatcom County are either moderate or smaller in size.

WSDOH considers 400 gallons per day per connection to be an average rate of consumption. This study assumed the WSDOH-recommended default screened interval of 10 feet (a screened interval is the length of metal or plastic slotted tube used to maintain a well opening in unconsolidated aquifer formations and to admit water being pumped from the aquifer) (Jennings, 1995). Since annual volume pumped was required to select the appropriate radius in feet, the following formula was used for the calculations:

Annual volume pumped =
\# of water system service connections
× 400 gallons per day per connection
× average days per year (365 days)

The resulting calculations allow one to select the travel-time areas listed in Table 1. A spreadsheet was created that calculated the annual volume pumped per system (based on the equation above) and, on the basis of these values, estimated the one-, five-, and 10-year time of travel radii (Table 1). These data were joined with the existing GPS data and brought into a GIS. The total gallons per year for each system and the one-, five- and 10-year radii, in feet, were recorded in a CFR database. Using June 2000 total service connections data separately for each system, the CFRs for all systems in Whatcom County (excluding inactive and surface water systems) were calculated. All public water system point positions were buffered with these new radii. Table 2 shows a small portion of the database created with these new buffers.

Further steps were taken to create even more realistic CFR areas for the time-of-travel area comparisons. If a system had more than one well in the same area, or well field, the total gallons per year were either

1. combined for that area to create one calculated fixed radius, including all wells, or
2. evenly divided by the number of wells (utilizing the values given in Table 1 to define the radii) so that the methods could be compared.

For example, the city of Blaine has two westerly wells in which the 10-year TOTs coalesce. The two CFRs that were calculated were combined into a single area.

GIS Polygons and Data Overlay Methods

A data-overlay approach was used to analyze these data. CFR areas were compared in the GIS to the analytical areas on a time-of-

TABLE 3

GIS Overlay Results for One-Year Wellhead Protection Areas

Public Water System	NC	NC Outside CFR	CFR Outside NC	Shared Area	% Captured	% Not Captured	% Over-captured
Blaine, city of (west well)	20.7	0	48.2	20.7	100.0%	0.0%	70.0%
2nd well going east	62.55	4.48	10.82	58.07	92.8%	7.2%	15.7%
3rd well going east	31.02	9.12	5.67	21.9	70.6%	29.4%	20.6%
4th (wellfield)	251.3	19.01	114.95	232.2	92.4%	7.6%	33.1%
Custer, W.A.	11.21	2	14.27	9.29	82.3%	17.7%	60.6%
Deer Creek, W.A.	60.76	45.77	54.49	14.99	24.7%	75.3%	78.4%
Everson, city of	91.97	20.54	67.17	71.43	77.7%	22.3%	48.5%
Glenhaven Lakes Club	14.37	0	54.53	14.37	100.0%	0.0%	79.1%
Hemmi Road, W.A.	19.22	11.17	5.84	8.05	41.9%	58.1%	42.0%
Joe Louie, W.A.	15.5	0.02	53.41	15.48	99.9%	0.1%	77.5%
Pole Road, W.A.—W. Guide	14.6	0	12.97	14.6	100.0%	0.0%	47.0%
Pole Road, W.A.—E. Guide	60.77	14.46	92.29	46.31	76.2%	23.8%	66.6%
Sandy Point Improvement Co.	34.38	0.21	34.73	34.17	99.4%	0.6%	50.4%
Sumas Water Dept.	203.9	159.02	93.68	44.92	22.0%	78.0%	67.6%
Upper Baker, W.S.	11.55	0.88	16.91	10.67	92.4%	7.6%	61.3%
Whatcom Meadows	1.27	0	137.33	1.27	100.0%	0.0%	99.1%
Average of TOT percentages					79.52%	20.48%	57.35%

NC = total area of the noncircular one-year wellhead protection area.
NC Outside CFR = the area that the one-year noncircular area captures outside of the one-year CFR area.
CFR Outside NC = the area that the one-year CFR captures outside of the one-year noncircular area.
Shared Area = the area that the one-year CFR shares with the one-year noncircular area.

TABLE 4

Averaged Time-of-Travel Percentages

	Area #1 Captured by CFR (Best If High %)	Area #2 Not Captured by CFR (Best If Low %)	Area #3 Overcaptured (Best If Low %)
1-year	79.52%	20.48%	57.35%
5-year	62.62%	37.38%	69.45%
10-year	57.55%	42.45%	74.83%

The one-year calculated fixed radius captured the best overall percentages; as distance from the well increased, the CFRs became (spatially) less accurate.

travel area-by-area basis. A process called unioning was utilized to separate CFR and noncircular TOT areas (areas derived by analytical or more complex methods), one area at a time (Figure 2). Unioning simply allows the GIS user to select areas of a graphic as separate polygons. According to Hutchinson and Daniel (2000), "This (union) process combines features of an input theme with the polygons from an overlay theme to produce an output theme that contains the attributes and full extent of both themes." This technique enabled each polygon (i.e., the areas where the CFR lines crossed over the noncircular lines) to be selected separately and its area to be recorded in acres.

With the polygon acres for each WHPA recorded, it was possible to spatially compare time-of-travel areas as percentages (by dividing polygons) of the recorded GIS-based areas. Three areas were utilized to calculate these percentages (description of the areas utilized for these comparisons can be found in the legend to Figure 2):

1. Area 1 = what the CFR captured of the noncircular area,
2. Area 2 = what the CFR missed of the noncircular area,
3. Area 3 = what the CFR overcaptured outside of the noncircular area.

When Area 1 was added to Area 2, the result was the total noncircular TOT area. When Area 1 was added to Area 3, the result was the total CFR TOT area. A list of the water systems that were compared is given in Table 3. Table 3 also compares areas of capture, noncapture, and overcapture found for the water systems. Comparisons were made for each TOT area.

The percentage of the noncircular area captured by the CFR is recorded in Table 4 ("best if high percentage"), as are the percentage not captured by the CFR ("best if low percentage") and the percentage overcaptured ("best if low percentage").

This process was completed for each TOT area. After these areas were compiled and averaged into percentages, the data were displayed for the one-, five-, and 10-year areas as a whole, in Table 4.

Results

Wellhead protection areas for 12 systems were used for this study (Table 3). A total of 16 separate wellhead protection areas (several public water systems have numerous WHPAs covering multiple sources) were utilized for the data overlay portion of this research (Table 3).

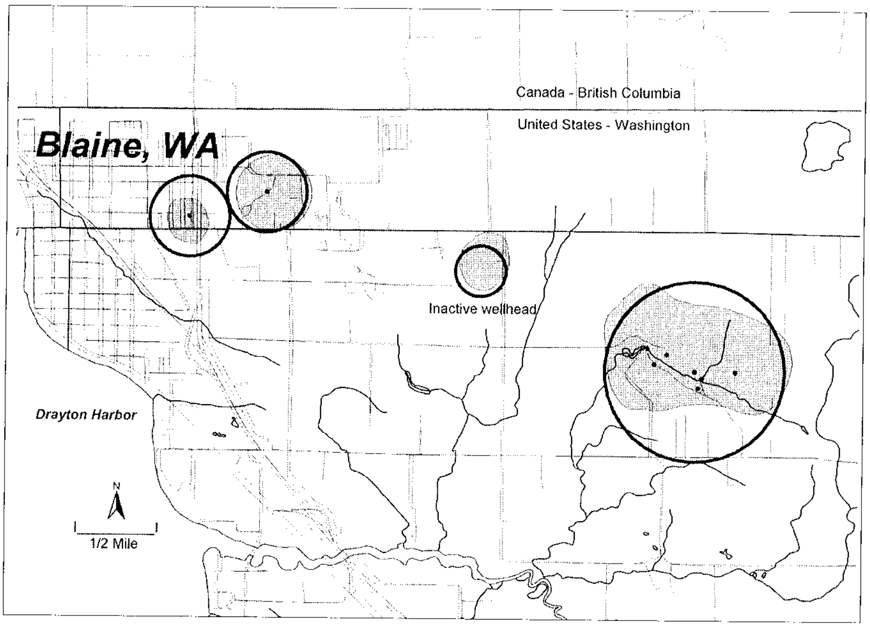
Graphical Representations and Data Overlay Results

Figure 3 displays the one-year TOT graphical overlay for the city of Blaine's multiple wellhead protection areas. Figure 4 is a graphical representation of the CFR overlays for the one-, five-, and 10-year TOT areas for the city of Blaine. The results of the GIS overlay comparisons (for the one-year TOT only) also can be found in Table 3. The results of all of the paper and electronic file conversions are found in the full Whatcom County Wellhead Protection Area map, including the new WHPAs extending into British Columbia via Canadian baseline data (Figure 1, Figure 4). Table 4 offers the results for each of the one-, five- and 10-year TOT data overlay comparisons as an average for each area.

When all TOT areas are compared, the one-year overlay areas are more alike than the 10-year overlay areas on the basis of overall percentages, indicating a trend toward lower viability of the CFR method at greater distances from the well. These percentages are fully consistent in each area averaged, as shown in Table 4 (one-, five-, and 10-year averages are given). When TOT areas are compared one area to the next (i.e., one-year versus five-year, or five-year versus 10-year), the difference between the one- and five-year percentages is greatest. This result further indicates that as distance from the well increases, the "best percentages" become more similar for the time-of-travel areas. The main conclusion is that the closer the area is to the well the more similar results from the CFR method become to results from more complex methods (i.e., there is good correspondence for one-to-five-year TOT areas).

FIGURE 3

One-Year Noncircular Wellhead Protection Areas (Numerical Model) for the City of Blaine, Overlaid with One-Year CFR Areas



Use of Wellhead Protection Areas for Local Land Use Decisions

Whatcom County Health Department (WCHD) staff have begun to use GIS to quickly and easily determine if an application for a proposed land use pertains to land within a wellhead protection area. This capability includes both the existing WHPAs and the calculated fixed radius areas created for all systems by the study results. Notification also could include subdivision plat applications, surface-mining operations, and any other activity that might be detrimental to water quality—a process already taking place in Whatcom County. Since this study indicates that CFR time-of-travel areas closer to the well are more similar to areas found by more complex groundwater delineation modeling, WCHD staff are more confident in the one- and five-year TOT areas than in the 10-year area. Furthermore, six-month CFRs were created from the data overlay results for all sources because the six-month TOT areas are most likely to closely resemble those delineated by more complex methods of groundwater modeling.

Discussion

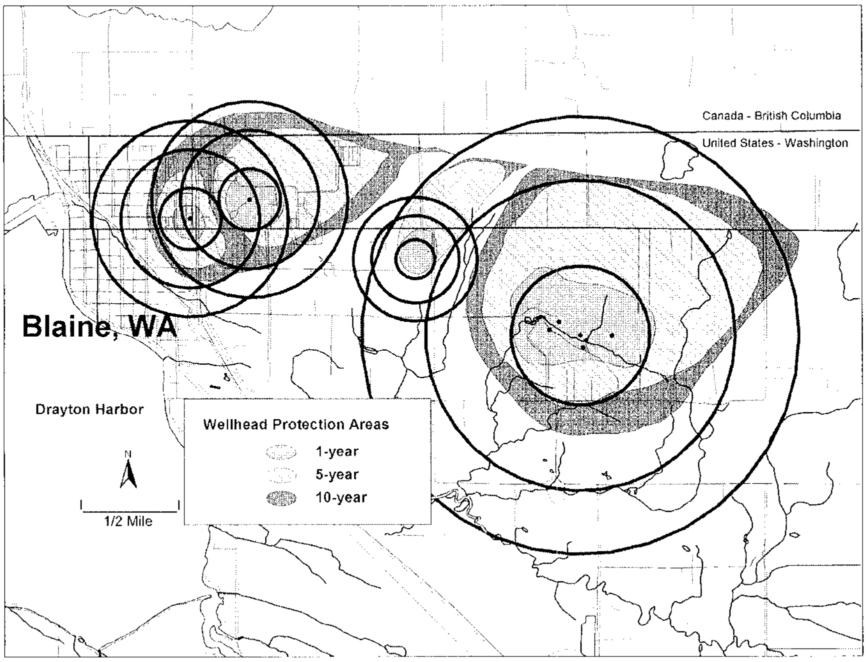
Extensive time was saved in retrieval and analysis of GIS data over conventional paper mapping—specifically, in circumstances under which the CFR method would be preferred (i.e., small systems with few resources). On the other hand, the overcapture of large areas as a result of the CFR method can waste time and money both of the water system and of government agencies.

Data problems included the unavoidable use of cartographically inaccurate base maps with different scales, multiple versions of databases that did not correlate, and the need to convert huge amounts of nongeographically referenced map and tabular data to digital databases. Postproject evaluation revealed that too much time was spent on data gathering, verification, and compilation.

Most of the responsibility for the implementation of a wellhead protection program lies at the local level, as does land use planning. Thus, local officials can select and implement the steps necessary to protect public water supplies. Furthermore, local planning and community development agencies play a key role in ensuring that public-drinking-water wellhead protection areas are recognized and that the recognition is integrated into the overall planning process. In areas with many medium- to small-sized systems (e.g., Whatcom County) however, a higher degree of coordination is necessary, including growth and watershed management programs.

FIGURE 4

Noncircular Wellhead Protection Areas (Numerical Model) for the City of Blaine, Overlaid with CFR Areas



Some public water systems gain authority to protect groundwater through zoning decisions, building and operating standards, land use controls, and public health ordinances since they are owned and operated by local jurisdictions. On the other hand, many systems have no land use authority. These systems should be especially aware of the need to work with local jurisdictions and regulatory agencies that have land use control authority.

Aside from the measures outlined in this study, which will be taken to protect groundwater supplies through wellhead protection, further work will include provision of calculated-fixed-radius areas for all sources that do not have a formal wellhead protection area. This information will be used for surface-mining, subdivision review, binding site plans, conditional use permits, and critical-areas ordinance planning.

Access to mapping will help agencies respond to inquiries of the various types that typically arise with respect to a specific water system—such as those from developers, individual property owners, water system managers, and engineers. As Lennox, Adams, and Chaplik (1990) argue, "According to the public utility, a technically sound recharge area map and education of both municipal officials and residents are the key elements for convincing a town to adopt a wellhead protection strategy."

Further Research

Further research into a GIS groundwater model is currently being conducted on a method-by-method basis. Instead of looking at how the CFR areas compare with results from more complex models as a whole, the authors are breaking down the area comparisons into the following pairs: CFR versus analytical, CFR versus hydrogeologic, and CFR versus numerical modeling. At least 10 new wellhead protection areas will be covered by these upcoming study results.

As Miller (1992) writes, "A thorough knowledge of groundwater flow systems and an understanding of how contaminants migrate through geologic formation leads to (even more) successful wellhead protection programs. Once there is a thorough understanding of the mechanics involved, areas of contribution can be mapped and (more specific) controls, such as limitations on land use, can be imposed." Recent GIS software developments such as ArcFlow GIS (Blum, 2000) are opening up new avenues to groundwater modeling. As Blum (2000) explains, "The specific reason for the development of ArcFlow is the need to rapidly assemble and test regional groundwater flow models to define capture areas of pumping wells. The purpose of (the ArcFlow GIS effort) is the protection of groundwater quality and public health, [through] wellhead protection. Many scientists seeking a better understanding of the natural world experience a great frustration resulting from having masses of data and a distinct lack of affordable tools to analyze that data quickly." A researcher could use this software for further analysis of the wellhead protection area data organized and created in this study.

Conclusion

This study has shown that the development and documentation of wellhead protection plans can be significantly enhanced with a spatial data overlay approach that uses a GIS. It also demonstrates that for one-to-five-year times of travel, the calculated-fixed-radius method defines wellhead protection areas comparable to those found by much more complex hydrogeologic models. Overlay comparisons show that 80 percent of the one-year time-of-travel area defined by a hydrogeologic model was captured by the CFR at the same well. There was, however, an overcapture of 57 percent. For a 10-year TOT, the CFR still captured 58 percent of the hydrogeologic model area, with an overcapture of 75 percent.

Because time-of-travel protection areas can be quickly and inexpensively calculated with a CFR, this method is an effective first step for small water systems lacking financial or personnel resources to establish more sophisticated wellhead protection programs. Incorporating six-month and one-to-five-year TOT calculated-fixed-radius protection areas on a GIS overlay also allows for efficient interagency cooperation in identifying land use practices such as residential development or surface mining that could threaten water quality. Under circumstances that pose such a threat, more rigorous wellhead protection schemes could be required.

Corresponding Author: Chris Miller, Environmental Health Specialist II, Environmental Health, Whatcom County Health Department, 509 Girard St., Bellingham, WA 98227. E-mail: cmiller@co.whatcom.wa.us.

References on page 24

REFERENCES

continued from page 23

Blum, J.L. (2000). *ArcFlow user manual, version 1.1—First draft* (p. 41.). St. Paul, MN: Minnesota Department of Health.

Bogue, K.S. (1994). *Evaluation of wellhead protection models: A case study, Xenia, Ohio* (p. 121). Dayton, OH: Wright State University.

Cleary, T.C.B.F., & Cleary, R.W. (1991). Delineation of wellhead protection areas: Theory and practice. *Water Science and Technology, 24*(11), 245.

Hansen, C.V. (1991). *Description and evaluation of selected methods used to delineate wellhead-protection areas around public-supply wells near Mt. Hope, Kansas* (Publication #I 19.42/4:90-4102, prepared in cooperation with the U.S. Environmental Protection Agency). Lawrence, KS; Denver, CO: U.S. Department of the Interior; U.S. Geological Survey.

Hutchinson, S., & Daniel, L. (2000). Beyond the basics. In *Inside ArcView GIS* (3rd ed., p. 315). Albany, NY: OnWord Press.

Jennings, D.G. (1995). *Washington State wellhead protection program guidance document* (Publication #331-018). Olympia, WA: Washington State Department of Health.

Landmeyer, J.E. (1994). *Description and application of capture zone delineation for a wellfield at Hilton Head Island, South Carolina* (Publication #I/9.42/4:94-4012, prepared in cooperation with the South Carolina Department of Health and Environmental Control). Columbia, SC: U.S. Department of the Interior; U.S. Geological Survey.

Lennox, J.B., Adams, C.F., & Chaplik, T.B. (1990). Overview of a wellhead protection program: From the determination of recharge areas to the development of aquifer protection regulations. *Journal of the New England Water Works Association, 104*(4), 238-247.

Marble, D.F. (1987). Geographic information systems: An overview. In W.J. Ripple (Ed.) *Geographic information systems for resource management: A compendium* (pp. 2-8). Falls Church, VA: American Society for Photogrammetry and Remote Sensing and American Congress on Surveying and Mapping.

Miller, D.W. (1992). Principles of groundwater protection: Proceedings of the Irrigation and Drainage Sessions at Water Forum 92. In T. Engman (Ed.) *American Society of Civil Engineers National Conference on Irrigation and Drainage, Baltimore, Maryland, August 2–6, 1992* (p. 634). New York: American Society of Civil Engineers.

Moore, B.A. (1993). *Case studies in wellhead protection area delineation and monitoring* (600/R-93/107). Las Vegas, NV: U.S. Environmental Protection Agency, Office of Research and Development, Environmental Monitoring Systems Laboratory.

Noake, K.D. (1989). Protecting groundwater from the bottom up: The fox (borough) guarding the aquifer coop: Local control at work. *Proceedings of the Conference on Local Responses to Wellhead Protection, Danvers, Massachusetts* (pp. 71-101). Oklahoma City, OK: Underground Injection Practices Council.

Olimpio, J.C., Flynn, E.C., Tso, S., & Steeves, P.A. (1990). *Use of a geographic information system to assess risk to ground-water quality at public-supply wells, Cape Cod, Massachusetts* (Water Resources Investigations Report 90-4140, prepared in cooperation with the Massachusetts Department of Environmental Protection, Division of Water Pollution Control). Boston, MA; Denver, CO: U.S. Department of Interior; U.S. Geological Survey.

Reilly, T.E., & Pollock, D.W. (1996). Sources of water to wells for transient cyclic systems. *Water Well Journal, 34*(6), 979-988.

Rifai, H.S., Hendricks, L.A., Kilborn, K., and Bedient, P.B. (1993). A geographic information system user interface for delineating wellhead protection areas. *Ground Water, 31*, 480-488.

Texas Water Commission and Texas Department of Health. (1990). *Texas wellhead protection program* (Rev. ed.). Austin, TX: Author.

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

ACCREDITED EH SCIENCE AND PROTECTION PROGRAMS

The following universities and colleges offer accredited environmental health science and protection programs for undergraduate degrees. For more information, please contact the schools directly or the National Environmental Health Science and Protection Accreditation Council Executive Director, Alejandra Tres, at (503) 235-6831 or e-mail at atres@aehap.org.

Boise State University
Boise, Idaho
Dr. Dale Stephenson
(208) 426-3795

Bowling Green State University
Bowling Green, Ohio
Gary Silverman, D.Env.
(419) 372-6062

California State University, Fresno
Fresno, California
Sandra Donohue, Ph.D.
(559) 278-4747

California State University, Northridge
Northridge, California
Peter Bellin
(818) 677-2346

Colorado State University
Fort Collins, Colorado
John Reif, Ph.D.
(970) 491-6074

East Carolina University
Greenville, North Carolina
Daniel D. Sprau
(252) 328-4249

East Central University, Oklahoma
Ada, Oklahoma
Doug Weirick, Ph.D.
(580) 332-8221, ext. 548

East Tennessee State University
Johnson City, Tennessee
Phillip Scheuerman
(423) 439-5245

Eastern Kentucky University
Richmond, Kentucky
Dr. D.B. Barnett, Chair
(859) 622-2191

Ferris State University
Big Rapids, Michigan
Michael Ells
(616) 592-2314

Illinois State University
Normal, Illinois
Tim Kelley, Ph.D.
(309) 438-5142

Indiana State University
Terre Haute, Indiana
Shiaw Fen Ferng, Ph.D.
(812) 237-3096

Mississippi Valley State University
Itta Bena, Mississippi
Moses Omishakin, Ph.D.
(662) 254-3391

Missouri Southern State College
Joplin, Missouri
Mike Fletcher, M.S.
(417) 625-9765

Old Dominion University
Norfolk, Virginia
James English, M.S.
(757) 683-3589

Ohio University
Athens, Ohio
Michele Morrone, Ph.D.
(614) 593-1223

Oregon State University
Corvallis, Oregon
Catherine Neumann, Ph.D.
(541) 737-3833

Richard Stockton College of New Jersey
Pomona, New Jersey
Bruce DeLussa, M.P.H.
(609) 652-4395

Salisbury State University
Salisbury, Maryland
Elicia A. Venso, Ph.D.
(410) 543-6499

University of Georgia, Athens
Athens, Georgia
Jeffrey Fisher, Ph.D.
(706) 542-2454

University of Washington
Seattle, Washington
Chuck Treser, M.P.H.
(206) 543-4207

University of Wisconsin
Eau Claire, Wisconsin
Bob Nelson, Ph.D.
(715) 836-2628

Western Carolina University
Cullowhee, North Carolina
Gary Smith, Ph.D.
(704) 227-7113

Wright State University
Dayton, Ohio
G. A. Burton, Ph.D.
(937) 775-2201