Underground Albemarle Revisited

The Role of Groundwater Ecosystem Services in Determining an Optimal Sustainable Population Size for the Charlottesville/Albemarle Community

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Nick H. Evans, PhD, PG and Michael C. Collins, MP, AICP

Virginia Groundwater, LLC

in cooperation with

The Center for Sustainable Groundwater and *Conserv: Marketplace for Ecosystem Restoration*

for

Advocates for a Sustainable Albemarle Population (ASAP)

ASAP
Advocates for a Sustainable Albemarle Population

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About the Authors

Nick Evans is a professional geologist with 25 years experience working in Virginia government and in the private sector. He has a BA in Environmental Sciences from the University of Virginia and a PhD in Geology from Virginia Tech. He is also a graduate of the Sorenson Institute for Political Leadership and is the Chairman of the Thomas Jefferson Soil and Water Conservation District.

Michael Collins is a former local and regional government planner. He has a BS in Biochemistry from Virginia Tech and an MP in Environmental and Land Use Planning from the University of Virginia. He has been a tenured public school science teacher and environmentally-friendly building supply store owner.

Nick and Mike founded Virginia Groundwater, LLC (www.virginiagroundwater.com) in 2002 as a “science-based well drilling” company. Today, Virginia Groundwater is a groundwater, geology, and geophysics consulting firm. In 2004-2007, Mike and others founded Conserv-Marketplace for Ecosystem Restoration (www.conservationrealestate.org) as a non-profit pilot project for the testing of environmental market initiatives. In 2009, Nick and Mike began the Center for Sustainable Groundwater (www.sustainablegroundwater.org), an offshoot of Virginia Groundwater, designed to meld Virginia Groundwater’s technical experience with Conserv’s knowledge of ecosystem services, with a focus on groundwater sustainability.

1: Executive Summary

The purpose of this study is to consider how groundwater management policy impacts optimal sustainable population size (OSPS) in Albemarle County and The City of Charlottesville, within an ecosystem services framework. The specific research question explored in this paper is:

Does groundwater availability impact the determination of an optimal sustainable population size in Albemarle County and the City of Charlottesville and if so, what is that impact?

The study embraces a holistic approach to exploring linkages between human population, land use, surface water and groundwater resources.

A number of terms not previously in the lexicon of local groundwater discourse are introduced and defined, including *extractive groundwater services, non-extractive groundwater services,* and *sustainable groundwater management*. A chronology of recent groundwater studies and reports is outlined.

A broad technical review is presented to provide the reader with basic current knowledge of groundwater occurrence and flow in the Charlottesville – Albemarle region. A theoretical water budget is developed that models overall average daily groundwater recharge in the study area at about 1079 gallons per acre.

Geophysical surveys representative of diverse hydrogeologic settings in the study area are presented to illustrate the heterogeneity of groundwater occurrence. These surveys show that groundwater recharge, flow and availability for extractive purposes are highly variable, and that potential impacts of groundwater extraction on non-extractive groundwater services are similarly variable.

A conceptual model for sustainable groundwater extractive and non-extractive services is created and applied to the theoretical water budget developed earlier. Degradation of aquatic ecosystems by increasing percentage of impervious land cover in the recharge area is used as a proxy for degradation of non-extractive groundwater services. The threshold for degradation of non-extractive services is estimated to be reached when impervious land cover in the recharge area reaches about 5 to 20%. It follows that under sustainable groundwater management, about 80 to 95% of natural recharge is required to support non-extractive groundwater services, with the remaining 5 to 20% theoretically available to support extractive services in a pristine watershed with 0% impervious land cover. Sustainable groundwater management by definition gives priority to supplying non-extractive services over supplying extractive services. Therefore, the maximum sustainable extraction rate is about 20% of natural recharge.

The 2003 Albemarle County Hydrogeologic Assessment (ENSAT Corporation and others, 2003) is evaluated in consideration of the ecosystem services model. A new model is presented for groundwater sustainability, along with a map showing zones of relative potential for sustainable groundwater extraction. Two high potential zones are identified, the Eastern Blue Ridge Flank (EBRF) and Mountain Run Fault Zone (MRFZ), with potential for significantly greater extraction than at present. A low potential zone is identified as having limited extraction potential. Much of the area is assigned to a zone of mixed potential, where site-specific studies would be necessary to make realistic assessments of individual land parcels.

The conceptual model of sustainable management is applied to the EBRF high potential groundwater zone where theoretical maximum sustainable extraction potential is estimated to be approximately 3.9 to 7.8 million gallons per day (MGD) if groundwater resources were fully developed within that portion of the County.

Findings and recommendations are presented in support of incorporating principles of sustainable groundwater management into local public policy.

Findings

1. New language has emerged in recent years to describe responsible stewardship of groundwater resources.

This report introduces and defines the terms:

- Sustainable groundwater management
- Extractive groundwater services
- Non-extractive groundwater services
- Sustainable groundwater extraction.

2. Geophysical images reveal that groundwater is not uniformly distributed throughout the study area. In addition, the images specifically reveal the following:

- Bedrock fractures are not uniformly distributed, even within the same rock-type on a small parcel of land, and are not always interconnected in a horizontal sense.

- Thickness and water storage and transmission capacity of saprolite (the near-surface sponge composed of weather bedrock) vary from place to place, even within the same rock type. In some geologic settings, the only water available for water supply wells exists in the soils and saprolite, above bedrock.
- Recharge to water-bearing zones in the saprolite and the bedrock may be very local in settings where both hydraulic gradient and interconnectivity among fractures are low. This means that in some situations, recharge may be affected much more by land cover changes in the immediate vicinity, than by activities that take place farther away.

3. The conceptual foundation of sustainable groundwater management is that demand for non-extractive groundwater services receives priority over fulfilling demands for extractive groundwater services.

The maximum amount of groundwater that can be sustainably pumped from the ground is the volume left over after non-extractive groundwater needs have been satisfied.

4. The County's previous groundwater studies and groundwater policy have been focused on extractive groundwater services.

The 2003 availability report (ENSAT Corporation and others, 2003) focused on absolute amounts of groundwater that occur in different parts of the county, capable of being "captured" for human use by drilling a well. It should be noted, however, that language in support of non-extractive groundwater services can be found in non-groundwater specific County policy, such as the Introduction to the Natural Resources Chapter of the Comprehensive Plan (Albemarle County, 1999).

5. Stream ecosystem health can be used as a proxy for non-extractive groundwater services, and an indicator for sustainable groundwater management.

The percentage of impervious land cover that is a threshold for onset of degradation of stream ecosystem health can be used to quantify the percentage of recharge required to supply non-extractive groundwater services. Locally, the degradation threshold appears to be in the range of 5 to 20% impervious land cover. In terms of groundwater recharge, the threshold of degradation to stream ecosystem health can be estimated at diminution of recharge by 5 to 20%. It follows that 80 to 95% of natural recharge is required to fulfill non-extractive groundwater services. This means that 80 to 95% of recharge must be left in the ground, and that a maximum of 5-20% of groundwater recharge in Charlottesville and Albemarle County can be used for extractive groundwater services.

6. The amount of groundwater available on a given parcel to provide for both extractive and non-extractive services varies as a function of hydrogeology, topography and land cover.

There are settings within the study area where groundwater recharge and flow across a given parcel are very large relative to the volume of groundwater needed for non-extractive services. In these settings, it is theoretically possible to sustainably pump significant quantities of water from the ground, and apply this water to a consumptive use where water is transported away from the local watershed. In other areas, groundwater flow and recharge are limited by hydrogeology and other factors. In these areas, the volume of water available for sustainable extraction may be relatively small.

Albemarle County contains two recognizable zones of high potential for significant sustainable groundwater extraction, and one recognizable zone of low potential (Figure 5, above). The remainder of the County and the entire City are within a zone characterized as having mixed potential. Within this area, site-specific study will be required to identify zones of high or low potential, to the extent that such may exist.

7. The use of groundwater for residential needs in the rural area of Albemarle is non-consumptive, in the sense that most of the water is returned to the ground after use via a sanitary drainfield.

Therefore in most cases, under current 2-acre minimum lot size zoning, domestic groundwater use in the rural areas of the county does not degrade non-extractive services, and is generally sustainable, regardless of hydrogeologic setting.

8. Sustainable groundwater management has implications for sustainable population size.

Under sustainable groundwater management, 80-95% of groundwater recharge is left in the ground to provide for non-extractive groundwater services. Simply stated, this means that under sustainable management, over the long-run, the great majority of groundwater is unavailable for extractive consumption by humans. This would seem to imply that the size of the community’s “sustainable” population may be less than—as presumed in previous assessments of water availability—if all available groundwater were to be extracted to supply human needs.

On the other hand, the impact of sustainable management (or lack thereof) could be particularly significant should Albemarle’s EBRF and MRFZ be utilized for groundwater supply. For example, rather than the 3.9 to 7.8 MGD estimated to be available for extractive services from the EBRF under a sustainable groundwater management regime, approximately 39 to 78 MGD could theoretically be pumped, in the short-term, to facilitate commensurate population growth above and beyond what is sustainable relative to protection of non-extractive groundwater services. The results of unsustainable groundwater mining such as this could be widespread lowering of the water table, causing elimination of base flow in many streams and landscape-scale desertification. This has the potential to drastically alter quality of life, and disrupt the local food supply, among other implications for the resident human population.

9. Sustainably managed groundwater could provide a significant proportion of future water needs for the City of Charlottesville and urban areas of the County.

Sustainable groundwater extraction from the Mountain Run Fault Zone (MRFZ) and Eastern Blue Ridge Flank (EBRF) could have a significant impact on maximum sustainable population size for the area. If the County and City were to decide to use groundwater for municipal water supply, a significant portion of the estimated future demand could be supplied via municipal well withdrawals from these two areas.

It should be noted, however, that the County's longstanding water supply policy is surface-water based. According to Mike Lynn, ACSA Operations Manager, as of August, 2009, the only municipal groundwater system in use by the Authority today is for a small cluster of homes on Red Hill Road.

The following exercise indicates that the EBRF may be capable of supplying from 25 to 49% of the future municipal water demand at build-out:

To estimate the population size at build-out within the County Growth Areas and City combined, we refer to estimates presented in the recent report *Estimating Impacts of Population Growth on Ecosystem Services for the Community of Albemarle County and Charlottesville, VA* (Jantz and Manual, 2009):

	2000 population	Build-out population
Charlottesville area	72,297	111,882
Crozet	7,101	25,106
Rivanna	3,960	14,205
Route 29	12,458	60,310
TOTAL	**95,816**	**211,503**

(difference between 2000 population and estimated build-out population = 115,687 persons)

According to the ACSA, the average water use for all single family residential customers (persons) is 4100 gallons per month or 137 gallons/day, assuming a 30 day month (Mike Lynn, personal communication, 2009). Applying this figure to the future build-out population of 115,687 persons, an additional 15.8 mgd will be needed.

We estimate the approximate availability of groundwater from the EBRF to be 3.9 to 7.8 MGD. This is equivalent to 25 to 49% of the total future demand needed at build-out of the Growth Areas and City, according to the Jantz and Manual projections. Additional groundwater capacity of a similar order of magnitude may be available on a sustainable basis from the Mountain Run Fault Zone, and perhaps from other areas yet to be identified within the mixed zone.

10. This study provides a conceptual framework with which to link residential density, stormwater management, impervious land cover, and non-extractive groundwater services in developing growth management strategies (see Recommendation 1 below).

Recommendations

1. Consider new policies linking groundwater, impervious land cover, stormwater management, and residential development density.

The County and City should consider new policies that limit watershed percentage impervious land cover, while maximizing stormwater infiltration, in order to maximize allowable groundwater extraction. Such policies (for example, see #5 below) would be designed to ensure that recharge necessary for non-extractive groundwater services is not reduced below a sustainable threshold. That threshold, conceptually pegged at a range of 80-95% of recharge in this study, will need to be scientifically determined in a separate investigation conducted by a team of hydrogeologists, ecologists, soils scientists, environmental planners, and others. The implications of such a threshold could have a significant impact on County and City stormwater policy and on County groundwater policy, particularly in areas with impervious land cover greater than 5-20%.

2. Further study potential recharge areas in the Blue Ridge Mountains and Southwestern Mountains in order to better quantify maximum sustainable extraction volumes for the ERBF and MRFZ.

3. Study land use policy and groundwater further in the zone of mixed potential for significant sustainable extraction, in order to identify areas of high and low potential for significant sustainable extraction.

4. Consider using sustainably managed groundwater extraction to augment municipal water supplies for the City and Growth Areas of the County.

5. Due to the cumulative impact of impervious land cover on groundwater recharge, residential development densities greater than approximately one house per two acres should be served through community water supply systems rather than individual wells to protect groundwater needed for non-extractive groundwater services.

6. Recognize that a community's sustainable population size is determined, in part, by the availability of sustainably managed groundwater—not simply by accessible groundwater.

7. Albemarle County and the City of Charlottesville, working with the Rivanna Water and Sewer Authority and the Albemarle County Service Authority, need to begin to address groundwater holistically. As a starting point, we suggest convening a broad-based committee charged with a mission to consider the role of groundwater from a sustainability and ecosystem services perspective, by addressing the following questions:

- If the majority of groundwater should remain in the ground to be used for non-extractive services, how does that impact human society in the region beyond those impacts discussed in this study?
- What is the extent of the upland recharge areas that supply the EBRF and MRFZ?
- How much water is likely to be available from the MRFZ in addition to the EBRF?
- How might the availability of groundwater from these zones impact water supply planning?
- How does groundwater viewed from the perspectives outlined in this paper impact stormwater policies and County Growth Area, Rural Area, and City of Charlottesville development policies?

- What new opportunities might be created for rural landowners interested in new sources of revenue for working lands (lands managed for agriculture and forestry), through protecting groundwater ecosystem services within the context of a broader ecosystem services marketplace?

4: Introduction

The impetus for this study has been a need to evaluate implications of groundwater availability as local population grows. The specific research question explored in this paper is:

Does groundwater availability impact the determination of an optimal sustainable population size in Albemarle County and the City of Charlottesville and if so, what is that impact?

Previous studies of groundwater in central Virginia view groundwater simply as a resource to be used to supply water for human usage, be it household water, irrigation water, water for manufacturing, or any number of other uses. An outline of earlier studies and publications that comprise the historical context of the present study is presented in Appendix B.

The 2002 and 2003 Albemarle County hydrogeologic studies (ENSAT Corporation and others, 2002; 2003) were designed to identify areas of the county where greater and lesser amounts of groundwater are thought to be available for human consumption:

> *The purpose of these proposed studies was to characterize groundwater availability and vulnerability in different parts of the county, in support of a proposed hydrogeologic testing ordinance, and as a tool to enable informed decision-making on land use planning and development issues.*
>
> *(ENSAT Corporation and others, 2002)*

Also relevant is a small section of the 2002 report entitled Project Perspective (page 1):

> *There is a particular hydrogeologic perspective that provides the basis for the scope of work developed for this project by the County and the Project Team. This perspective can be characterized by the County's desire to conserve the functionality of the hydrology of the rural areas of the County over the long-term time horizon. This concept has been articulated by the County as a groundwater goal in the Comprehensive Plan: "Protect the availability and quality of groundwater resources". A related goal was developed by the Albemarle County Groundwater Committee: "Promote the sustainable use of groundwater as a* ***water supply*** *for the Rural Areas". [Emphasis added]*

This language is indicative of local government's groundwater management viewpoint in 2002: groundwater is a resource that is needed for water supply.

From the studies of 2002 and 2003, Albemarle County developed a tiered regulatory approach that requires development applicants to provide information with which to evaluate adequacy of supply for the proposed usage, threats to groundwater quality from the proposed development, and potential threats to existing users of groundwater on nearby properties. Again, the aims of this program are built on the viewpoint that services provided by groundwater are exclusively within the framework of supplying water to fulfill human needs. The program is applied at the time of each permit application, without a long-term framework that considers cumulative impact of incremental development.

The present report proposes an evolution in the conceptual model of groundwater --- in which services provided to natural ecosystems by water left in the ground, termed *non-extractive groundwater services,* are considered along with services provided through extraction of water, now termed *extractive groundwater services.* A *sustainable groundwater management* paradigm is not linked exclusively to the amount of water that is pumped from the ground to perform extractive services. Rather, sustainability is linked to the non-extractive services provided by water left in the ground. A glossary of these and other terms is provided in Appendix A of this report.

It should be noted that the proposed conceptual model---to consider both extractive and non-extractive groundwater services--is essentially anthropocentric. The non-extractive services that groundwater provides are all thought to benefit human society. This includes, for example, water that is needed for aquatic habitat. While it is certainly arguable that groundwater is needed by aquatic ecosystems in their own right, human society, for its own survival, also needs those aquatic ecosystems to be fully functional. Thus the use of the word “services” to define benefits non-extractive groundwater provides. The conceptual model for sustainable groundwater management presented in this report is consistent with the conceptual model of ecosystem services used to describe impacts of population growth in the accompanying report *Estimating Impacts of Population Growth on Ecosystem Services for the Community of Albemarle County and Charlottesville, VA* (Jantz and Manuel, 2009).

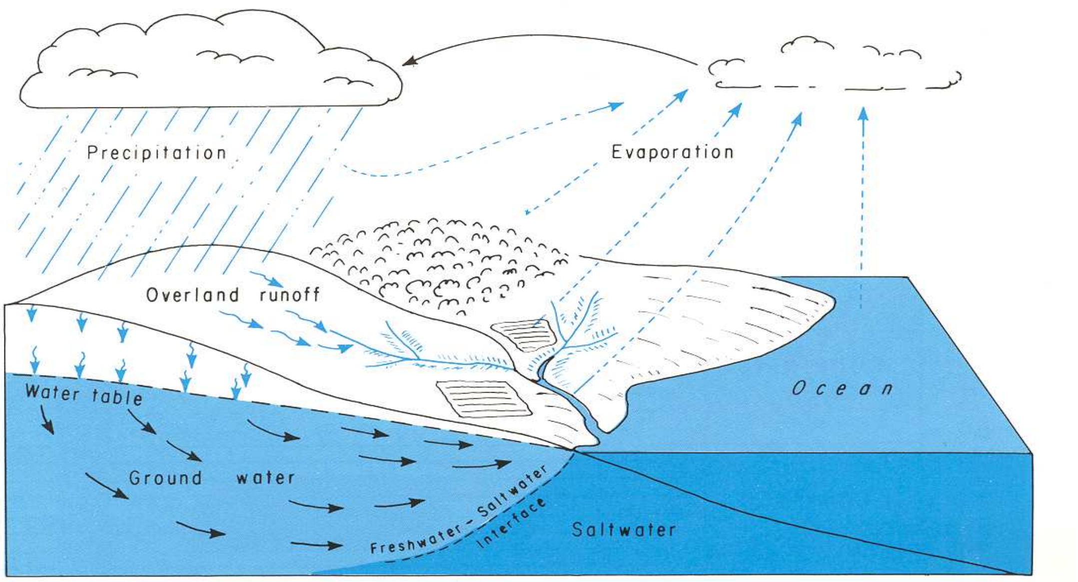
5: Technical Overview

Groundwater: Part of the Hydrologic Cycle

When precipitation falls from the sky, a portion runs off along the surface and flows into creeks, rivers, lakes and the ocean. Another portion gets soaked up by trees and plants, and is returned to the atmosphere by processes evaporation and photosynthesis (termed evapotranspiration, or ET). The remainder soaks into the ground and becomes groundwater recharge. Groundwater is defined as water that occurs beneath the surface of the ground, within a zone that is saturated with water.

Groundwater, surface water and atmospheric water exist within a dynamic continuum called the hydrologic cycle (Figure 1). The hydrologic cycle can be significantly affected by actions of man.

Figure 1: The Hydrologic Cycle



In the natural (undisturbed) hydrologic cycle, in humid climates, groundwater flows underground along hydraulic gradients and discharges into rivers, streams, lakes and the oceans. During periods of low flow, when there has been no precipitation for a few days or longer, most of the water in the rivers and streams is supplied by groundwater discharge. Groundwater also provides moisture to soils, crucial to sustaining plants and trees during times of drought.

When groundwater is pumped from a well and not returned to the ground through a drainfield or injection well, the activity is termed a consumptive use of groundwater. If future growth in Charlottesville and Albemarle is accompanied by significant consumptive use of groundwater beyond the capacity of available recharge, negative impacts are likely. These impacts potentially affect the amount of groundwater available for human use in water wells, but also potentially affect services provided by groundwater for ecological needs.

The proportion of precipitation that actually soaks into the ground and ends up recharging groundwater is determined by type of land cover. Undisturbed forest land, while returning significant rainfall to the atmosphere through evapotranspiration, also allows a high percentage of rainfall to soak into the ground. In contrast an asphalt parking lot does not permit any rainfall to soak into the ground. If future growth is accompanied by widespread conversion of rural land cover from natural wooded vegetation to less permeable cover, significant impacts to groundwater recharge are inevitable.

A Theoretical Water Budget for Charlottesville/Albemarle

In order to better understand the relationship among precipitation, groundwater recharge and surface water runoff, it is instructive to model the present-day hydrologic cycle in central Virginia using best available numbers in a hydrologic equation. A theoretical water budget can be expressed by the equation:

Total precipitation = (surface water runoff) + (groundwater recharge) + (water lost to evapotranspiration (ET)).

Or,

Groundwater recharge = (total precipitation) – (surface water runoff) – (evapotranspiration (ET)).

Accurate numbers exist for annual precipitation in the Charlottesville area thanks to many decades of historic climatic records. Surface water runoff can be estimated quantitatively by examining available discharge data from stream gaging stations operated by the US Geological Survey. Absolute values for groundwater recharge and ET are not as readily available. “Groundwater recharge” for purposes of this discussion represents simply the volume of precipitation that enters the ground. After entering the ground, groundwater moves through a complex dynamic system where a portion enters the vadose zone; a portion contributes to groundwater storage within the aquifer media, and a portion is ultimately discharged into rivers and streams.

Simplistically, a quantitative evaluation of the quantity (groundwater recharge + ET) is possible for the entire James River basin above Cartersville, which includes the City of

Charlottesville Albemarle County, because of availability of precipitation data, and surface water runoff data from a USGS gaging station on the James at Cartersville.

For the period October 2005 through September 2006, the precipitation total for the James River basin above Cartersville is estimated at 44.56 inches. Total discharge for the James River measured at Cartersville during that same time period was the equivalent of 15.39 inches of rain over the entire basin upstream. This means that within this basin, on an annual basis, about 34.5%, or roughly one third of total precipitation, runs off into surface streams and rivers.

The remaining 65.5%, or about two thirds of total precipitation, goes to a combination of ET and groundwater recharge annually. There is very little empirical data with which to evaluate the relative proportions of recharge and ET in the equation. ET varies seasonally, as plants and trees go through their annual cycle of growth and dormancy. Groundwater recharge is affected by snow cover and frozen soils in the winter, and by rates of precipitation during other times of the year. For example, a very intense thunderstorm may produce several inches of rainfall locally, but runoff may be so rapid that only a small proportion of the storm precipitation has an opportunity to soak into the ground. For purposes of this report, groundwater recharge and ET in central Virginia are considered roughly equal over the course of an entire year, implying that overall, groundwater recharge comprises about 33 percent of total precipitation.

Under conditions of 33% precipitation going to groundwater recharge, a theoretical water budget for Charlottesville – Albemarle is:

> Annual precipitation: 44 inches
>
> Annual groundwater recharge: 14.52 inches
>
> Daily groundwater recharge: .04 inches (.003 feet)
>
> Daily recharge per acre: 144.32 cubic feet = 1079.5 gallons
>
> Daily recharge of the entire county (726 square miles): 501,578,880 gallons.

The roughly 500 million gallons per day of groundwater recharge dictated by the water budget equation is, in a sense, the daily deposit to the bank account for ecosystem services provided by groundwater to human and natural ecosystem clients. In order for the equation to be in balance, the three terms (groundwater recharge), (surface water runoff) and (ET) must always add up to (total precipitation available). If one term, such as runoff, increases, the other two terms must decrease.

If, for example, future growth in Charlottesville and Albemarle results in a significant increase in impervious land cover, surface water runoff could increase from 34.5% to

50%. Under these conditions, only 25% of precipitation would end up as groundwater recharge. The water budget equation would be as follows:

Annual precipitation: 44 inches

Annual groundwater recharge: 11 inches

Daily groundwater recharge: .03 inches (.0025 feet)

Daily recharge per acre: 109 cubic feet = 818 gallons

Daily recharge for the entire county: 380,075,520 gallons.

Under these conditions, the daily deposit into the groundwater "bank account" would be about 121 million gallons less than under present conditions.

Would a decrease of this magnitude in groundwater recharge result in measurable diminution of groundwater services? If the changes were to occur incrementally over a 50 year time period, as residential development gradually extended into what are currently fields and forests, would they be noticeable? Answers to these questions require a holistic approach to assessing groundwater availability that considers the services groundwater provides both when it is extracted and left in the ground.

Groundwater Occurrence in Charlottesville / Albemarle: Fractured Rock Aquifer

In the Blue Ridge and Piedmont of central Virginia, an area which includes Albemarle county and the City of Charlottesville, groundwater occurs within aquifer systems controlled in part by fractured bedrock. The principal components of these aquifer systems are shown in Figure 2 below. Rainwater that enters the ground to recharge groundwater moves by force of gravity slowly downward, through soils and saprolite into the underlying fractured bedrock. The soils and saprolite serves as a sponge that soaks up rainwater on the surface, and feeds water to fractures in the rock underneath. Groundwater flows down hydrologic gradients through both the soil / saprolite layer, and within interconnected bedrock fractures, ultimately discharging into rivers, streams and other surface water bodies. In stream and river bottoms, alluvial material may be a significant conduit for groundwater.

The water table, blue line near the top of bedrock in Figure 2, is an invisible surface below which the soils, saprolite, alluvium and bedrock are saturated with groundwater. Above the water table, both air and water droplets occupy the spaces between soil and mineral grains, and fractures in the bedrock. Groundwater within bedrock fractures has been cleansed as it passed downward through soils and saprolite. In terms of water quality, bedrock water is the most desirable for human consumption. Water in bedrock fractures is the target of most water supply wells drilled today in central Virginia.

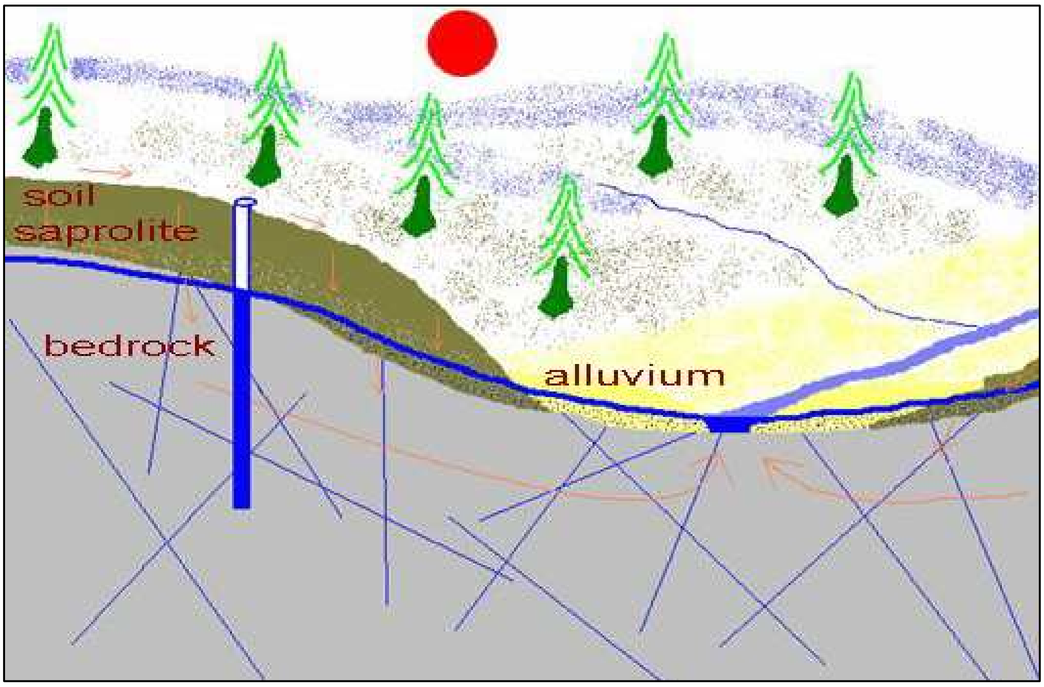


Figure 2: Fractured Rock Aquifer System

Geophysical Imaging: A Virtual Tour of Underground Albemarle

Although Figure 2 presents an adequate conceptual model for groundwater flow in Albemarle and Charlottesville, there is considerable variability in physical characteristics of soils, saprolite and bedrock within the area. As a result there is a lot of variability in both the quantity and quality of groundwater that exists from place to place. Recent advances in geophysical technology enable us to image groundwater in the subsurface, and gain a far more precise understanding of the physical occurrence of groundwater relative to geological features (soils, saprolite and bedrock) than was previously possible.

The geophysical technology involves mapping the distribution of electrical resistivity in the subsurface, down to depths of 300 feet or more. There is a strong correlation between low electrical resistivity values and presence of groundwater.

- The geophysical surveys can be between 800 and 1200 feet in length, depending on design requirements and site layout. The procedure is to drive a series of 56, 24-inch stakes into the ground, then string cables and electrode switches between the stakes. The equipment sequentially applies a maximum of 400 volts across pairs of electrodes, and measures voltages that are returned through other pairs of electrodes. It takes a couple of hours for the hardware to go through all permutations of pairs of electrodes and collect the data.

- Following the field survey, the data are downloaded and processed on a computer in the office. The end result is a visual image that contours values of electrical resistivity along the line of profile to depths of around 300 feet. Dry rock returns electrical resistivity values that are many orders of magnitude greater than rock that contains water. The images produced from the field survey data highlight water-bearing zones that occur in otherwise dry rock. This technology has proven to be a very reliable tool for locating successful water wells.
- A minimum of two surveys are required in order to be able to model the subsurface in 3 dimensions. Several surveys may be required on a large or geologically complex property in order to identify optimal drilling targets.
- Detailed descriptions of the technology and survey procedures are available on line at www.agiusa.com and www.viginiagroundwater.com.

The images below result from electrical resistivity geophysical surveys conducted by Virginia Groundwater LLC during the years 2002 through 2009 in central Virginia. These images have been selected to illustrate the variability in groundwater occurrence and availability in Albemarle County and Charlottesville, although not all are strictly from within the boundaries of the City and County. Images are presented in order of relative abundance of groundwater. For illustrative purposes, all images are projected relative to a horizontal surface.

The horizontal scale along the top of each image is in feet; each black dot represents the location of one of 56 survey electrodes. The vertical scale on the left side of each image represents depth in feet; the legend on the right is a vertical scale representing resistivity in Ohm-meters. Note that high resistivity values (dry rock) are represented by reds, oranges and yellows. Low resistivity values are blue (water likely present).

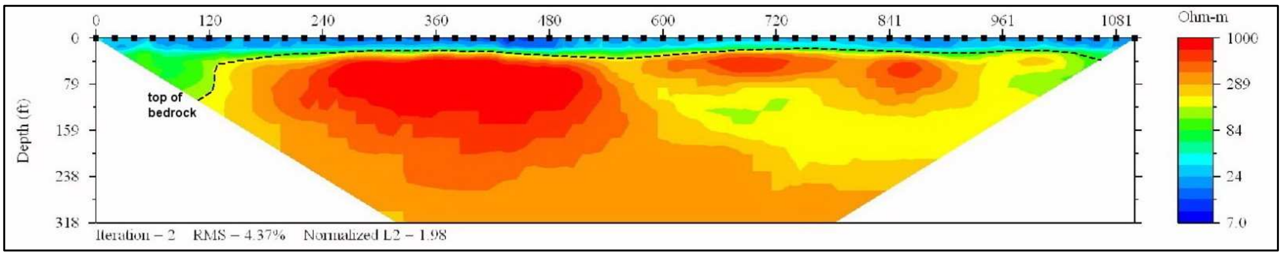


Image 1:Diabase Bedrock, Fauquier County

In Image 1, the interface (dashed line) between the soils – saprolite layer and the top of bedrock is readily visible at about 30 feet. Some water is present in the upper 15 feet of the soils and saprolite layer, but the bedrock itself contains no visible water-bearing fractures. This illustrates that bedrock is not uniformly fractured throughout the Virginia Piedmont. The image also illustrates a setting where the soils and saprolite layer is very thin. The minimal thickness of this layer means that its capacity to soak up and store water that percolates downward from the surface is minimal, limiting recharge potential to any bedrock fractures that exist. There is no viable drilling target visible in this image.

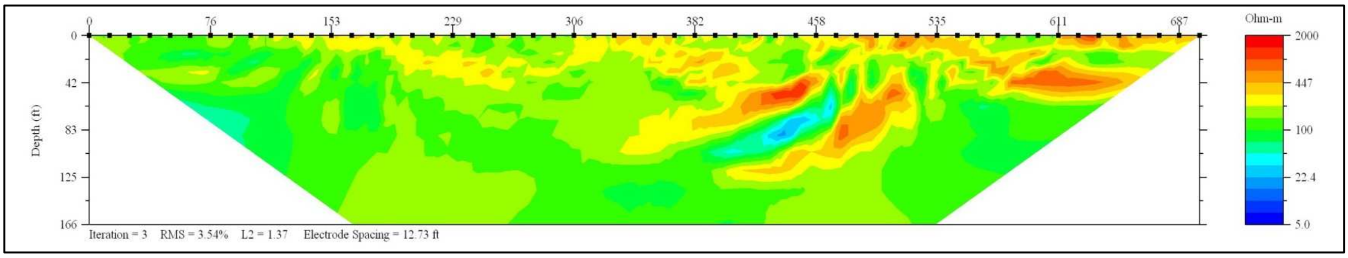


Image 2: Phyllite and Schist Bedrock, Eastern Albemarle County

In the geology illustrated by Image 2, the phyllite and schist bedrock is very soft, and the saprolite zone extends to depths of more than 150 feet in places, below the bottom of the image. The saprolite generally has high moisture content, and relatively low resistivity values, but in this image, free water is likely present in only one zone, in the center–right portion of the image. It is notable that the groundwater appears to occur in a pocket that is not connected to any other pockets of water, at least in the plane of this image. Additional images that were run in different orientations confirmed that this is an isolated pocket. If a well were drilled to intersect this pocket, the most efficient recharge would likely come from the immediately overlying weathered rock material surrounding the well, due to the limited ability of this type of saprolite to transmit groundwater. This is an illustration of a situation where recharge to a well is very local, likely occurring primarily from within a few hundred feet radius of the well head at the surface.

Image 2 illustrates one of the most challenging geologic settings in Albemarle in terms of groundwater availability. Groundwater occurs in small pockets with limited recharge capability, typically within 100 feet of the surface. Wells that capture water from these pockets typically yield less than one gallon per minute. In some cases, because the rock is so soft, it is necessary to extend the well casing below the level where the water occurs, which results in a dry hole. Due to the local nature of recharge in this type of geology, local changes in land cover that prevent rain water from entering the ground have potentially significant impacts on recharge to local wells.

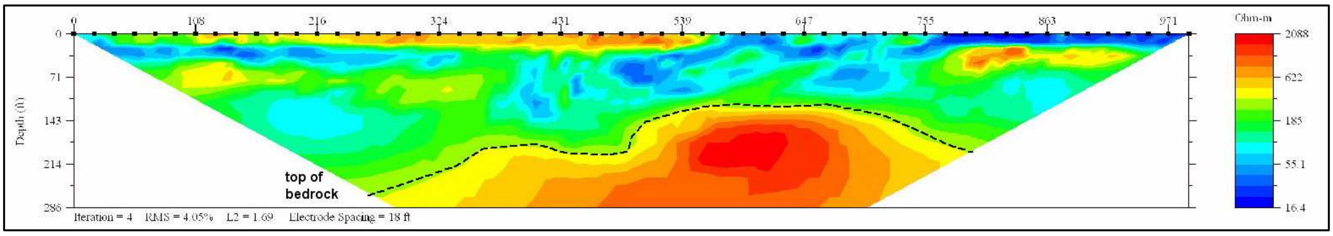


Image 3: Biotite Gneiss Bedrock, Orange County

Image 3 is from a geologic belt of metamorphosed sedimentary rocks that extends through western Orange County, central Albemarle County, and the City of Charlottesville. The image shows a thick band of saprolite containing pockets of water, above bedrock that does not appear to contain water-bearing fractures. Several of the water pockets in the saprolite are visibly connected with water bearing soils near or at the surface (the right portion of the image is wetland at the surface). This illustrates the localized flow of groundwater recharge from the surface, and the “sponge” nature of the saprolite layer.

The percolation of groundwater through relatively short distances of soil and saprolite is commonly sufficient to cleanse the water of impurities that are present at the surface. Many wells in Albemarle County tap water that is situated above the interface of saprolite with unweathered bedrock. It is possible, depending on length of casing required, that successful wells could be constructed to capture some of the saprolite water shown in this image.

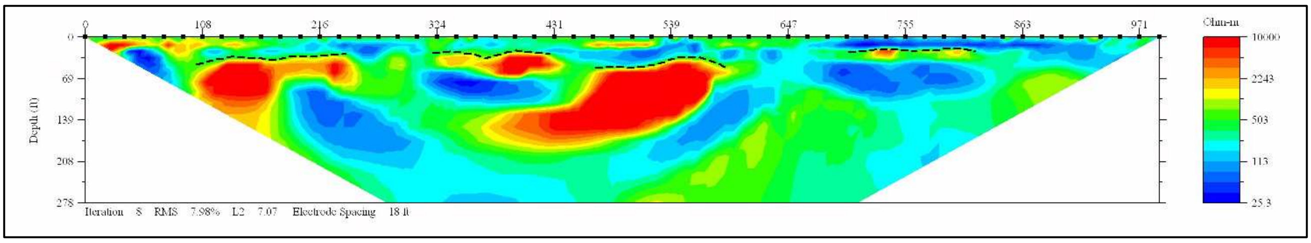


Image 4: Granite Gneiss Bedrock, Albemarle County

Image 4 illustrates granite gneiss bedrock with a well-developed fracture network. At the depth of the image, unweathered bedrock is present only as isolated pods surrounded by saprolite. The saprolite originated within fractures, and spread outward into the surrounding rock with passage of time. Pockets of water are interconnected with each other within the plane of this image. Groundwater recharge flow may have a significant horizontal component in these rocks, depending on hydrologic gradient, in addition to a more local vertical component. This is favorable geology for construction of water supply wells.

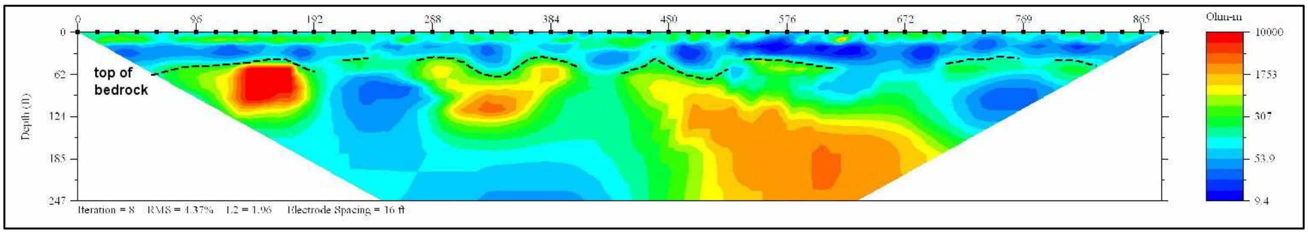


Image 5: Greenstone Overlain by Colluvium, Loudoun County

Image 5 illustrates a very productive groundwater regime that exists on the eastern flank of the Blue Ridge from northern Virginia southwestward, through Albemarle County and beyond. The greenstone bedrock contains well-developed fracture zones. In addition to saprolite, unweathered bedrock is overlain by a wedge of colluvium. This sedimentary material is very porous and serves as a very efficient conduit to groundwater recharge. Recharge can be very rapid and of substantial volume in settings where large acreage of hardwood forest exist up hydraulic gradient from a site. Wells with yields in excess of 100 gallons per minute have been constructed in this setting.

Summary: What do the Geophysical Images Show?

1. Groundwater is not uniformly distributed below the surface of the ground.
2. Bedrock fractures are not uniformly distributed, even within the same rock-type on a small parcel of land, and are not always interconnected in a horizontal sense.
3. Thickness and water storage and transmission capacity of saprolite vary from place to place, even within the same rock type. In some geologic settings, the only water available for water supply wells exists in the soils and saprolite, above bedrock.
4. Recharge to water-bearing zones in the saprolite and the bedrock may be very local in settings where both hydraulic gradient and interconnectivity among fractures are low. This means that in some situations, recharge may be affected much more by land cover changes in the immediate vicinity, than by activities that take place farther away.

6: Groundwater Availability: 2003 Assessment

The most recent published groundwater availability study for Albemarle, completed for the County by ENSAT Corporation and others in 2003, defined nine distinct hydrogeologic units on the basis of unique geology, soils and topographic characteristics (Figure 3, below; ENSAT Corporation and others, 2003). These hydrogeologic units formed the framework for a county-wide “potential relative groundwater availability” assessment based on evaluation of the interrelated variables

- Thickness of overburden (soils plus saprolite),
- Saprolite permeability,
- Background fracturing as indicated by reported yields of randomly sited domestic wells.

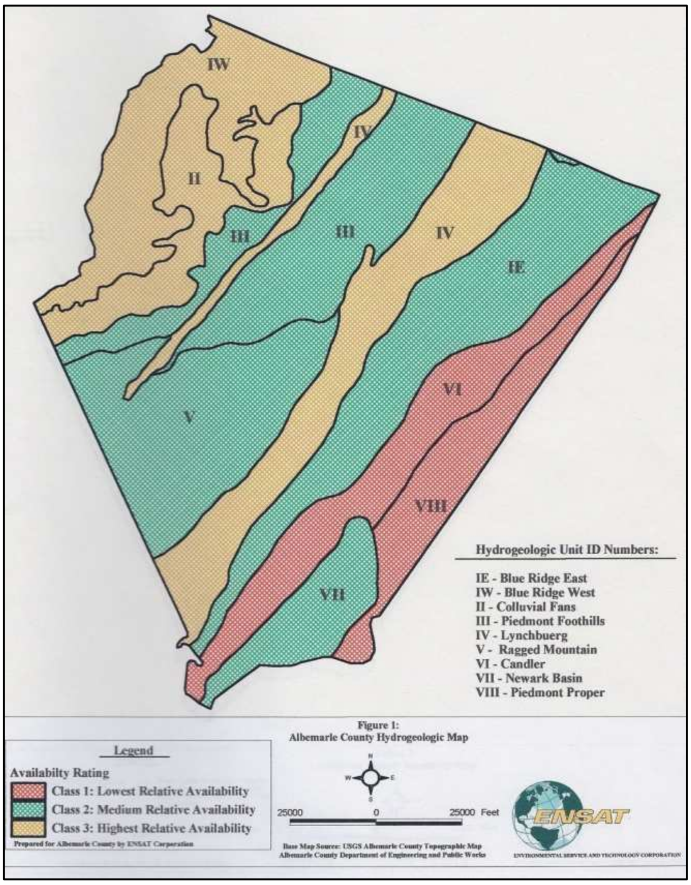


Figure 3: 2003 Groundwater Availability Map

A quantitative availability model was constructed based on data from the existing Albemarle County water well database, and from data generated by in situ permeability testing. The 2003 availability map delineates three groundwater availability zones (low, medium and high) within Charlottesville and Albemarle; the study's findings were "generated at a broad scale…meant only for County-wide planning considerations and as a way to provide focus for site-level groundwater assessments" (ENSAT Corporation and others, 2003, p 1). The County and City are far more heterogeneous in terms of hydrogeologic characteristics than the map implies. The goal of developing a manageable and defensible prototype planning tool required simplification and generalization of what is in reality a very complex hydrogeologic picture.

The 2003 availability model focused on absolute amounts of groundwater that occur in different parts of the county, capable of being "captured" for human use by drilling a well. Groundwater availability in this sense is purely a function of physical factors such as thickness and permeability of the soil and saprolite layer, and density and openness of bedrock fractures. Groundwater availability was defined largely on the basis of historical data on reported well yields and casing lengths from wells constructed in the past. That study did not attempt to evaluate availability within a context of continuously changing variables related to population growth and shifting land use. For example, the 2003 model does not take into consideration implications of changes over time in:

- net groundwater withdrawal for human consumption;
- land cover that potentially compromises local recharge; and
- regional climate.

The 2003 study did not attempt to evaluate non-extractive groundwater services.

7: Proposal for the Sustainable Management of Groundwater using an Ecosystem Services Model

Introduction

The previous chapters of this report provide an introduction to some of the technical and conceptual issues in understanding groundwater in our community, and a summary of assessments over the past 20 years of groundwater availability. Building on this background, Chapters 7 and 8 of this report consider the availability and use of groundwater from an ecological perspective which takes into account the needs of flora and fauna as well as long-term human consumption. The sustainability of human society within any ecosystem is ultimately based on understanding of the needs of other organisms society depends upon. The ecosystem services model, in which groundwater is one component in a complex ecological system, helps provide a foundation for sustainable groundwater management.

Ecosystem Services: An Overview

Ecosystem services are the conditions and processes through which natural ecosytems, and the species that make them up, sustain and fulfill human life (Daily, 1997). These services maintain biodiversity and the production of *ecosystem goods*, such as seafood, forage, timber, biomass fuels, natural fiber, many pharmaceuticals, and industrial products. The harvest and trade of these goods represent an important part of the human economy. In addition to the production of these goods, ecosystem services provide life-support functions, as well as intangible aesthetic and cultural benefits.

Groundwater services, a subset of ecosystem services, include *extractive* services where groundwater pumped from the ground is utilized for a variety of human needs. Groundwater services also include *non-extractive* services, such as providing moisture to soils and water for base flow in streams. Ultimately, these indirect non-extractive groundwater services are also vital to human society’s quality of life, and ultimately to our very ability to inhabit Charlottesville and Albemarle County.

Groundwater Services and Sustainable Groundwater Management

The ecosystem services model recognizes that nature provides free services to the human economy; if we lose them, we have to create artificial systems to compENSAT Corporatone for their loss. The County’s current groundwater management program, while sophisticated, may be predicated only on protection and enhancement of extractive groundwater services, a policy embodied in the County’s Comprehensive Plan:

> *Objective: Protect the availability and quality of groundwater resources (page 51, Albemarle County Comprehensive Plan, Water Resources)*

The County's Comprehensive Plan does however embrace elements of ecosystem services. The Introduction to the "Natural Resources" chapter states:

> *The ecological functions provided the County's environmental resources are critical to our economy, health, welfare, safety, and quality of life. These functions include:*
>
> - *purification of air and water*
> - *mitigation of floods and droughts*
> - *Detoxification of floods and droughts*
> - *detoxification and decomposition of wastes*
> - *generation and renewal of soil fertility*
> - *pollination of crops*
> - *control of pests*
> - *maintenance of biodiversity for human needs*
> - *moderation of climate, including temperature extremes, wind, etc.*
> - *aesthetic beauty and intellectual stimulation*
> - *recreation*
>
> *(Albemarle County, 1999, Page 1).*

Sustainable groundwater management is defined in this report as a withdrawal rate of groundwater for extractive groundwater services that does not degrade non-extractive groundwater services. "Extractive groundwater services" involve water pumped from the ground and used by human society for water supply. These services include water for drinking, cooking, washing, and other household uses; for manufacturing, thermoelectric power generation, and other industrial uses; for irrigation of crops, parks, golf courses, etc., and for aquaculture. "Non-extractive groundwater services" involve water left in the ground to provide soil moisture to the vadose zone via capillary action; base flow for streams to sustain aquatic ecosystems in streams, lakes and rivers; and water for recreational swimming and boating opportunities. Sustainable groundwater management therefore involves evaluating the volume of groundwater needed for extractive and non-extractive services, considered in the contexts of the hydrogeology of the supply wells and recharge areas, and of changing climatic conditions and land uses.

Stream Ecosystem Health as a Proxy for Non-extractive Groundwater Services

If sustainable groundwater management hinges on non-extractive groundwater services, how are such services to be quantified? The empirical data necessary to precisely quantify these services, such as groundwater flow, storage and recharge rates; river and stream base flow; and rates of evapotranspiration, are unavailable for the Charlottesville region. Until such data become available, it is appropriate to consider the use of a proxy for non-extractive groundwater ecosystem services. We have chosen stream ecosystem health as such a proxy through the following sequence of logic:

1. There is a direct relationship between rainfall and groundwater recharge.
2. Assuming no net change in groundwater storage, the volume of water used for non-extractive groundwater services *plus* the volume of water used for extractive groundwater services *equals or is less than* volume of total recharge.
3. Assuming no extractive groundwater services (a condition that exists in the remote undeveloped watersheds of Albemarle County), water volume used for non-extractive groundwater services is less than or equals recharge.
4. Increasing impervious land cover in a given watershed results in a proportional decrease in groundwater recharge.
5. Increasing impervious land cover in a given watershed is correlated with degradation of stream ecosystem health (documentation below).
6. Degradation of stream ecosystem health in a given watershed may be correlated with decrease in groundwater available to provide non-extractive services.

Relationship between Recharge and Impervious Land Cover

As impervious land cover increases, recharge decreases. According to Paul and Meyer (2001), the following relationships exist between evapotranspiration (ET), runoff, shallow infiltration, deep infiltration, and land cover (note that shallow infiltration combined with deep infiltration comprises recharge):

Forested land cover: ET 40%, runoff 10%, shallow infiltration 25%, deep infiltration 25%

10-20% Impervious land cover: ET 38%, runoff 20%, shallow infiltration 21%, deep infiltration 21%

35-50% Impervious land cover: ET 35%, runoff 30%, shallow infiltration 20%, deep infiltration 15%

75-100% Impervious land cover: ET 30%, runoff 55%, shallow infiltration 10%, deep infiltration 5%

Figure 4 below graphs these percentages, showing that in forested land cover, the percentage of evapotranspiration and shallow and deep infiltration are highest, yet runoff is lowest. In areas that are 75-100% impervious, the opposite is found.

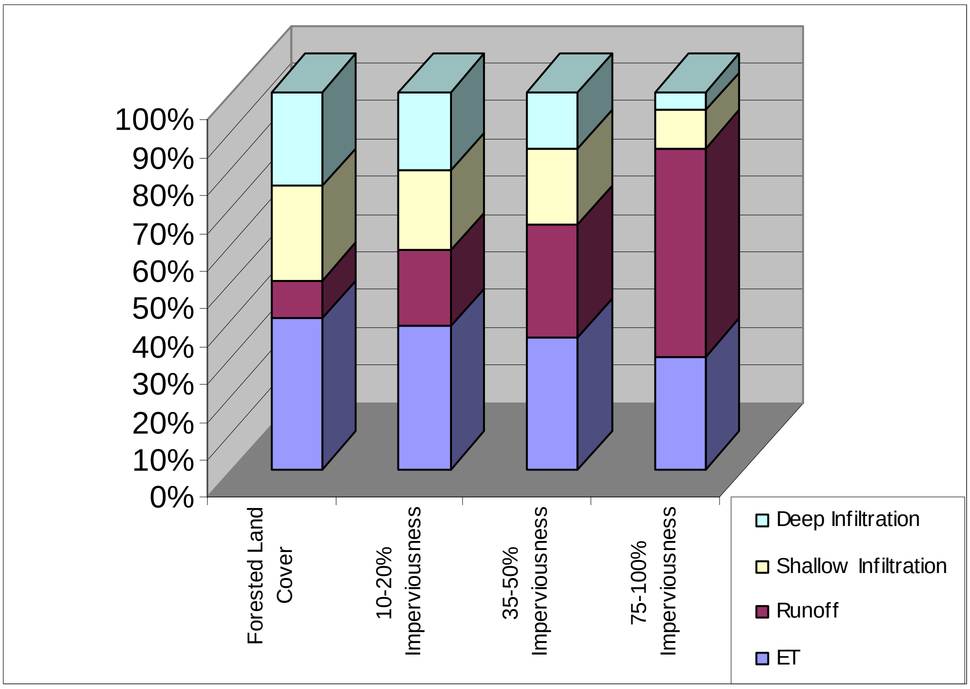


Figure 4: Relationship of Percent Impervious Land Cover to Infiltration Rate

Natural recharge to groundwater is controlled by a nuber of factors, primarily land cover, slope and soil permeability. However, for purposes of the present study, the most significant implication of the Paul and Meyer analyses is that as impervious land cover increases, natural recharge decreases proportionally. This is not surprising: as more and more of the land's surface is rendered impervious, therefore not allowing rainfall to soak into the ground, recharge logically decreases. For illustrative purposes, we estimate that the percentage of reduction in recharge is negatively correlated with percent increase in impervious land cover. Thus, a 75% increase in impervious land cover results in a 75% reduction in recharge.

Quantitative Link between Watershed Impervious Land Cover and Aquatic Ecosystem Health

According to a review published in 2009 in the Journal of Hydrologic Engineering, since 2003, nearly 250 research studies have confirmed that stream health can be predicted on the basis of impervious land cover (Schueler and others, 2009). Most habitat metrics are initially sensitive to impervious cover in the 5 to 20% range. Other studies that confirm this range of values include research by the Delaware Department of Natural Resources, showing that biological habitat drops sharply in nontidal, Piedmont streams at percentages of watershed impervious land cover ranging from 8-15% (Maxted and Shaver, 1994). The Center for Watershed Protection cites research conducted in many areas of the U.S. that shows stream degradation occurring at levels of impervious land cover, ranging from 10-20% (Schueler, 1995). Research completed in Maryland shows that macroinvertebrate density declines above 10% impervious land cover (Schueler and Galli, 1992 as cited in Schuler, 1995). In Maryland, the health of brown trout was shown to decline at 10-15% impervious land cover (Galli, 1993).

To date, no local studies similar to those cited above have been completed. Streamwatch, an Albemarle County-based organization, is currently conducting research that will provide information with which to correlate land cover with macroinvertebrate health. Another study in the ASAP Optimal Sustainable Population Size Project—"Impacts of Population Density and Forest Cover on Stream Health in the Rivanna River Basin", undertaken by Rob Kurtz (to be completed in February 2010)—also examines the effects of land use on stream health.

Relationship between Stream Health and Non-extractive Groundwater Services

The primary role of nonextractivce groundwater services in promoting stream health is in providing base flow that keeps the streams running between precipitation events and in times of drought. While base flow is only one metric among many that determine a stream's health, base flow is arguably the most significant during times of the year when there is little or no contribution to streams by surface water runoff. The studies above suggest that impervious land cover on the order of 5-20% leads to degradation of stream health. By extension, this is equivalent to a diminution of recharge by 5-20%, which is equivalent to diminution of non-extractive groundwater services by 5-20% in a watershed where no water is being extracted for human water supply. This implies that in an undisturbed watershed, 80-95% of groundwater recharge is needed for non-extractive groundwater services.

The above assessment has profound implications for groundwater use as a water supply for humans. The volume of groundwater needed for non-extractive services is significantly greater than the volume available for sustainable extraction. In practical terms this means that maximum sustainable extraction rates, when considered through a sustainable groundwater management paradigm, may be substantially reduced from what drillers and consulting geologists report as available yields.

Sustainable Groundwater Management in Charlottesville/Albemarle

Sustainable management of groundwater requires that groundwater extraction not negatively impact non-extractive groundwater services. Under normal climatic conditions (non-drought conditions), the volume of water pumped to provide extractive services is restricted to the 5-20% of available recharge not needed for non-extractive services. Sustainable groundwater management requires that groundwater extraction must not cut into the 80-95% of available recharge that is needed to provide for non-extractive services.

Under drought conditions, there could be hydrogeologic settings where the total volume of available recharge is less than needed to provide for non-extractive services. Under these conditions, even small amounts of groundwater extraction are unsustainable. These conditions occurred as recently as 2002 in the Charlottesville area, when severe drought caused base flow in many small local streams to disappear entirely.

The amount of groundwater available on a given parcel to provide for both extractive and non-extractive services varies as a function of hydrogeology, topography and land cover. There are settings within the study area where groundwater recharge and flow across a given parcel are very large relative to the volume of groundwater needed for non-extractive services. In these settings, it is theoretically possible to sustainably pump significant quantities of water from the ground, and apply it to a consumptive use such as commercially bottled water, where it is transported away from the local watershed. In other areas, groundwater flow and recharge are limited by hydrogeology and other factors. In theses areas, the volume of water available for extraction may be relatively small. Sustainable management of groundwater requires accurate knowledge of the hydrogeologic setting of a well. A change in hydrogeologic conditions, land cover or climate might change a groundwater use from sustainable to unsustainable.

In most situations, the use of groundwater for residential needs in the rural area of Albemarle is non-consumptive, in the sense that most of the water is returned to the ground after use via a sanitary drainfield. Therefore in most cases, domestic groundwater use in the rural areas of the county does not degrade non-extractive services, and is generally sustainable, regardless of hydrogeologic setting.

However, each time a house is constructed on previously agricultural or forested land, land cover is altered, and the local water budget (the allocation of water between precipitation, recharge, surface runoff, and in-ground storage) is incrementally changed, due to reduction in infiltration caused by an increase in impervious land cover.

The cumulative impact of widespread land conversion and residential development may, over time, render existing uses unsustainable due to compromised recharge capacity leading to a local lowering of the water table.

8: Groundwater Availability in Charlottesville & Albemarle: 2009 Assessment

Introduction

The 2003 groundwater availability model for Albemarle focused on extractive groundwater services dedicated to supplying human needs (ENSAT Corporation and others, 2003). However, as discussed above, groundwater also provides non-extractive services to clients other than human beings. The natural ecosystems dependent on groundwater not only enhance quality of life for human beings, but are also crucial for our survival. In that sense, non-extractive services provided to non-human clients in the natural world ultimately serve human interests.

In developing a groundwater availability model in 2009, it is appropriate to adopt the concept s*ustainable* groundwater extraction. S*ustainable* extraction of groundwater is a rate of groundwater withdrawal that does not, over time, result in a negative impact on non-extractive groundwater services. This rate of withdrawal must always be evaluated within the context of specific hydrogeologic settings and specific points in time. The theoretical maximum sustainable extraction volume for a given site can be expressed as:

> (volume of groundwater recharge available to site) minus (volume of groundwater required to support existing non-extractive groundwater services).

The groundwater recharge component of the equation can be evaluated, at least qualitatively, by examining factors including acreage, land cover and topographic position relative to the "receiving" parcel, in addition to hydrogeologic factors such as bedrock geology and transmissivity of soils and saprolite. These factors were also considered in the 2003 ENSAT Corporation and others report. The volume of groundwater required to support non-extractive groundwater services relative to the site is difficult to quantify, although a theoretical basis using percentage of impervious land cover as a proxy for diminution of non-extractive groundwater services has been developed above. This is based on data that suggest that damage to natural ecosystems becomes significant when the percentage of impervious land cover in a given watershed surpasses 5-20%, which by proxy is roughly equivalent to a diminution of available recharge by the same percentage.

The present study has reexamined the area's hydrogeology in light of more recent data obtained from geophysical and geological investigations conducted by Virginia Groundwater LLC, in addition to recent drilling and aquifer testing. Individual hydrogeologic settings within the study area have been evaluated with respect to recharge availability, and relative volume of groundwater needed to support non-extractive groundwater services. These estimates of recharge and non-extractive volumetric requirements provided the basis for assessing potential for *sustainable* extraction of groundwater within the City and County.

Residential development on 2-acre lots allowed by current County zoning, with individual wells and drainfields, appears sustainable in most areas, to the extent that groundwater use is non-consumptive, with most water being returned to the ground through the drainfields. The increase in impervious land cover associated with residential development, even at 2-acre density, does have an incremental impact on the amount of overall groundwater recharge. In areas of widespread build-out, the cumulative impact of impervious land cover associated with buildings, roads and driveways has the potential to diminish overall groundwater recharge, effectively lowering the local water table.

Is it possible to identify areas where groundwater resources exist substantially in excess of what is needed to supply both residential usage and non-extractive needs, to the extent that excess groundwater could sustainable be extracted for municipal, agricultural or industrial purposes? Conversely, is it possible to identify areas where groundwater resources are barely adequate to supply residential usage and non-extractive needs, or perhaps insufficient? The answers to these questions have implications for future population growth in this area, and are the focus of the 2009 availability assessment.

In reviewing the hydrogeologic units defined in the 2003 study (ENSAT Corporation and others, 2003), it became apparent that several units, comprising all of the City and significant land area in the County, are too heterogeneous to categorize in terms of *sustainable groundwater extraction potential* without further site-specific study. Other hydrogeologic units identified by ENSAT Corporation and others (2003) are sufficiently homogeneous and unambiguous as to be readily characterized in relative terms as having either *high* or *low* potential for sustainable extraction. In addition, one hydrogeologic unit not recognized in the 2003 report—underlying an area adjacent to the Southwest Mountains in eastern Albemarle County--was defined and characterized in the present study. The result of this exercise is a 2009 groundwater availability map for the City and County (Figure 5, below).

The 2009 availability map illustrates the potential to achieve *significant* sustainable groundwater extractions across the study area. *Significant* sustainable extractions are defined in this report as groundwater volumes that could be extracted sustainably, that are substantially larger than groundwater volumes necessary to support current extractive usage (or extractive usage theoretically enabled under current zoning densities). Areas of *high potential* for significant sustainable groundwater extraction are areas where potential exists for pumping substantially more groundwater than current usage (or allowable under current zoning) without negative impacts to non-extractive groundwater services. Areas of *low potential* for significant sustainable extraction are those areas where achievable maximum sustainable extractions are likely at or below levels of current usage (or allowable under current zoning). Areas of *mixed potential*, which comprise the City and large portions of the County, are areas that are heterogeneous in terms of hydrogeology, topography and other factors that affect potential for sustainable extraction. Evaluating maximum sustainable extraction in this area requires site-specific study of individual land parcels.

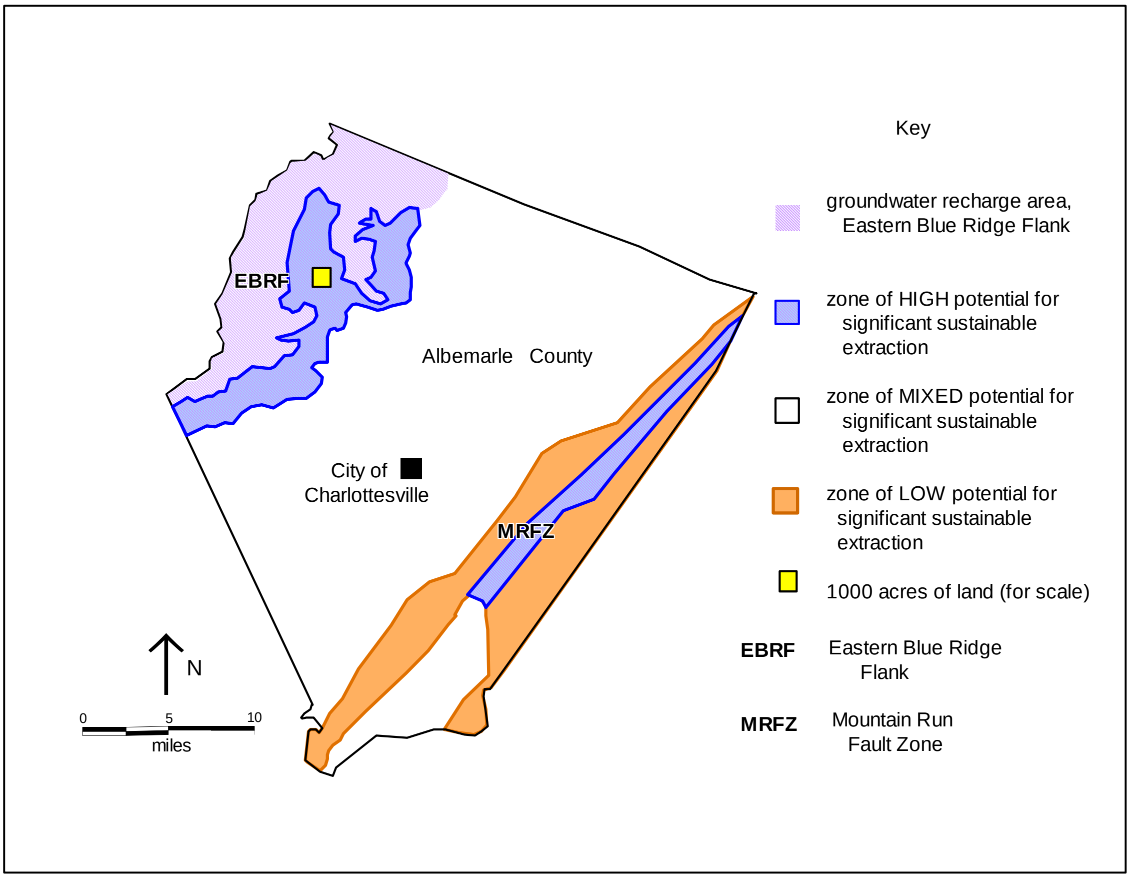


Figure 5: Zones of Low, Mixed, and High Potential for Significant Sustainable Groundwater Extraction in Albemarle County and the City of Charlottesville.

Zones of High Potential for Significant Sustainable Groundwater Extraction

Two hydrogeologically distinct zones of high potential for significant sustainable extraction are identified in Figure 5. These zones have unique hydrogeologic characteristics favorable to groundwater recharge and flow.

1) *Eastern Blue Ridge Flank (EBRF):* This zone includes hydrogeologic units II ("colluvial fans") and 1W ("Blue Ridge West") from the 2003 study. The hydrogeologic setting combines amply fractured bedrock, highly transmissive colluvial deposits, and vast acreages of up-gradient undisturbed forest recharge area, creating the possibility of multiple wells capable of sustaining yields on the order of several tens of gallons per minute. This zone is presently host to several very productive wells with yields on the order of several tens of gallons per minute or more.

2) *Mountain Run fault Zone (MRFZ):* This hydrogeologic zone straddles the boundary between units VI (Candler) and VIII (Piedmont Proper) of the 2003 study, but was not defined as a separate unit at that time. Nor did the 2002 assessment identify the MRFZ as a zone of high potential for significant sustainable extraction. Geologically, the MRFZ is a fault zone that extends from Orange County through eastern Albemarle and beyond. Geographically, the zone roughly corresponds to the drainage valleys of Mechunk, Limestone, and Buck Island Creeks, to the northeast and southwest of the Rivanna River in eastern Albemarle County. The hydrogeologic setting is one of fractured, faulted bedrock that includes lenses of limestone with solution cavities. The soils and saprolite layer is thick and highly transmissive, providing ample storage and recharge potential to bedrock water-bearing zones.

   The MRFZ receives recharge from acreage adjacent to the creek drainages themselves, plus likely receives recharge via northwest-trending fracture systems intersecting the Southwestern Mountains to the west. This zone is presently host to several highly productive community, agricultural, and domestic wells with yields on the order of several tens of gallons per minute. Pumping tests on community wells within this zone imply that the aquifer system is not being stressed by existing users. This is "implied" due to the fact that pumping the community wells at full capacity over a period of days did not produce significant drawdown in nearby observation wells. These tests did not however monitor implications of heavy continuous pumping on non-extractive services, such as in-stream flow. Further testing that includes evaluating non-extractive services impacts would be necessary to fully assess sustainable extraction potential of the MRFZ.

   Note: The 2003 report (ENSAT Corporation and others, 2003) also included hydrologic unit IV (Lynchburg) within that report's highest availability zone. While unit IV indeed exhibits higher than average yields on the basis of available water well data, the hydrogeologic setting is significantly different from both the EBRF and MRFZ, in terms of areal extent, topographic setting, and hydrologic character of likely recharge areas. Possibilities for multiple wells with significant sustainable extraction potential do not appear to be widespread within the Lynchburg zone, although detailed site-specific studies could reveal such if undertaken in the future.

Quantitative Analysis: Sustainable Extraction Potential, Eastern Blue Ridge Flank (EBRF)

A quantitative estimate of sustainable groundwater extraction potential in the EBRF is possible using the water budget data discussed in Chapter 5 of this report, and data from a recent groundwater development project on a roughly 1000-acre parcel located within the zone. This parcel is a private piece of land; both the location and actual hydrogeologic data are proprietary. Data have been made available for purposes of this discussion.

The geographic area supplying groundwater recharge to the EBRF, including the zone itself, comprising colluvial fans near the base of the Blue Ridge, and forested uplands on the mountain flank, is about 138 square miles, or 88,320 acres. While it is likely that considerable hydraulic communication (and potential for groundwater recharge) exists between the forested mountainside above the 1000-acre parcel, and the colluvial and bedrock aquifers on the parcel itself, this recharge contribution from off-site cannot be quantified using existing data. For purposes of this analysis it is assumed that recharge available to the property is at minimum the overall average determined for the County in the water budget analysis (Chapter 5, above), of 1079 gallons per day per acre. Thus the parcel under consideration theoretically receives about 1,079,000 GPD of recharge.

The 1000-acre parcel underwent an extensive program of geological and geophysical investigations, after which a series of wells were constructed at the most favorable drilling sites. Pumps were installed, and the wells were pumped simultaneously over a period of multiple days while water levels in nearby wells were monitored. Pumping levels were adjusted to what appeared to be “safe” long-term extraction rates, that is, rates that did not cause excessive drawdown of the pumping wells, or of nearby monitoring wells. At the end of the tests, the consultant interpreted the data as indicating the well field was capable of producing about 216,000 GPD (.216 MGD) of water without compromising the production wells or nearby existing wells.

The consultant’s analysis of groundwater capacity for this site did not attempt to consider impacts to non-extractive groundwater services during the pumping tests. The recommended maximum pumping capacity may or may not approximate maximum sustainable extraction for the site. The reported aggregate yield (.216 MGD) represents about 20% of theoretical recharge to the parcel (1.08 MGD). This figure is at the high end of the theoretical maximum sustainable extraction (5 to 20% of available recharge, or .108 to .216 MGD).

The geographic area of the EBRF zone itself (Unit II, Colluvial Fans unit of the 2003 map) is about 56.6 square miles, or 36,224 acres. To the extent that it would be theoretically possible to fully develop groundwater potential over the entire zone, and sustainably extract between .108 and .216 MGD of groundwater per 1000 acres throughout, the overall availability within the zone would be on the order of 3,900,000 to 7,800,000 GPD (3.9 to 7.8 MGD).

While this is a coarse approximation of absolute numbers for maximum sustainable extraction in the EBRF, it does suggest that substantial groundwater resources do exist in that part of the county that could be utilized sustainably in the future to serve agricultural, industrial, and municipal supply needs. In order to sustainably develop these resources on a large scale, research would need to be conducted in order to better quantify the recharge contribution to particular well sites of forested uplands up hydraulic gradient on the flank of the Blue Ridge.

Sustainable Extraction Potential, Mountain Run Fault Zone (MRFZ)

Potential for sustainable groundwater extraction in the Mountain Run Fault zone (MRFZ, Figure 5) also substantially exceeds what is currently being extracted for municipal and agricultural use. Multi-day pumping tests of wells at Keswick Hall and elsewhere within the zone have established that abundant groundwater exists. However, the existing data do not enable quantitative assessment of overall groundwater availability within the zone on a GPD per-acre basis. Similar to the EBRF, there is likelihood that the MRFZ receives recharge via northwest-trending bedrock fractures from forested up-gradient lands on the eastern flank of the Southwest Mountains. In order to further develop the MRFZ sustainably, it will be necessary to better understand and quantify recharge to the zone. Additional pumping tests will need to be conducted in which non-extractive groundwater services indicators, such as stream base flow, are monitored.

It should be noted that a change in hydrogeology (e.g. catastrophic debris flow or landslide), climatic conditions (e.g. severe drought), or land cover (e.g. forest fire or clear cut in recharge area) could change an existing sustainable groundwater extraction to unsustainable. Diminution of recharge by whatever means results in diminution of maximum sustainable extraction volume.

Zone of Low Potential for Significant Sustainable Extraction

The lowest potential for significant sustainable groundwater extraction within the study area exist~~s~~ within the belt of phyllite and schist in the eastern part of the County. This is an area where groundwater resources may, locally, be insufficient to sustainably supply residential development at current zoning densities. This low availability area was recognized in the ENSAT Corporation and others study (2003), and includes Hydrogeologic Zones VI and VIII. Ironically, one of the zones of high potential, the MRFZ, is situated in the center of this lowest availability zone.

The hydrogeologic setting of the low potential zone is illustrated by geophysical Image 2 (above), and related discussion. Groundwater-bearing fractures tend to be shallow, isolated, and locally recharged. Well yields are low, and in this setting are particularly vulnerable to fluctuations in annual precipitation. Availability of groundwater within this zone is generally adequate to sustainably fulfill the needs of individual residences on 2-acre lots, although a successful well may be difficult to site on some parcels. The fact that recharge in this particular hydrogeologic setting is local, rather than from far away, implies that over-pumping a well in this zone (exceeding sustainable extraction) will likely have primarily local affects in terms of lowering of the water table, potentially compromising groundwater services locally as opposed to regionally.

Zone of Mixed Potential for Significant Sustainable Extraction

Within the zone of mixed potential (Figure 5)—covering Charlottesville and roughly 60% of Albemarle County--the hydrogeologic settings are too heterogeneous to assign sustainable extraction potential without more information. In general, availability appears to be at least adequate to sustainably supply existing residential development on minimum 2-acre lots, as permitted under current zoning in the rural area of the County. It is possible that discrete hydrogeologic settings with high potential exist within the zone of mixed potential. However site-specific study of individual land parcels would be necessary in order to identify such zones.

9: Conclusions

Findings

1. New language has emerged in recent years to describe responsible stewardship of groundwater resources.

This report introduces and defines the terms:

- Sustainable groundwater management
- Extractive groundwater services
- Non-extractive groundwater services
- Sustainable groundwater extraction.

2. Geophysical images reveal that groundwater is not uniformly distributed throughout the study area. In addition, the images specifically reveal the following:

- Bedrock fractures are not uniformly distributed, even within the same rock-type on a small parcel of land, and are not always interconnected in a horizontal sense.
- Thickness and water storage and transmission capacity of saprolite (the near-surface sponge composed of weather bedrock) vary from place to place, even within the same rock type. In some geologic settings, the only water available for water supply wells exists in the soils and saprolite, above bedrock.
- Recharge to water-bearing zones in the saprolite and the bedrock may be very local in settings where both hydraulic gradient and interconnectivity among fractures are low. This means that in some situations, recharge may be affected much more by land cover changes in the immediate vicinity, than by activities that take place farther away.

3. The conceptual foundation of sustainable groundwater management is that demand for non-extractive groundwater services receives priority over fulfilling demands for extractive groundwater services.

The maximum amount of groundwater that can be sustainably pumped from the ground is the volume left over after non-extractive groundwater needs have been satisfied.

4. The County's previous groundwater studies and groundwater policy have been focused on extractive groundwater services.

The 2003 availability report (ENSAT Corporation and others, 2003) focused on absolute amounts of groundwater that occur in different parts of the county, capable of being "captured" for human use by drilling a well. It should be noted, however, that language in support of non-extractive groundwater services can be found in non-groundwater specific County policy, such as the Introduction to the Natural Resources Chapter of the Comprehensive Plan (Albemarle County, 1999).

5. Stream ecosystem health can be used as a proxy for non-extractive groundwater services, and an indicator for sustainable groundwater management.

The percentage of impervious land cover that is a threshold for onset of degradation of stream ecosystem health can be used to quantify the percentage of recharge required to supply non-extractive groundwater services. Locally, the degradation threshold appears to be in the range of 5 to 20% impervious land cover. In terms of groundwater recharge, the threshold of degradation to stream ecosystem health can be estimated at diminution of recharge by 5 to 20%. It follows that 80 to 95% of natural recharge is required to fulfill non-extractive groundwater services. This means that 80 to 95% of recharge must be left in the ground, and that a maximum of 5-20% of groundwater recharge in Charlottesville and Albemarle County can be used for extractive groundwater services.

6. The amount of groundwater available on a given parcel to provide for both extractive and non-extractive services varies as a function of hydrogeology, topography and land cover.

There are settings within the study area where groundwater recharge and flow across a given parcel are very large relative to the volume of groundwater needed for non-extractive services. In these settings, it is theoretically possible to sustainably pump significant quantities of water from the ground, and apply this water to a consumptive use where water is transported away from the local watershed. In other areas, groundwater flow and recharge are limited by hydrogeology and other factors. In these areas, the volume of water available for sustainable extraction may be relatively small.

Albemarle County contains two recognizable zones of high potential for significant sustainable groundwater extraction, and one recognizable zone of low potential (Figure 5, above). The remainder of the County and the entire City are within a zone characterized as having mixed potential. Within this area, site-specific study will be required to identify zones of high or low potential, to the extent that such may exist.

7. The use of groundwater for residential needs in the rural area of Albemarle is non-consumptive, in the sense that most of the water is returned to the ground after use via a sanitary drainfield.

Therefore in most cases, under current 2-acre minimum lot size zoning, domestic groundwater use in the rural areas of the county does not degrade non-extractive services, and is generally sustainable, regardless of hydrogeologic setting.

8. Sustainable groundwater management has implications for sustainable population size.

Under sustainable groundwater management, 80-95% of groundwater recharge is left in the ground to provide for non-extractive groundwater services. Simply stated, this means that under sustainable management, over the long-run, the great majority of groundwater is unavailable for extractive consumption by humans. This would seem to imply that the size of the community's "sustainable" population may be less than—as presumed in previous assessments of water availability—if all available groundwater were to be extracted to supply human needs.

On the other hand, the impact of sustainable management (or lack thereof) could be particularly significant should Albemarle's EBRF and MRFZ be utilized for groundwater supply. For example, rather than the 3.9 to 7.8 MGD estimated to be available for extractive services from the EBRF under a sustainable groundwater management regime, approximately 39 to 78 MGD could theoretically be pumped, in the short-term, to facilitate commensurate population growth above and beyond what is sustainable relative to protection of non-extractive groundwater services. The results of unsustainable groundwater mining such as this could be widespread lowering of the water table, causing elimination of base flow in many streams and landscape-scale desertification. This has the potential to drastically alter quality of life, and disrupt the local food supply, among other implications for the resident human population.

9. Sustainably managed groundwater could provide a significant proportion of future water needs for the City of Charlottesville and urban areas of the County.

Sustainable groundwater extraction from the Mountain Run Fault Zone (MRFZ) and Eastern Blue Ridge Flank (EBRF) could have a significant impact on maximum sustainable population size for the area. If the County and City were to decide to use groundwater for municipal water supply, a significant portion of the estimated future demand could be supplied via municipal well withdrawals from these two areas.

It should be noted, however, that the County's longstanding water supply policy is surface-water based. According to Mike Lynn, ACSA Operations Manager, as of August, 2009, the only municipal groundwater system in use by the Authority today is for a small cluster of homes on Red Hill Road.

The following exercise indicates that the EBRF may be capable of supplying from 25 to 49% of the future municipal water demand at build-out:

To estimate the population size at build-out within the County Growth Areas and City combined, we refer to estimates presented in the recent report *Estimating Impacts of Population Growth on Ecosystem Services for the Community of Albemarle County and Charlottesville, VA* (Jantz and Manual, 2009):

	2000 population	Build-out population
Charlottesville area	72,297	111,882
Crozet	7,101	25,106
Rivanna	3,960	14,205
Route 29	12,458	60,310
TOTAL	**95,816**	**211,503**

(difference between 2000 population and estimated build-out population = 115,687 persons)

According to the ACSA, the average water use for all single family residential customers (persons) is 4100 gallons per month or 137 gallons/day, assuming a 30 day month (Mike Lynn, personal communication, 2009). Applying this figure to the future build-out population of 115,687 persons, an additional 15.8 mgd will be needed.

We estimate the approximate availability of groundwater from the EBRF to be 3.9 to 7.8 MGD. This is equivalent to 25 to 49% of the total future demand needed at build-out of the Growth Areas and City, according to the Jantz and Manual projections. Additional groundwater capacity of a similar order of magnitude may be available on a sustainable basis from the Mountain Run Fault Zone, and perhaps from other areas yet to be identified within the mixed zone.

10. This study provides a conceptual framework with which to link residential density, stormwater management, impervious land cover, and non-extractive groundwater services in developing growth management strategies (see Recommendation 1 below).

Recommendations

1. Consider new policies linking groundwater, impervious land cover, stormwater management, and residential development density.

The County and City should consider new policies that limit watershed percentage impervious land cover, while maximizing stormwater infiltration, in order to maximize allowable groundwater extraction. Such policies (for example, see #5 below) would be designed to ensure that recharge necessary for non-extractive groundwater services is not reduced below a sustainable threshold. That threshold, conceptually pegged at a range of 80-95% of recharge in this study, will need to be scientifically determined in a separate investigation conducted by a team of hydrogeologists, ecologists, soils scientists, environmental planners, and others. The implications of such a threshold could have a significant impact on County and City stormwater policy and on County groundwater policy, particularly in areas with impervious land cover greater than 5-20%.

2. Further study potential recharge areas in the Blue Ridge Mountains and Southwestern Mountains in order to better quantify maximum sustainable extraction volumes for the ERBF and MRFZ.

3. Study land use policy and groundwater further in the zone of mixed potential for significant sustainable extraction, in order to identify areas of high and low potential for significant sustainable extraction.

4. Consider using sustainably managed groundwater extraction to augment municipal water supplies for the City and Growth Areas of the County.

5. Due to the cumulative impact of impervious land cover on groundwater recharge, residential development densities greater than approximately one house per two acres should be served through community water supply systems rather than individual wells to protect groundwater needed for non-extractive groundwater services.

6. Recognize that a community's sustainable population size is determined, in part, by the availability of sustainably managed groundwater—not simply by accessible groundwater.

7. Albemarle County and the City of Charlottesville, working with the Rivanna Water and Sewer Authority and the Albemarle County Service Authority, need to begin to address groundwater holistically. As a starting

point, we suggest convening a broad-based committee charged with a mission to consider the role of groundwater from a sustainability and ecosystem services perspective, by addressing the following questions:

- If the majority of groundwater should remain in the ground to be used for non-extractive services, how does that impact human society in the region beyond those impacts discussed in this study?
- What is the extent of the upland recharge areas that supply the EBRF and MRFZ?
- How much water is likely to be available from the MRFZ in addition to the EBRF?
- How might the availability of groundwater from these zones impact water supply planning?
- How does groundwater viewed from the perspectives outlined in this paper impact stormwater policies and County Growth Area, Rural Area, and City of Charlottesville development policies?
- What new opportunities might be created for rural landowners interested in new sources of revenue for working lands (lands managed for agriculture and forestry), through protecting groundwater ecosystem services within the context of a broader ecosystem services marketplace?

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Appendix A: Glossary of Terms

Alluvium: General term for unconsolidated detrital material (clay, sand, gravel) deposited in relatively recent geologic time, by a stream or other body of running water, in the bed of the stream or on its flood plain.

Bedrock: Un-weathered rock that underlies soils and weathered rock (saprolite); may contain fractures (cracks) through which groundwater may flow.

Ecosystem services: the conditions and processes through which natural ecosystems and the species that make them up, sustain and fulfill human life (Daily, 1997).

Evapotranspiration (ET): transfer of water to the atmosphere by processes of evaporation and photosynthesis.

Extractive groundwater services are used for water supply. These includes (Daily, 1997):

- Drinking, cooking, washing, and other household uses
- Manufacturing, thermoelectric power generation, and other industrial uses
- Irrigation of crops, parks, golf courses, etc.
- Aquaculture.

Fractured rock aquifer: a conduit for groundwater made up of fractures and fissures in bedrock otherwise impermeable to groundwater flow.

Geophysics: The study of the Earth by quantitative physical methods.

Groundwater: water that occurs beneath the surface of the ground within the zone of saturation.

Groundwater availability: the amount of groundwater present in the ground at a given time and location that could be extracted for human use.

Groundwater extraction: the withdrawal of groundwater from the ground to supply human needs.

Groundwater services: the conditions & processes through which groundwater provides benefits to human society.

Groundwater mining: groundwater extraction that results in degradation of extractive and/or non-extractive groundwater services.

Groundwater recharge: natural replenishment of groundwater storage from surface waters, primarily rainfall, but under some circumstances including water from rivers, streams, lakes and ponds.

Groundwater storage: the quantity of water within the zone of saturation.

Hydrogeology: the study of the distribution and movement of groundwater relative to subsurface geology.

Maximum sustainable extraction: the largest quantity of groundwater that can be sustainably extracted over time on a given site.

Non-extractive groundwater services are used to:

- Contribute soil moisture to the vadose zone via capillary action to sustain plants and trees
- Provide base flow to rivers, streams, ponds, and lakes to sustain aquatic ecosystems
- Provide water for recreational swimming and boating.

Overburden: soils and weathered rock material (saprolite) above bedrock.

Permeability: the capacity of a soil, sediment or porous rock to transmit a fluid (water).

Phyllite: A metamorphic rock intermediate between a slate and a schist, composed primarily of the micaceous minerals sericite and chlorite.

Saprolite: weathered rock material that exists below near-surface soil horizons, and above bedrock.

Schist: A metamorphic rock that can be readily split into flakes or slabs due to the well-developed parallelism of more than 50% of the minerals present.

Sustainable groundwater extraction: groundwater extraction that does not result in degradation of non-extractive groundwater services.

Sustainable groundwater management: groundwater management that does not degrade non-extractive groundwater services.

Transmissivity: the rate at which groundwater can be transmitted through aquifer media (soils, saprolite or bedrock).

Vadose zone (zone of aeration): a subsurface zone above the water table, where interstices in soils, saprolite and rock contain air plus water droplets.

Water table: the surface between the zone of aeration and the zone of saturation.

Water budget (theoretical): the relationship between precipitation, evapotranspiration, runoff and groundwater recharge & storage expressed by a hydrologic equation.

Zone of Saturation: A subsurface zone below the water table where interstices in soils, saprolite and rock are filled with water.

Appendix B: Historical Context

This report is preceded by, and builds upon, discussion, events and previous works generated over the past 20 years. Key elements of the time line are summarized below:

- *Groundwater Protection Study (1990; Albemarle County document archives):* Compendium put together by the County Water Resources Manager, of recommendations for the study of groundwater and policy initiatives (Albemarle County document).
- *Water Resources Committee Update of the Groundwater Protection Study (1993; Albemarle County document archives):* Prioritized recommendations in the original study; high priority assigned to conducting a pilot groundwater study.
- *Pilot Groundwater Study for the Hardware River Watershed (1994; Albemarle County document archives):* Pilot study provided a watershed-scale snapshot of water quantity and quality. Lists several recommendations for County groundwater program based on results of the study.
- Virginia Division of Mineral Resources and Thomas Jefferson Planning District Commission (1995 – 2001): Cooperative effort to develop pilot hydrogeologic databases for Albemarle and neighboring counties, incorporating water well data and geologic mapping in a GIS environment. Intent was to provide basic hydrogeologic data and groundwater availability information to localities in need of such.
- *Evaluation of Household Water Quality in Albemarle County, Virginia (Virginia Cooperative Extension Service, 1996):* Program tested five hundred private wells in the County and provided educational materials to hundreds of households.
- *Chapter Two of the Albemarle County Comprehensive Plan: Natural Resources & Cultural Assets (1999):* Update of the Plan has an expanded list of strategies related to groundwater, including formation of a groundwater committee.
- *Groundwater: our unprotected resource (Charlottesville/Albemarle League of Women Voters, 1999):* Brochure advocates for public policy based on sound hydrogeologic data to protect groundwater.
- *Verifying Adequate Groundwater Supplies for Rural Subdivisions (2000; Albemarle County document archives):* Produced by County staff in response to request from the Planning Commission, report summarized what other Virginia localities were doing at the time with regard to hydrogeologic testing. Report provided framework for formation of the Groundwater Committee.
- *Underground Albemarle: A Report from the Groundwater Committee (2001):* Committee report summarizes the committee's findings and recommendations in a number of areas related to groundwater policy, including a proposed

hydrogeologic testing ordinance. This led to funding of the first of five recommended watershed-scale hydrogeologic studies within the county.

- *Albemarle County Hydrogeologic Assessment Phase I: Mechums River and Ivy Creek Basins (2002; Albemarle County Department of Community Development archives):* The first of five proposed regional studies intended to characterize groundwater availability and vulnerability within hydrologically distinct areas of the County, in support of proposed hydrogeologic testing ordinance.
- *Albemarle County Hydrogeologic Assessment Phase II: Groundwater availability and sensitivity assessment with proposed groundwater assessment standards (2003; Albemarle County Department of Community Cevelopemnt archives):* Groundwater availability and groundwater quality assessments are developed on a County-wide scale. The combined results of these assessments are used in preparation of a County Groundwater Assessment Standards Manual, modeled on the tiered assessment approach originally outlined by the Groundwater Committee.
- February 8, 2005: Groundwater Ordinance based on the Groundwater Assessment Standards Manual goes into effect. County creates and fills a Groundwater Manager position to administer program.
- April, 2009: Groundwater Manager resigns; position to remain vacant indefinitely under current County hiring freeze.