ANNUAL AND SEASONAL WATER BUDGETS FOR THE MONOCACY/CATOCTIN DRAINAGE AREA
- Final Report

By

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TABLE OF CONTENTS

TABLES

FIGURES

Acknowledgements

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Executive Summary

The Potomac River basin comprises a 14,670 square mile drainage area which includes the city of Washington, DC, and some of the most rapidly growing counties in our nation. The recent period of drought in the region, from 1999 through 2002, focused public attention on water supply issues and the potential vulnerability of developing areas to future water shortages. Basin residents rely upon both ground water and surface water resources, with ground water being a major source of water supply for the majority of people living outside of the major urban centers. Many people living in the upper portion of the basin, upstream of the Washington, DC metropolitan area, obtain their water from wells drawing from aquifers in the fractured bedrock formations in the Piedmont, Blue Ridge, and Appalachian Valley and Ridge physiographic provinces. A large number of residents of the lower portion of the basin rely on water from a system of confined aquifers in the sand and gravel formations underlying the Coastal Plains province. In Washington, DC and surrounding areas, the primary source of water supply is the Potomac River itself.

The upper portion of the Potomac basin poses a challenge for water availability assessment for two reasons. First, ground water and surface water resources are closely interconnected. Ground water contained in the fractured bedrock aquifers of the upper basin continually discharges to the network of streams in the basin's watersheds and eventually flows into the Potomac River. Thus, ground water in the upper portion of the basin provides water for human consumption via both withdrawals from wells and withdrawals from surface waters, and also provides stream flow necessary to sustain the ecological health of our streams and rivers. Second, potential water supply problems are seasonal in nature. Concern about water availability is generally restricted to the summer and early autumn months, when both water levels in wells and ground water discharge to streams, i.e. stream baseflow, typically fall to their lowest levels of the year.

Groundwater availability is extremely difficult to characterize on a regional scale, and water management agencies often rely on a watershed water budget approach, which provides a relatively simple accounting of the quantity of water entering and leaving a system of interest in a given time frame. Water budgets are particularly useful for assessments of watersheds underlain by fractured bedrock aquifers, where, because of the interconnection between ground water and surface water, stream flow data can be used to help estimate important water budget components. However, water budget analyses use a variety of simplifying assumptions which may limit their accuracy and usefulness in particular cases.

The objective of this study is to assess the quantity of water available in the fractured bedrock aquifers underlying a pilot study area in the upper portion of the Potomac River basin, within the framework of the watershed water budget approach. The water budget analyses in this report rely on estimates of the quantities of ground water discharging to basin streams to obtain estimates of ground water recharge. The resulting estimates of water availability pertain to the quantity of water available in the interconnected stream network/aquifer system under conditions resulting in nonzero stream baseflow. The estimates in this study do not provide an assessment of the quantity of ground water remaining in a sub-basin aquifer in situations where ground water has dropped to a level resulting in zero stream flow.

In particular, the goal of this study is to evaluate and compare the predictions of two different water budget methodologies and to provide water supply planners with estimates, at the sub-basin scale, of water availability. The pilot study area includes the adjoining watersheds of the Monocacy River and Catoctin Creek, and drains a 1115 square mile area of Adams County, Pennsylvania and Frederick, Carroll, and Montgomery Counties, Maryland. Communities in the Monocacy/Catoctin drainage area, including Frederick, MD and Gettysburg, PA, are rapidly attracting new residents who commute daily to the Washington, DC metropolitan area.

Two different analyses are applied to the Monocacy/Catoctin drainage area to help assess water availability, the first based on an annual water budget and the second on a seasonal water budget. Both water budget analyses rely primarily on stream flow data from gaged sub-basins within or near the study area. The first analysis provides estimates of annual recharge to sub-basin aquifers throughout the study area. Estimates of annual recharge are believed to be reasonably reliable, and are sometimes used by water resource managers as a rough indication of the annual quantity of water available in a basin for both human consumptive use and maintenance of adequate stream baseflow to sustain the ecological health of basin streams. The second analysis, only carried out for a limited number of sub-basins within the study area, investigates the importance of seasonal effects and storage on water availability estimates. In this seasonal water budget approach, a simple measure of water availability is defined, as the volume of water stored in the upper portion of the sub-basin aquifer at the beginning of summer plus the volume provided by summer recharge.

Annual Water Budget Results

In the annual water budget analysis, ground water recharge was estimated from estimates of annual ground water discharge, i.e., annual stream baseflow, for 34 sub-basins where stream flow data was available. Annual baseflow statistics were extrapolated to ungaged portions of the study area using multiple linear regression techniques. The explanatory variables considered in the study were drainage area and percent of sub-basin in each of four hydrogeomorphic regions represented in the study area, Piedmont Crystalline (PCR), Mesozoic Lowlands (ML), Blue Ridge (BR), and Piedmont Carbonate (PCA). The annual water budget analysis used the simplifying assumptions that there is no change in storage from the beginning of one year to the beginning of the next and that water withdrawals are negligible. The main results of this analysis are the following:

- The set of parameters used to describe the geology/hydrogeology of the study area sub-basins were all significant predictors, at the 90% confidence level, of stream baseflow for the 10-year and the 20-year drought.

- Annual recharge rates for an average year for the PCR, ML, BR, and PCA hydrogeomorphic regions were estimated to be 8.5, 5.3, 12.2, and 14 inches, respectively, or equivalently, 630, 390, 910, and 1000 gpd/ac (gallons per day per acre).

- Annual recharge rates for a dry year (20-year drought) for the PCR, ML, BR, and PCA hydrogeomorphic regions were estimated to be 5.2, 2.4, 6.8, 14 inches, respectively, or equivalently, 390, 180, 510, and 1000 gpd/ac. Based on these estimates, the recharge rate for the Mesozoic Lowlands, underlain primarily by shale and sandstone formations, is less than half of that found in other regions. Results for PCA are subject to considerable uncertainty because of the more limited extent of this HGMR in the study area.

- Uncertainties for the dry year annual recharge estimates are on the order of roughly ± 50%.

Seasonal Water Budget Results

In the seasonal water budget analysis, sub-basin precipitation, stream baseflow, aquifer recharge, total evapotranspiration, and other water budget components were computed for every quarter in the time period, 1960 through 2002, for four sub-basins in the study area: Catoctin Creek, the upper Monocacy basin (above gage at Bridgeport, MD), Big Pipe Creek and Bennett Creek. Seasonal estimates were also made of ground water withdrawals throughout the time period of the study. The seasonal water budget includes seasonal changes in ground water storage, computed using information from ground water recession analyses. A summary of methods and results appears below:

- Baseflow recession coefficients were computed for the four sub-basins of interest. The recession coefficient is an estimate of the amount of time it takes, during periods of no precipitation, for stream baseflow to fall to 10% of its initial value. Median and mean values were found to range from approximately 30 to 90 days for the four sub-basins, indicating fairly poor storage properties for the upper portion of the fractured bedrock aquifers, especially in the upper Monocacy and Catoctin Creek sub-basins.

- "Beginning-of-quarter storage", that is, the volume of water stored in a sub-basin aquifer above the zero stream discharge level, was computed using baseflow recession indices, estimates of "beginning-of-quarter stream baseflow", and the standard assumption of log linear baseflow recession. The match between beginning-of-quarter storage and mean water levels from available well data, plotted over time, was found to be quite good, indicating that the storage estimates are reasonably reliable.

- A measure of the quantity of water available in the summertime, V_{Q3}, was defined as the sum of beginning-of-summer aquifer storage (above the zero stream discharge level) and summer recharge. The seasonal water budget was used to compute this quantity for each of the 42 summers (i.e. July, August, September) in the time period of interest, and frequency analyses were done to predict summer water availability in average years and in dry years.

- Summer water availability for an average year for the Catoctin, upper Monocacy, Big Pipe, and Bennett sub-basins were estimated to be 0.7, 0.4, 1.5, 1.4 inches per quarter, respectively, or equivalently, 210, 120, 460, and 420 gpd/ac.

- Summer water availability for a dry year (20-year drought) for the Catoctin, upper Monocacy, Big Pipe, and Bennett sub-basins was estimated to be 0.2, 0.1, 0.5, 0.5 inches per quarter, respectively, or equivalently, 60, 30, 150, and 160 gpd/ac.

- Summer water availability predictions for dry years for the Catoctin and upper Monocacy sub-basins are much lower than the corresponding annual recharge rates, and are on the order of only twice the rate of current ground water withdrawals in those sub-basins, estimated to be 24 and 15 gpd/ac, respectively (estimated primarily from 2001 data).

Conclusions

The results of this study provide two different estimates of the quantity of water available in the stream network/aquifer systems of sub-basins in the Monocacy/Catoctin Creek drainage areas, under conditions of non-zero stream flow. Water supply planners must apportion available quantities in a manner that meets both the consumptive use needs of human society and the requirements to maintain stream baseflow at levels adequate to sustain the ecological health of our streams. Provided that seasonal water budget components can be reliably computed, they should give more accurate predictions of summer water availability than analyses based on annual averages, since they include the effects of seasonality and aquifer storage. The approach to computing seasonal water budget components developed in this study, based on a baseflow recession analysis using "beginning-of-quarter" baseflow estimates, appears to give reasonably reliable results when compared with available well data. It is not surprising that the seasonal water budget analysis predicts considerably lower summertime water availability than annual recharge estimates, since water supply problems in the region typically occur only in summer and early fall. The seasonal water budget's extremely low predictions for dry-year summer water availability for the Catoctin and upper Monocacy sub-basins appear in part to be the result of these aquifers' poor ability to store recharge, as indicated by their low recession indices. For this type of sub-basin, it appears that the annual recharge estimates, which include the significant recharge which occurs in fall and winter, can mask the presence of potential water supply problems in the summer months. It should be noted that the Catoctin and upper Monocacy sub-basins, which primarily represent the BR and ML hydrogeomorphic regions, respectively, have both experienced significant water availability problems during times of drought.

In this study, a simple approach was developed to estimate seasonal water availability in sub-basins with closely interconnected stream network/fractured bedrock aquifer systems. In the four gaged sub-basins considered, the seasonal water availability estimates appeared to give important information concerning summertime availability which was not provided by the more commonly used annual recharge estimates. In order to extend this seasonal water budget approach to other areas in the upper Potomac River basin, it will be necessary to extrapolate results from gaged sub-basins to sub-basins where no stream flow data is available. As a first step, statistical regression analyses must be conducted to see whether the quantities used in summer availability predictions, that is, recession indices, beginning-of-summer baseflow, and summer recharge, can be estimated for ungaged sub-basins. Results from the regression analyses for annual baseflow characteristics carried out in this study indicate that hydrogeomorphic regions may be useful predictors of sub-basin flow characteristics.

Estimates of water availability made in this report, in both the annual and the seasonal analyses, were computed from stream flow data collected at USGS stream gage stations. Daily flow values from continuous record gage stations provide the most useful data, allowing the computation of baseflow recession indices and more accurate estimates of annual and seasonal baseflow. However, at this time only a handful of these stations are still in operation in the study area. Continuation of stream gage data collection programs is crucial for developing a better understanding of water availability in the Potomac River basin.

I. Introduction

I.1 Background

The Potomac River basin comprises a 14,670 square mile drainage area which includes the city of Washington, DC and some of the most rapidly growing counties in our nation. The recent period of drought in the region, from 1999 through 2002, focused public attention on water supply issues and the potential vulnerability of developing areas to future water shortages. Subsequent to 2002, the basin states of Maryland, Pennsylvania, Virginia, and West Virginia all initiated new water resource assessment and planning efforts. Basin residents rely upon both ground water and surface water resources, with ground water being a major source of water supply for the majority of people living outside of the major urban centers. Many people living in the upper portion of the basin, upstream of the Washington, DC metropolitan area, obtain their water from wells drawing from aquifers in the fractured bedrock formations in the Piedmont, Blue Ridge, and Appalachian Valley and Ridge physiographic provinces. A large number of residents of the lower portion of the basin rely on water from a system of confined aquifers in the sand and gravel formations underlying the Coastal Plains province. In Washington, DC and surrounding areas, the primary source of water supply is the Potomac River itself.

It is recognized that science-based assessments of water resources are essential for successful water resource planning programs. However, the technical tools currently available for water availability assessments on a regional scale are limited. Ground water flow or integrated ground water/surface water flow simulation models can provide the necessary answers to water supply planning questions, but the cost of a regional-scale modeling effort is often prohibitive. The alternative to flow simulation modeling is the water budget approach, but the results provided to date by simple water budget analyses may be too limited to provide answers to questions of potential importance.

The upper portion of the Potomac basin poses a challenge for water availability assessment for two reasons. First, ground water and surface water resources are closely interconnected. Ground water contained in the fractured bedrock aquifers of the upper basin continually discharges to the network of streams in the basin's watersheds and eventually flows into the Potomac River. Thus, ground water in the upper portion of the basin provides water for human consumption via both withdrawals from wells and withdrawals from surface waters, and also provides stream flow necessary to sustain the ecological health of our streams and rivers. Second, potential water supply problems are seasonal in nature. Concern about water availability is generally restricted to the summer and early autumn months, when both water levels in wells and ground water discharge to streams, i.e. stream baseflow, typically fall to their lowest levels of the year.

This report describes the results of a study carried out by the Interstate Commission on the Potomac River Basin (ICPRB) in an effort to improve and extend the ability of the water budget approach to assess ground water and surface water availability in the upper portion of the Potomac basin, in watersheds underlain by fractured bedrock aquifers. The study was carried out as part of the activities of the first year of the Potomac River Basin Ground Water Assessment project, a joint effort by ICPRB and the US Geological Survey (USGS), made possible by funding allocated in the Federal Fiscal 2003 budget for the initiation of an assessment of ground water availability in the Potomac River Basin. The study focuses on two sub-watersheds of the upper Potomac basin, the Monocacy River basin and the adjoining Catoctin Creek drainage area, and applies a combination of existing and newly developed technical tools within the framework of the water budget approach, to both assess water availability in these watersheds and to evaluate the usefulness of these tools for water availability assessments in the fractured bedrock aquifers of the upper Potomac basin.

I.2 Objective of Study

The objective of this study is to assess the quantity of water available in the fractured bedrock aquifers underlying a pilot study area in the upper portion of the Potomac River basin, within the framework of the watershed water budget approach. The study area is comprised of two adjoining watersheds in the upper portion of the Potomac basin, the Monocacy River watershed and the Catoctin Creek watershed. Two water budget analyses are carried out for the Monocacy/Catoctin watersheds. In the first, estimates are made of annual recharge, based on annual baseflow, for a set of gaged sub-basins within or near the Monocacy/Catoctin watersheds. Statistical analysis tools are used to extrapolate these results to ungaged areas based on sub-basin hydrogeology. In the second analysis, a simple approach is developed to estimate seasonal water availability using seasonal water budgets, incorporating the effects of aquifer storage. Seasonal water budgets are computed for four gaged sub-basins located in the study area. An indicator of summertime water availability, formed from the sum of beginning-of-summer storage and summer recharge, is constructed, and results from frequency analysis are compared to those from the annual water budget approach.

The water budget analyses in this study rely on estimates of the quantities of ground water discharging to basin streams to obtain estimates of ground water recharge. The resulting estimates of water availability pertain to the quantity of water available in the interconnected stream network/aquifer system under conditions resulting in nonzero stream baseflow. The estimates in this study do not provide an assessment of the quantity of ground water remaining in a sub-basin aquifer in situations where ground water has dropped to a level resulting in zero stream flow.

II. Basin Description

II.1 General

The study area, including the Monocacy River watershed and the adjoining Catoctin Creek watershed, drains a total of approximately 1115 square miles of Frederick, Carroll, and Montgomery Counties in Maryland and Adams County and a small area of Washington County in Pennsylvania (see Figure 1 and Figure 3). Communities in the Monocacy/Catoctin watersheds, including Frederick, MD and Gettysburg, PA, are attracting new residents who commute daily to the Washington, DC metropolitan area. Population growth for Frederick, Carroll, and Adams counties, based on U.S. Census Bureau data and depicted in Figure 2, has accelerated during the past decades.

Figure 1. Location of study area

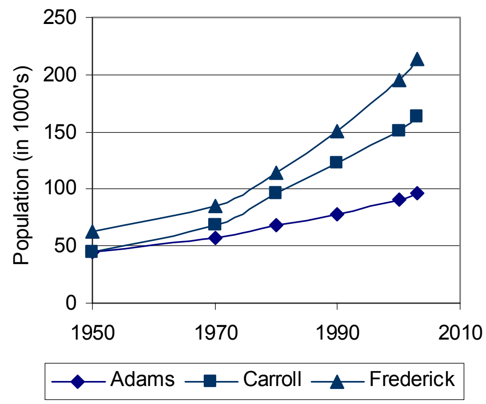


Figure 2. Population growth in Monocacy/Catoctin counties (from US Census data)

The Monocacy River has a drainage area of approximately 960 square miles and an average annual discharge of approximately 600 million gallons per day (based on the streamflow record from 1930 to 2002 at USGS gage 01643000, Monocacy River at Jug Bridge near Frederick Maryland). Catoctin Creek has a drainage area of approximately 122 square miles and an average annual discharge of approximately 50 million gallon per day (at USGS gage 01637500, Catoctin Creek near Middletown, MD, based on streamflow records from 1948 to 2002). Both the Monocacy River and Catoctin Creek discharge into the Potomac River; the Monocacy River downstream of Point of Rocks, MD and Catoctin Creek upstream of Point of Rocks, MD (Figure 3).

The climate of the study area is moderately-humid temperate. The mean annual temperature at Frederick is 53.3°F (Duigon and Dine, 1987). Precipitation records of varying record length are available at several stations within and nearby the basin (see Table 10 and Figure 8). Precipitation is fairly uniform throughout the study area based on records for the period 1960 to 2002, with average annual precipitation ranging from approximately 40 inches at Frederick to approximately 48 inches at the Catoctin gage.

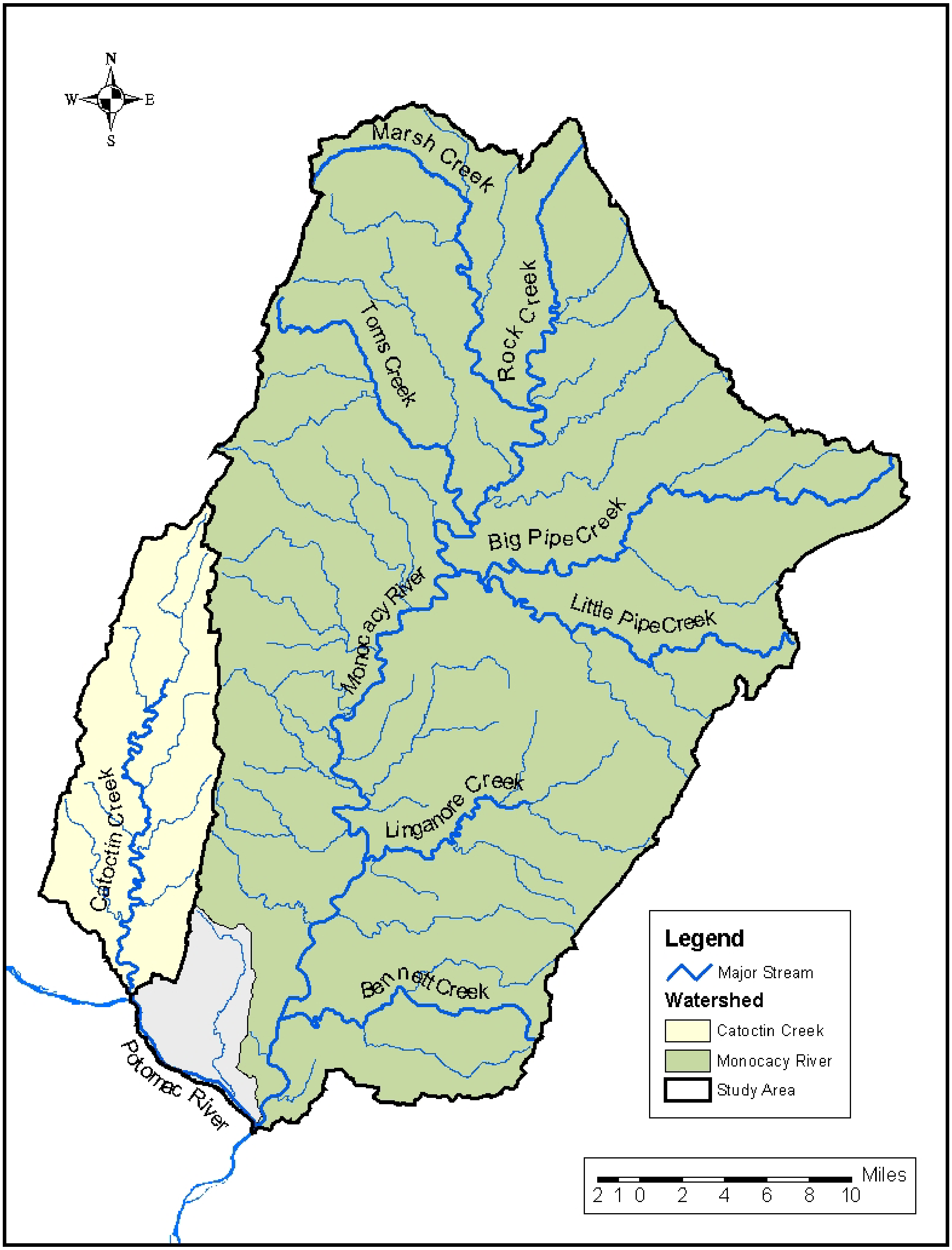


Figure 3. Monocacy/Catoctin streams

II.2 Geology

The Monocacy River Basin is located in central Maryland and part of Adams County in southern Pennsylvania. The watershed is located in parts of two major physiographic provinces, the Blue Ridge province and the Piedmont province (as described in Fenneman, 1938). The Piedmont physiographic province in this area has been further subdivided into the Western Piedmont and Mesozoic Lowland provinces. Catoctin Creek is located in Frederick County, MD, and is in the Blue Ridge physiographic province. In their study relating ground-water discharge and nitrate load to hydrogeomorphic classifications in the Chesapeake Bay watershed, Bachman et al (1998) combined physiographic provinces with the generalized lithology to define eleven hydrogeomorphic regions (HGMRs) for the entire Chesapeake Bay watershed. Four of these eleven HGMRs are represented within the Monocacy/Catoctin drainage area (Figure 4); the Piedmont Crystalline, the Piedmont Carbonate, the Mesozoic Lowland, and the Blue Ridge.

The Monocacy River Basin physiography varies from gently rolling hills of the south central part of Frederick County, Maryland, and central Adams County, Pennsylvania to the relatively steep mountainous eastern edge of the Blue Ridge Mountains. The rock types range from carbonates and sedimentary rocks of the central lowland areas to the metavolcanic rocks of Catoctin Mountain. Overlying all these rocks is a layer of overburden, or regolith, of weathered bedrock, soil, alluvium, and colluvium.

Hydrogeomorphic Regions of the Monocacy/Catoctin Watersheds

The Piedmont Crystalline HGMR (PCR) forms the eastern boundary of the Monocacy River basin, is from 5 to about 13 miles wide in the basin and is present mostly in Frederick and Carroll Counties in Maryland with lesser areas in Montgomery County, MD, and Adams County, PA. It forms a gently rolling upland with an average elevation of 700 to 800 ft, with relief generally less than 500 ft and is incised by many deep narrow stream valleys. The Piedmont Crystalline is underlain by Precambrian and Cambrian metamorphic and igneous rocks with some areas underlain by carbonates and quartzite. The Marburg Schist (a bluish-gray to silvery-green, fine-grained schist) underlies an area of about 40 square miles in Carroll County and another area in the southeastern part of the basin in Frederick and Montgomery counties. The Ijamsville Formation, consisting of blue, green or purple phyllite and phyllitic slate and interbedded metasiltstone and metagraywacke, underlies an area of approximately 100 square miles in Frederick and Carroll counties. Intermingled in this area with the Ijamsville Formation are the Sams Creek Metabasalt, the Urbana Formation phyllite, metasiltstone, and quartzite, the Silver Run Limestone, the Wakefield Marble and the Libertytown Metarhyolite. The Sams Creek Metabasalt is exposed in places in an area from near Union Bridge to Westminster where the overlying Ijamsville Formation has been removed. At the southwestern corner of the basin is a monadnock called Sugar Loaf Mountain with a summit of 1,282 ft above sea level. This mountain is composed of Sugarloaf Mountain Quartzite overlying Urbana Formation phyllite (Stose and Stose, 1946).

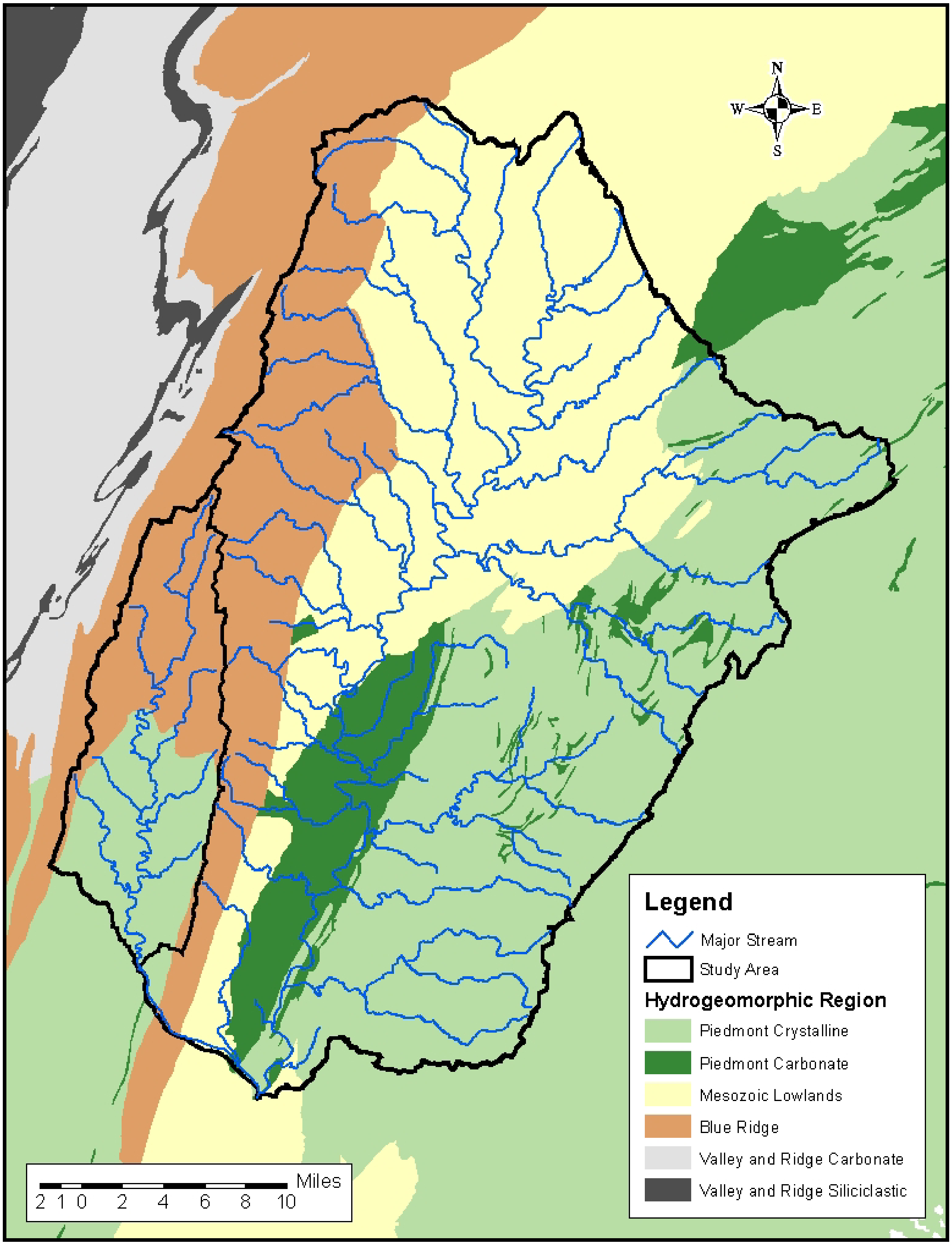


Figure 4. Monocacy/Catoctin hydrogeomorphic regions

The Piedmont Crystalline HGMR is also present in the Catoctin Creek basin, making up approximately 59 square miles of the floor of Middletown Valley. The valley is flanked on the east by Catoctin Mountain, on the west by South Mountain, to the north by the convergence the two ridges, and by the Potomac River to the south. Both Catoctin Mountain and South Mountain represent the Blue Ridge HGMR. The South Mountain-Catoctin Mountain area has been described as an overturned anticlinorium. The rocks underlying the floor of the valley are early Precambrian granitic gneisses with numerous late Precambrian dikes of metadiabase (Stose and Stose, 1946).

The Piedmont Carbonate HGMR (PCA) is represented in the Monocacy River Basin in the central part of Frederick County, MD and in the northeast-most corner of the basin in Adams County, PA. The rocks underlying Frederick Valley form a syncline, bounded on the west by the Triassic Border Fault, a Triassic high-angle reverse fault, and on the east by the Piedmont Upland. Three formations of carbonate rocks are exposed in Frederick Valley. The Tomstown Dolomite is the lowermost stratigraphically and the oldest. It is exposed only in a narrow belt along the foothills of Catoctin Mountain and adjacent to the Triassic border fault. In most places the Tomstown Dolomite is covered by mountain wash. The Tomstown Dolomite is typically a light colored thin-bedded dolomite with some gray limestone, which weathers to a red clay. Overlying the Tomstown Dolomite in, and making up most of the floor of, the Frederick Valley is the Frederick Limestone. The Frederick Limestone is a thin-bedded, dark colored clayey limestone, which weathers to slabby medium colored layers. The Grove Limestone overlies the Frederick Limestone in a narrow strip about a mile wide in the central part of the Frederick Valley syncline. There are several small outcrops mapped as Grove Limestone along the western edge of the Frederick Limestone exposure, but these have been questioned based on fossil identification (Nutter, 1973). Stose and Stose (1946) correlated the Grove Limestone in Frederick Valley to basal beds of the Conestoga Limestone in the Hanover Valley in Pennsylvania. There is a small exposure of limestone which is identified as the Conestoga Limestone in the northeastern part of the Monocacy River basin in Adams County, PA. The Grove Limestone is a thick-bedded pure limestone with fine-grained dolomite in the lower part and a basal highly quartzose limestone. It weathers to a reddish-brown clay with sand or sandy clay at the base (Nutter, 1973).

The Mesozoic Lowland HGMR (ML) is an area of gently rolling lowlands and occasional hills with the elevation ranging from about 300 ft to over 800 ft in the foothills of Catoctin and South Mountains in the northwestern corner of the basin. It is present in central and northeastern Frederick County and northwestern Carroll County and central Adams County. This HGMR is characterized by its underlying geology of Triassic age sedimentary rocks and Jurassic age igneous intrusions. These rocks are a part of a series of disconnected sedimentary basins extending from at least Connecticut to South Carolina. In most of these sedimentary basins at least one margin is down-faulted, forming a halfgraben, and the sediments deposited in the basins thicken and dip toward the faulted margin. Most of these basins have subsequently been intruded by diabase dikes and sills. The Triassic rocks north of the City of Frederick are part of the Newark-Gettysburg basin, the largest of these sedimentary basins, which extends from the New York City area to Frederick. The Triassic rocks south of Frederick are part of the Culpepper basin, which extends from Frederick to near Charlottesville, VA (Nutter, 1975).

The Triassic rocks in the Monocacy River basin are comprised of two primary formations, the Gettysburg Formation and the underlying New Oxford Formation. The Gettysburg Formation is in general a soft, reddish-brown shale containing interbeds of siltstone and sandstone and is exposed in the western part of the Pennsylvania section of the basin and the northwestern part of the Maryland section of the basin. The interbeds consist of sandstones, quartz conglomerates and limestone conglomerates. One of these interbeds, the Heidlersburg Member, in exposed at the surface over about 24 square miles in the Pennsylvania part of the basin. The New Oxford Formation underlies the Gettysburg Formation and is exposed in the eastern part of the Mesozoic Lowland HGMR in both Pennsylvania and Maryland. The New Oxford Formation accounts for about 75% of the Triassic rocks at the surface in Maryland and about 18% in Pennsylvania. The New Oxford Formation consists of an interbedded sequence of sandstones, siltstones, shales and conglomerates. Beds are generally lenticular and grade rapidly into rocks of different textures. The siltstones and shales, which are present throughout, are generally red, but other colors are also present. Quartzose conglomerates occur mostly in the lower two-thirds of the formation and limestone conglomerates have been reported near the contact with underlying Paleozoic age rocks (Low and Dugas, 1999). Jurassic age diabase sills and numerous dikes have intruded the Triassic rocks and are exposed at the surface in approximately 30 square miles of the basin. The diabase is dark gray, to black, medium- to coarse-grained in large intrusions and fine grained in narrow dikes (Low and Dugas, 1999). The diabase in the sills contains primarily plagioclase feldspar in a pyroxene groundmass and the diabase in the dikes consists of green feldspar crystals in a dark augite groundmass (Nutter, 1975).

The Blue Ridge HGMR (BR) makes up the western boundary of the Monocacy River basin and the flanks of the Catoctin Creek basin. The Blue Ridge HGMR is present as Catoctin Mountain, a high ridge extending from the Potomac River at Point of Rocks to west of Emmitsburg, MD, and South Mountain, a high, narrow ridge extending from the Potomac River to the northwestern corner of the basin northwest of Gettysburg, PA. Between these two ridges is Middletown Valley, the rocks of which are Precambrian age gneisses of the Piedmont Crystalline HGMR. The rocks of the Blue Ridge HGMR are principally Late Precambrian age metavolcanic rocks that make up the Catoctin Formation and include metabasalt, metarhyolite, and greenstone schist (Low and Dugas, 1999). Smaller areas are underlain by quartzites, phyllites, shale, or dolomite. The Catoctin metabasalt is the basal member of the Catoctin Formation with the conglomerate and phyllite of the Loudoun Formation above this and the Weverton Formation quartzites above this. These rocks make up both Catoctin Mountain and South Mountain. South of Braddock Heights, where Catoctin Mountain is narrow, the Weverton Formation, if present at all, forms only the peak of the mountain with the Loudoun Formation and the Catoctin metabasalt accounting for the remainder of the mountain. North of Braddock Heights, where the mountain is broader, the Triassic Border fault between Catoctin Mountain and Frederick Valley has cut off the metabasalt and the Loudoun Formation thus preventing exposure of these rocks on the east side of the mountain. North of Catoctin Mountain, where the western boundary of the basin is formed by South Mountain, the metabasalt and metarhyolite are extensively exposed with the stratigraphically higher Loudoun and Weverton Formations capping the peaks of ridges (Stose and Stose, 1946).

The regolith-fractured bedrock aquifer system

As described above, the Monocacy River and Catoctin Creek basins are underlain by a complex assortment of folded and fractured bedrock of various types. This bedrock is overlain by regolith, consisting of saprolite, alluvium, and soil, ranging in thickness from zero to more than 150 ft (Rutledge and Mesko, 1996). The regolith consists of a mixture of clay and fragments of the underlying rock material ranging in grain size from silt to boulders. The porosity of the regolith is considerably greater than the porosity of the bedrock, except possibly in the carbonate bedrock areas, and provides the bulk of the ground water storage within the aquifer system. The saprolite is the clay-rich, residual material derived from in-situ weathering of the underlying bedrock. Saprolite is usually the dominant component of the regolith with a thin layer of soil on top. Alluvium is present above the saprolite only in locations of active or former stream channels. At the base of the saprolite is the transition zone, where unconsolidated material grades into bedrock. The transition zone consists of partially weathered bedrock with saprolite between the rock fragments. The thickness and texture of the transition zone is dependent on the texture and composition of the parent rock. The porosity of the transition zone is less than in the saprolite and decreases with depth as the degree of weathering decreases, however, the transmissivity of the transition zone is greater than in the saprolite (Daniel and Harned, 1998).

In general, in the regolith-fractured rock aquifer system, the regolith receives recharge primarily from precipitation and serves as the storage reservoir for the water. The fracture network provides the conduits to convey the water to points of discharge such as streams and wells. The vertical permeability of the regolith determines the rate at which precipitation recharges the reservoir and the rate at which the reservoir recharges the fracture network. The thickness and porosity of the regolith determines the volume of water which can be stored in the reservoir. The density, size and interconnectedness of the fractures determines the rate at which the fractures discharge water to the discharge points. Obviously there are many factors which affect each of these components of the regolith-fractured rock aquifer system.

III. Water Budget Approach for Assessing Water Availability

Groundwater availability is extremely difficult to characterize on a regional scale, and water management agencies often rely on a watershed water budget approach, which provides a relatively simple accounting of water inflows and outflows to the system of interest. Water budgets are particularly useful for assessments of watersheds underlain by fractured bedrock aquifers, where ground water and surface water are closely interconnected and stream flow data can be used to help estimate important water budget components. Depending on the assumptions used, water budget analyses for a watershed may include estimates of precipitation, ground water recharge, evapotranspiration, ground water discharge to streams, surface water runoff during storm events, ground water withdrawals, as well as other types of basin inflows and outflows.

Water budget analyses incorporate different levels of detail depending on the time interval of interest. Water budgets based on long-term averages and water budgets computed on an annual basis often use the simplifying assumption that aquifer storage does not change from the beginning of one year to the beginning of the next (Schreffler, 1996; New Jersey Water Authority, 2000). Thus, also assuming other water budget components are relatively small, annual ground water recharge can be readily computed by equating it with estimates of annual aquifer discharge to streams, i.e. annual stream baseflow. In a seasonal water budget, it is generally important to consider seasonal changes in storage, since in many regions, including the upper portion of the Potomac basin, ground water levels exhibit a pronounced seasonal pattern. Because reliable estimates of changes in storage are difficult to obtain, computations of seasonal water budgets are not often attempted.

In this study, ground water availability in the Monocacy/Catoctin watersheds is assessed by means of both annual and seasonal water budget estimates. Both water budget analyses rely primarily on stream flow data from gaged sub-basins within or near the study area. In the annual water budget analysis, data from ten continuous record stations and 24 partial record stations were used to estimate annual aquifer recharge for the 34 gaged sub-basins, and results were extrapolated to ungaged areas of the Monocacy/Catoctin drainage area based on sub-basin hydrogeomorphology using multiple regression techniques. In the seasonal water budget analysis, a time series of seasonal water budget components was constructed for four gaged sub-basins in the study area using information from ground water recession analyses to calculate seasonal changes in ground water storage. A quantity representing summer water availability is formed from the sum of beginning-of-summer storage and summer recharge and is compared to availability estimates obtained from the annual water budget. For some portions of the Monocacy/Catoctin watersheds, results from the annual and the seasonal approaches are found to differ significantly.

III.1 Monocacy/Catoctin Water Budget Components

Water budgets are constructed for sub-basins of the Monocacy/Catoctin drainage area in order to quantify the inflows and outflows to the fractured bedrock aquifer underlying each sub-basin. The water budget can be expressed by the following equation for the change in aquifer storage, ΔS_i, over a given interval of time, $\Delta t_i = t_{i+1} - t_i$, given by the difference between aquifer inflows and outflows:

$$\begin{aligned} \Delta S_i &= S_{i+1} - S_i \\ &= inflows - outflows \\ &= R_i - (q_{BF\,i} + RET_i + W_i) \end{aligned} \qquad (1)$$

where

ΔS_i	=	change over time interval, Δt_i , in volume of water stored in aquifer
S_i	=	volume stored at time t_i , the beginning of the time interval
S_{i+1}	=	volume stored at time t_{i+1} , the end of the time interval
R_i	=	total ground water recharge during time interval
$q_{BF\,i}$	=	total discharge to stream baseflow during time interval
RET_i	=	total riparian evapotranspiration during time interval
W_i	=	total net ground water withdrawals during time interval

Aquifer inflow, or recharge, is sometimes computed from sub-basin precipitation, storm flow runoff, and unsaturated zone evapotranspiration via the relationship

$$R_i = P_i - q_{SF\,i} - UET_i \qquad (2)$$

where

P_i	=	total sub-basin precipitation in time interval
$q_{SF\,i}$	=	total stream storm flow in time interval
UET_i	=	total unsaturated zone evapotranspiration in time interval

Equations (1) and (2) describe a sub-basin water budget for the underlying water table aquifer residing in the upper portion of the fractured bedrock aquifer, under a number of simplifying assumptions. It is assumed that ground water divides closely follow topographic divides so that inflow and outflow to and from other sub-basin aquifers are negligible, implying that aquifer discharge is primarily to the sub-basin stream network. Inter-basin transfers by water users are assumed to be negligible. In equation (2), it is assumed that changes in the moisture content of the unsaturated zone are negligible. Evapotranspiration is broken into two components in the water budget given by equations (1) and (2). Unsaturated zone evapotranspiration, UET, is defined to be the portion of precipitation that is lost in the unsaturated zone to evaporation and transpiration before it has a chance to reach the aquifer. Riparian zone evapotranspiration, RET, appearing in equation (1) as an aquifer outflow, is defined as the amount of water which is lost directly from the aquifer from evaporation and transpiration by vegetation in the riparian zone. In their study of the fractured bedrock aquifers of the Appalachian Valley and Ridge, Piedmont, and Blue Ridge Provinces, Rutledge and Mesko (1996) estimated that RET is on the order of 1 to 2 inches per year. However, because RET is very difficult to measure, in this study it will be combined with recharge by defining net recharge as

$$R_{net} = R - RET \qquad \textbf{(3)}$$

In gaged sub-basins, daily stream flow data can be used to estimate two important water budget components, stream baseflow, q_{BF}, and stream stormflow from runoff, q_{SF}, where total stream flow, q_{Total}, is the sum of baseflow and stormflow, that is, $q_{Total} = q_{BF} + q_{SF}$. It will be assumed throughout this study that stream baseflow is a reasonable estimate of ground water discharge to streams, that is, that the net quantity of water withdrawn from sub-basin streams is negligible. Though stream baseflow is very difficult to measure directly, hydrographic separation techniques are used with daily stream flow data to obtain estimates of baseflow (White and Sloto, 1991; Rutledge, 1992; 1998).

III.2 Annual Water Budget Analysis

Because aquifer discharge to streams, that is, stream baseflow, is relatively easy to estimate, water management agencies have used statistical analyses of annual baseflow to assess ground water availability (Delaware River Basin Commission, 1999). Within the framework of the water budget defined by equation (1), the assumption is often made that from the beginning of one year to the beginning of the next, $\Delta S = 0$, implying that net annual recharge is simply equal to annual stream baseflow plus ground water withdrawals, that is,

$$R_{net} = q_{BF} + W \qquad \textbf{(4)}$$

It will be assumed in the analyses in this section that equation (4) is valid and that current annual ground water withdrawals, W, and also surface water withdrawals in the study area are negligible when compared to annual baseflows (Wolman, 2004). Therefore, annual baseflow represents a rough approximation of how much water is available on a basin-wide scale to be apportioned between stream flow necessary to maintain the ecological health of the stream, and development for water supply purposes. In Section III.3, the more detailed seasonal water budget approach for four selected sub-basins, non-zero estimates of ΔS and W will be computed and incorporated into the analysis.

Geology is thought to be one of the primary natural influences on baseflow (White and Sloto 1990). A study of the Potomac River Basin (Smith, 1982) found that low stream flow indicators appeared to be associated with the geology of the basin. In studies in Virginia and Pennsylvania (Flippo, 1982; Hayes, 1991) geologic variables were found to be statistically significant in some of the regression equations developed to estimate low flow statistics. An analysis of characteristics of streams in the Valley and Ridge, the Blue Ridge, and the Piedmont physiographic provinces of Virginia (Nelms et al., 1997) showed that mean and median baseflow were significantly different for some of the physiographic provinces.

Schreffler (1996) used differences in baseflow between different geologic rock types to estimate baseflow frequencies at ungaged locations. This method estimates the amount of baseflow contributed by a given rock type by calculating baseflow recurrence intervals of interest at one stream gage with a drainage basin underlain predominantly by that rock type. Baseflow recurrence intervals are calculated at a gage representing each rock type. Baseflow recurrence intervals are then estimated for ungaged sub-basins based on the percentage of each rock type underlying the ungaged basins. Although the method is appealing in that it is simple to implement, there is no way to statistically verify the resulting model's accuracy. Also, the method requires that the sizes of the gaged drainage basins used for flow estimation are similar to each other and to the ungaged basins where baseflow is predicted, which greatly limits which gages can be included in the analysis.

Multiple linear regression has long been used to estimate low flow, peak flow and other flow characteristics at ungaged locations (Flynn, 2002; Ries et al, 2000; Carpenter and Hayes, 1996; Hayes, 1991) and does have a statistical basis by which to measure the results. In this study, multiple linear regression was used to investigate whether regional equations can be developed to predict annual baseflow recurrence intervals at ungaged sites within the Monocacy basin using drainage area and HGMR (rock type) as explanatory variables.

Methods

In linear regression, one or more explanatory variables of a population (in this case, drainage area and percent of the drainage area underlain by a particular HGMR) and one response variable within the same population (in this case, the annual baseflow for a recurrence interval of interest) are used to estimate the linear relationship between the explanatory and response variables (Helsel and Hirsch, 2002). The result of the analysis is an equation in the form of:

$$\hat{Y}_k = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_n x_n + \varepsilon_k \qquad \textbf{(5)}$$

where

$\hat{Y}_k$	= estimate of the dependent variable at site k
x_1 to x_n	= explanatory variables
β_0 to β_n	= regression model coefficients (determined by the regression)
ε_k	= random error at site k

The regression analysis relies on a number of assumptions, including the assumptions that the regression equation adequately describes the relationship between the explanatory variables, and that the error terms, ε_k , are normally distributed and independent random variables with zero means, and with variances which are constant and independent of the explanatory variables.

Because streamflow and basin characteristics are typically log-normally distributed, the flow statistics and basin characteristics often need to be log-transformed in order to satisfy the assumptions above (Ries, 2000). Using the logarithms of both the explanatory and the independent variables in the regression equation, the relationship between an annual baseflow recurrence interval and basin characteristics will be assumed to have the following form:

$$\log Q_{n-year} = \beta_0 + \beta_1 \log DA + \beta_2 \log a_1 + \beta_3 \log a_2 + \beta_4 \log a_3 \quad \textbf{(6)}$$

where

$Q_{n\text{-}year}$ = n-year annual baseflow recurrence interval for sub-basin
DA = sub-basin drainage area
a_m = 1 + 0.01* (percentage of sub-basin drainage area in HGMR, m)

Sub-basin HGMR percentages were converted to the form (1.0+0.01*(% HGMR)) before they were log- transformed in order to make the relationship between flow characteristics and HGMRs approximately linear (Stuckey and Reed, 2000). Also, this transformation makes it possible to include basins in the analysis that have zero percent of a particular HGMR. The log of zero is undefined, but adding a constant to all variables enables zero value explanatory variables to be log-transformed (Carpenter and Hayes, 1996). Though four HGMRs are represented in the study area, only three are used as explanatory variable in equation (6), since in a given sub-basin the sum of the % HGMR equals 100%, leaving only three independent variables.

Flow statistic calculations and determination of basin characteristics

The 365-day baseflows for the 2-year, 10-year and 20-year recurrence intervals were computed at 10 USGS continuous-record stream gaging stations (Table 1 and Figure 5) located within the Monocacy basin or just outside the basin in hydrologically similar areas. In this report, frequency of an annual baseflow event designates how often a given annual baseflow will not be exceeded during a given period of time. A recurrence interval, in years, sometimes also referred to as a return period, is the reciprocal of the baseflow event frequency. Therefore, the 2-year 365-day baseflow represents the average annual baseflow that in any given year has a 50-percent chance of not being exceeded, while the 10-year 365-day baseflow represents the average annual baseflow that has just a ten percent chance in any given year of not being exceeded.

Table 1. USGS Continuous Record Gages Used in the Regression Analysis

USGS Site Number	Period of record used for analysis (Climatic year April-March)	Number of years of data used in analysis	2-year 365-day baseflow (cfs)	10-year 365-day baseflow (cfs)	20-year 365-day baseflow (cfs)
01637500	4/49-3/85	36	41.7	26.5	22.9
01639000	4/49-3/85	36	70.2	46.3	40.1
01639500	4/49-3/85	36	63.0	40.2	34.8
01640500	4/59-3/84	25	6.3	3.8	3.3
01641000	4/50-3/70	20	14.2	9.7	8.7
01641500	4/49-3/84	35	9.1	6.1	5.4
01642500	4/49-3/70	21	44.0	30.9	27.9
01643000	4/49-3/85	36	445.3	287.6	251.5
01643500	4/49-3/58, 4/67-3/85	27	39.8	27.02	24.2
01645000	4/49-3/85	36	61.9	41.0	36.8

USGS continuous record stations are those gages where daily flow data is collected. Flow data from continuous record USGS gages were acquired from the USGS National Water Information System (NWIS) website. In order to make the periods of record among the stations as consistent as possible and to avoid impacts on gage data caused by water development in the 1990s, only data between 1950 and 1985 were used in the analysis. The periods of record of all continuous record gages used in the analysis spanned at least 20 years. Data collected during a time of known flow regulation were excluded from analysis. Annual baseflow was estimated using the local minimum method in the HYSEP hydrograph separation program (Sloto and Crouse, 1996). SWSTAT (Lumb et. al, 1990), a USGS-developed statistical program, was used to calculate baseflow recurrence intervals by ranking the annual 365-day mean baseflows and fitting them to a log-Pearson Type III distribution. The log-Pearson Type III distribution is commonly used for calculation of annual low flow statistics (Carpenter and Hayes, 1996; Hayes, 1991). Climatic years (April-March) were used to calculate annual flow statistics in order to keep low flow portions of the year together.

Because more gages were needed for the regression, 24 partial record stations were also included in the analysis (Table 2 and Figure 5). USGS partial record stations are those gage stations where flow measurements are taken periodically during periods of low flow (Carpenter and Hayes, 1996). Stations where less than 10 years of data were collected during the base period were treated as partial record stations. Criteria for inclusion of partial record gages in the study were the following: 1) more than 10 flow measurements were taken at the gage; 2) flow measurements at the gage were taken over the course of at least 3 years; and 3) the drainage area of the partial record gage is less than 50% of a continuous record gage on the same stream which was used in the analysis (Carpenter and Hayes, 1996). Data that appeared not to be taken during baseflow conditions (from analysis of nearby precipitation gages), data collected outside the base period (1950-1985), and data that appeared to be extreme outliers, were excluded from analysis. The one exception is site 01638800, which is in a particularly underrepresented portion of the basin. In this case, one baseflow measurement was used outside the base period of record in order to gain enough data at the station to correlate it to a nearby site.

In order to estimate flow at partial record stations, partial record station measurements were correlated with concurrent flow measurements at nearby continuous record stations. Logarithms of flow at partial record stations were first plotted against the logarithms of concurrent flow at a nearby continuous gage station and were inspected for fit. If the fit appeared to be reasonable and the r^2 value was greater than 0.8, the continuous record gage was thought to be sufficient to be used for estimation of baseflow frequency at the partial record station. If there were several continuous record stations that could be used for baseflow estimation at a given partial record gage, the continuous record gage with the best fit and most similar drainage basin characteristics was chosen.

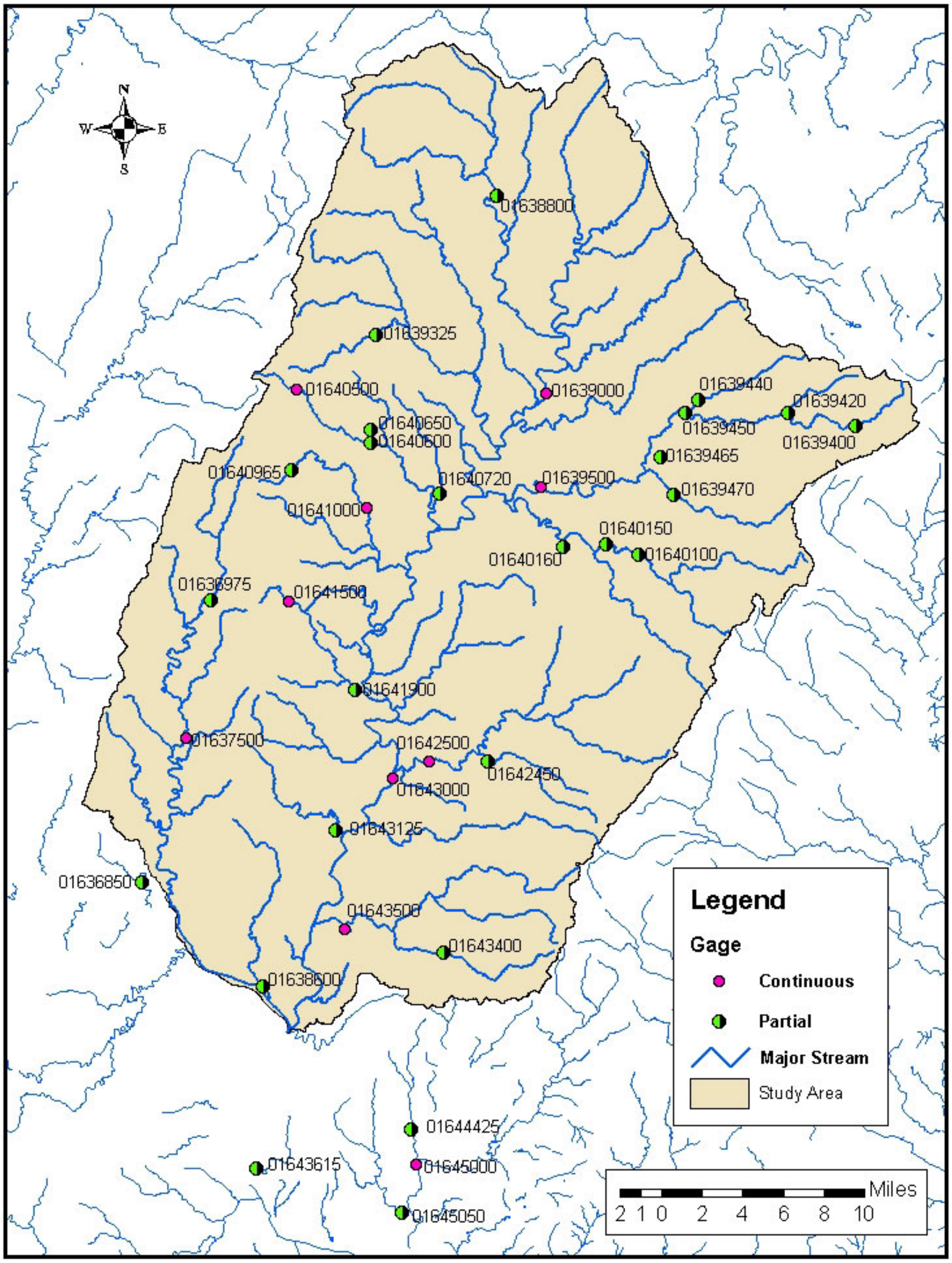


Figure 5. Location of stream gage stations

Table 2. USGS Partial Record Gages Used in the Regression Analysis

USGS Site Number	Number of measurements used in the regression	Continuous gage station used for correlation	Adjusted R^2 for regression with continuous gage station	Estimated* 2-year 365-day baseflow (cfs)	Estimated* 10-year 365-day baseflow (cfs)	Estimated* 20-year 365-day baseflow (cfs)
01636850	19	01643500	0.96	3.1	1.6	1.3
01636975	13	01637500	0.93	17	8.8	7.1
01638600	15	01643500	0.9	12	7.6	6.7
01638800	10	01638800	0.8	33	20	17
01639325	19	01640500	0.94	7.5	3.1	2.3
01639400	12	01639500	0.83	8.3	5.6	5.0
01639420	10	01643500	0.96	3.5	1.9	1.6
01639440	17	01639500	0.98	4.8	2.6	2.2
01639450	11	01639500	0.98	36	23	20
01639465	16	01639500	0.93	8.7	5.7	5.1
01639470	12	01639500	0.97	8.7	6.0	5.3
01640100	12	01639500	0.91	1.5	1.1	1.0
01640150	12	01639500	0.96	27	19	17
01640160	13	01643500	0.96	3.8	2.6	2.3
01640600	11	01640500	0.96	13	7.3	6.0
01640650	10	01641500	0.96	6.3	3.5	2.9
01640965	10	01637500	0.95	1.3	0.61	0.48
01641900	16	01640500	0.87	11	5.9	4.9
01642450	16	01643500	0.95	7.7	5.3	4.7
01643125	19	01637500	0.83	15	9.2	7.9
01643400	15	01645000	0.95	7.4	4.3	3.8
01643615	13	01643500	0.9	4.2	1.6	1.2
01644425	16	01643500	0.95	5.2	3.3	2.9
01645050	16	01643500	0.9	5.4	2.6	2.1

* Estimates made by Stedinger-Thomas method

Annual baseflow estimation at partial record stations was made using the moment-estimator technique described by Stedinger and Thomas (1985), originally developed for low-flow recurrence interval estimation. This method uses the following equation to relate the T-year flow to estimates of mean and variance:

$$\hat{Y}_T = \hat{\mu}_V + K_V \hat{\sigma}_V^{\,2} \qquad \textbf{(7)}$$

where

- $\hat{Y}_T$ = estimated annual D-day, T-year flow, in log units, at partial record station Y
- K_y = log Pearson type III frequency factor (a function of skew and variance)
- $\hat{\mu}_V$ = estimated mean of the logarithms of annual D-day flows at the partial record site Y
- $\hat{\sigma}_V^{\,2}$ = estimated variance of the logarithms of annual D-day flows at partial record site Y.

The parameters, $\hat{\mu}_V$ and $\hat{\sigma}_V{}^2$, were computed from comparisons of baseflow measurements at the partial record station and concurrent daily mean flows at the continuous record station; see Stedinger and Thomas (1985) or Stedinger and Thomas (1986). Drainage basins were delineated using the CRWR Pre-pro GIS tool (see **h**ttp://www.crwr.utexas.edu/gis/gisenv98/class/gisex/ex298/prepro htm#computer**)** in Arc View 3.2. The percent of each HGMR in each basin was determined using the USGS-developed HGMR GIS layer (available at http://water.usgs.gov/GIS/metadata/usgswrd/hgmr.htm). The drainage basin characteristics of all of the basins are given in Table 3.

Table 3. Drainage Basin Characteristics of All Gages Used in the Regression Analysis.

USGS Site Number	Drainage Area (sq mi)	% of drainage area underlain by Mesozoic Lowland HGMR (ML)	% of drainage area underlain by Piedmont Crystalline HGMR (PCR)	% of drainage area underlain by Blue Ridge HGMR (BR)	% of drainage area underlain by Piedmont Carbonate HGMR (PCA)
1636850	8.64	0.0	93.0	7.0	0.0
1636975	22.7	0.0	0.0	100.0	0.0
1637500	66.9	0.0	15.0	85.0	0.0
1638600	20.3	46.9	0.0	28.2	25.0
1638800	49.6	59.3	0.0	40.7	0.0
1639000	173	87.2	0.0	11.9	0.9
1639325	12.2	0.0	0.0	100.0	0.0
1639400	9.39	0.0	94.9	0.0	5.1
1639420	5.46	0.0	100.0	0.0	0.0
1639440	8.77	3.2	89.3	0.0	7.5
1639450	51.6	6.9	90.5	0.0	2.6
1639465	13.9	24.1	75.1	0.0	0.8
1639470	12.6	1.6	93.7	0.0	4.7
1639500	102	29.7	68.2	0.0	2.1
1640100	2.01	0.0	57.6	0.0	42.4
1640150	40.4	0.0	82.0	0.0	18.0
1640160	7.04	8.6	90.3	0.0	1.1
1640500	5.93	0.0	0.0	100.0	0.0
1640600	14.4	0.0	0.0	100.0	0.0
1640650	6.16	0.0	0.0	100.0	0.0
1640720	6.53	64.5	0.0	35.5	0.0
1640965	2.14	0.0	0.0	100.0	0.0
1641000	18.4	13.5	0.0	86.5	0.0
1641500	7.29	0.0	0.0	100.0	0.0
1641900	16.5	29.3	0.0	63.7	7.0
1642450	11.8	0.0	91.8	0.0	8.2
1642500	82.3	0.0	95.4	0.0	4.6
1643000	817	43.1	30.5	18.3	8.0
1643125	20.2	30.3	0.7	34.0	35.0
1643400	12.8	0.0	100.0	0.0	0.0
1643500	62.8	0.0	100.0	0.0	0.0
1643615	14	99.6	0.4	0.0	0.0
1644425	8.47	29.9	70.1	0.0	0.0
1645000	101	8.4	91.6	0.0	0.0
1645050	19.2	68.1	32.0	0.0	0.0

Model selection

Preliminary regression analyses were done using an initial set of potential explanatory variables which included percentage of sub-basin drainage area in each HGMR, given in Table 3, and several other sub-basin characteristics, the statistical program S-PLUS was used to explore the best combinations of variables to use in the model. Using an all-subset regression function, the most promising combinations of variables were chosen using the Predicted Residual Sum of Squares (PRESS) statistic, t-statistics of the explanatory variables, and physical reasoning. Minimizing PRESS, the sum of squared prediction errors, results in a model selection that produces the least error when making new predictions (Helsel and Hirsch, 2002). For those combinations of predictors that appeared promising in the all-subsets analysis, variance inflation factors (VIFs) were calculated to determine if certain combinations of variables were intercorrelated. Regression equation variables that are highly intercorrelated may result in predictions that are unreliable (Flynn, 2002). The VIF of variable j is calculated by (Helsel and Hirsch, 2002): $VIF_j = 1/1\text{-}R_j^2$ where R_j^2 is the R^2 of a regression of the explanatory variable j on all other explanatory variables. The ideal VIF is approximately one and serious problems are associated with VIFs greater than 10 (Helsel and Hirsch, 2002). In this study, combinations of variables with VIFs greater than three were not considered for further analysis.

For final model selection, based on the results of the preliminary regression analyses and limitations imposed by the fairly small sample size, the set of potential explanatory variables was restricted to sub-basin area, and those variables describing % of sub-basin area in each HGMR, as given in Table 3. Streamflow frequency statistics are correlated in both space and time; therefore the assumption that the errors (ε_k) are independent from each other is typically not satisfied in regressions of streamflow statistics using Ordinary Least Squares (Ries, 2000). To account for this, a Generalized Least Squares analysis using the USGS program, GLSnet (Stedinger and Tasker, 1989), was used for the final computation of baseflow regression coefficients and error parameters. GLSnet uses a generalized least squares regression method to develop regional regression equations based on drainage basin characteristics, and it accounts for differences in lengths of record and spatial correlation among sites (Tasker and Stedinger, 1989).

Bias correction factor and confidence interval calculations

Predictions from retransformed logarithmic equations slightly underpredict the mean response of the dependent variable (Koch and Smillie, 1986; Ferguson, 1986). Bias correction factors are often developed in low flow regression analyses to correct for this bias. Duan's smearing estimate (Duan, 1983) is often used as a bias correction factor in flow regression studies, but because of the equal weighting of the residual errors in the GLS regression, this method is not appropriate for use with GLS (Flynn, 2002). In this study, the formula $\exp(0.5*S^2*5.302)$ (Ferguson, 1985) was used as the bias correction factor, where S = the average prediction error in log 10 units. S can be computed from the equation, S^2 = (average model error variance + average sampling error variance), where average model error variance and average sampling error variance are both given as output by GSLnet. This method is more appropriate for GLS regression than Duan's smearing estimate (Flynn, 2002). Bias correction factors are applied to the exponentiated form of equation (6) as a final multiplicative factor.

Confidence intervals express the statistical uncertainty associated with the use of regression equations and are calculated at a percent confidence level for a given regression estimate. The method used in this study to compute confidence intervals is described in Appendix A and is adapted from Flynn (2002) and Ries (2000).

Average prediction error is a measure of how well the regression equations will estimate flows at ungaged locations (Flynn, 2002), and is a commonly used measure of model adequacy. The average prediction error in log 10 units is calculated for a GLS model by taking the square root of the sum of the average model error variance and the average sampling error variance (Flynn, 2002). The average prediction error expressed as a percent is calculated as: $100[\exp(5.3018(\text{average model error variance} + \text{average prediction error variance})) - 1]^{0.5}$, where the average model error variance and the average prediction error variance are defined as above and given as outputs from GLSnet. (See Feaster Guimaraes, 2004; Ries, 1994b.)

The median absolute percent error of estimates is also sometimes used as a measure of regression equation quality. It is calculated as the median of the absolute values of the percent error of the flow estimates at the gages used to develop the regression equations. The percentage error of predictions made at ungaged sites will likely be larger than the percent error of predictions at gages used to develop the regression equations (Ries, 1994b).

Results

The GLS regression analysis leads to a set of equations predicting annual baseflow recurrence intervals from the selected sub-basin characterics, drainage area (DA), % of sub-basin area in the Mesozoic lowlands HGMR (ML), % of sub-basin in the Blue Ridge HGMR (BR), and % sub-basin in the Piedmont Carbonate Rock HGMR (PCA). Note that the variable, % of sub-basin area in the Piedmont Crystalline Rock, PCR, is still implicitly included in the analysis because of the relationship, (ML + BR + PCA + PCR) = 100%. Using the exponentiated form of the regression equation, (6), the calculated regression coefficients, β_i, from Table 5, and multiplying each of the three results by the appropriate bias correction factor, the resulting prediction equations can be written as:

2-year annual baseflow (cfs):

$$Q_{2\text{-year}} = 1.02*10^{-0.20177}*DA^{0.99318}*ML^{-0.68803}*BR^{0.52134}*PCA^{0.68408}$$

10-year annual baseflow (cfs):

$$Q_{10\text{-year}} = 1.05*10^{-0.44964}*DA^{1.03232}*ML^{-1.00817}*BR^{0.43855}*PCA^{1.26814}$$

20-year annual baseflow (cfs):

$$Q_{20\text{-year}} = 1.06*10^{-0.51871}*DA^{1.04195}*ML^{-1.09795}*BR^{0.39841}*PCA^{1.42868} \quad (8)$$

The predicted annual baseflows for the sample set of gaged sub-basins used in the study are shown in Table 4 and compared with values estimated from gage data (Tables 1 and 2) in Figure 6. The t-statistics of the explanatory variables in each regression equation are shown in Table 5, and regression adequacy measures are found in Table 6. The covariance matrices, U, required for confidence interval estimation, are found in Table 7. As can be seen from the results in Table 5, all variables with the exception of PCA were significant at the 90% confidence level in all three prediction equations. PCA was not significant at the 90% confidence level for the equation predicting 2-year annual baseflow, but was retained as a variable in this equation in order to maintain consistency with the other regression equations in the set.

Table 4. Regression equation predictions for gages used to develop the regression equations

USGS Site Number	Predicted 2-year 365-day baseflow (cfs)	Predicted 10-year 365-day baseflow (cfs)	Predicted 20-year 365-day baseflow (cfs)
1636850	5.7	3.6	3.1
1636975	20.5	12.7	11
1637500	57.7	37.5	32.8
1638600	13	8.4	7.4
1638800	27	15.3	12.9
1639000	74.5	43.1	36.8
1639325	11.1	6.7	5.7
1639400	6.2	4	3.6
1639420	3.5	2.2	1.9
1639440	5.7	3.7	3.3
1639450	31.5	21.2	18.9
1639465	7.6	4.6	4
1639470	8.1	5.3	4.7
1639500	54	34.9	30.8
1640100	1.6	1.2	1.1
1640150	28.4	20.9	19.2
1640160	4.3	2.6	2.3
1640500	5.4	3.2	2.7
1640600	13.1	7.9	6.8
1640650	5.6	3.3	2.8
1640965	2	1.1	1.2
1641000	14.7	8.7	7.5
1641500	6.6	3.9	3.4
1641900	11.8	7	6
1642450	7.9	5.3	4.7
1642500	53	37.5	33.9
1643000	451.8	313.2	280.2
1643125	15.2	10.6	9.5
1643400	8.1	5.2	4.6
1643500	39.3	26.8	24
1643615	5.5	2.8	2.4
1644425	4.5	2.6	2.2
1645000	59.6	40.4	36.1
1645050	8.5	4.7	3.9

Table 5. Regression results from GLSnet, and bias correction factors

	Bias correction factor		β_0	β_1 (DA coefficient)	β_2 (ML coefficient)	β_3 (BR coefficient)	β_4 (PCA coefficient)
2-year, 365-day baseflow	1.02	Coefficient	-0.20177	0.99318	-0.68803	0.52134	0.68406
		t-statistic	-3.33625	29.00977	-3.32335	3.79420	1.58390
		p-value	0.0023	0.0001	0.0024	0.0007	0.1241
10-year 365-day baseflow	1.05	Coefficient	-0.44964	1.03232	-1.00817	0.43855	1.26814
		t-statistic	-5.27916	21.24498	-3.39876	2.16194	2.05259
		p-value	0.0000	0.0001	0.0020	0.0390	0.0492
20-year 365-day baseflow	1.06	Coefficient	-0.51871	1.04195	-1.09795	0.39841	1.42868
		t-statistic	-5.50160	19.50837	-3.36075	1.76006	2.10480
		p-value	0.0000	0.0001	0.0022	0.0889	0.0441

DA = drainage area; ML = % of basin underlain by Mesozoic Lowland HGMR; BR = % of basin underlain by Blue Ridge HGMR; PCA = % of basin underlain by Piedmont Carbonate HGMR

Table 6. Summary of measures of regression equation adequacy

	Model Error Variance	Sampling Error Variance	PRESS/n	Average Error of Prediction (log units)	Root mean square prediction error (%)	Median absolute error of the estimates, from cfs (%)
2-year 365-day baseflow	0.0073	0.0019	0.0110	0.0959	22.4	12.3
10-year 365-day baseflow	0.0148	0.0040	0.0245	0.1371	32.4	16.1
20-year 365-day baseflow	0.0176	0.0049	0.0304	0.1500	35.6	18.7

Table 7. Covariance matrices (U) calculated for each recurrence interval

2-year recurrence interval:

	Constant	Drainage area	% Mesozoic Lowland	% Blue Ridge	% Piedmont Carbonate
Constant	3.66E-03	-1.64E-03	1.32E-03	-3.67E-03	-9.61E-03
Drainage area	-1.64E-03	1.17E-03	-2.92E-03	8.28E-04	3.10E-03
% Mesozoic Lowland	1.32E-03	-2.92E-03	4.29E-02	3.38E-03	-9.49E-03
% Blue Ridge	-3.67E-03	8.28E-04	3.38E-03	1.89E-02	1.15E-02
% Piedmont Carbonate	-9.61E-03	3.10E-03	-9.49E-03	1.15E-02	0.18652

10-year recurrence interval:

	Constant	Drainage area	% Mesozoic Lowland	% Blue Ridge	% Piedmont Carbonate
Constant	7.25E-03	-3.27E-03	2.39E-03	-6.81E-03	-1.81E-02
Drainage area	-3.27E-03	2.36E-03	-5.79E-03	1.55E-03	5.99E-03
% Mesozoic Lowland	2.39E-03	-5.79E-03	8.80E-02	7.72E-03	-1.96E-02
% Blue Ridge	-6.81E-03	1.55E-03	7.72E-03	4.11E-02	2.10E-02
% Piedmont Carbonate	-1.81E-02	5.99E-03	-1.96E-02	2.10E-02	0.38171

20-year recurrence interval:

	Constant	Drainage area	% Mesozoic Lowland	% Blue Ridge	% Piedmont Carbonate
Constant	8.89E-03	-3.96E-03	2.95E-03	-8.24E-03	-2.17E-02
Drainage area	-3.96E-03	2.85E-03	-7.00E-03	1.93E-03	7.23E-03
% Mesozoic Lowland	2.95E-03	-7.00E-03	0.10673	9.28E-03	-2.44E-02
% Blue Ridge	-8.24E-03	1.93E-03	9.28E-03	5.12E-02	2.50E-02
% Piedmont Carbonate	-2.17E-02	7.23E-03	-2.44E-02	2.50E-02	0.46073

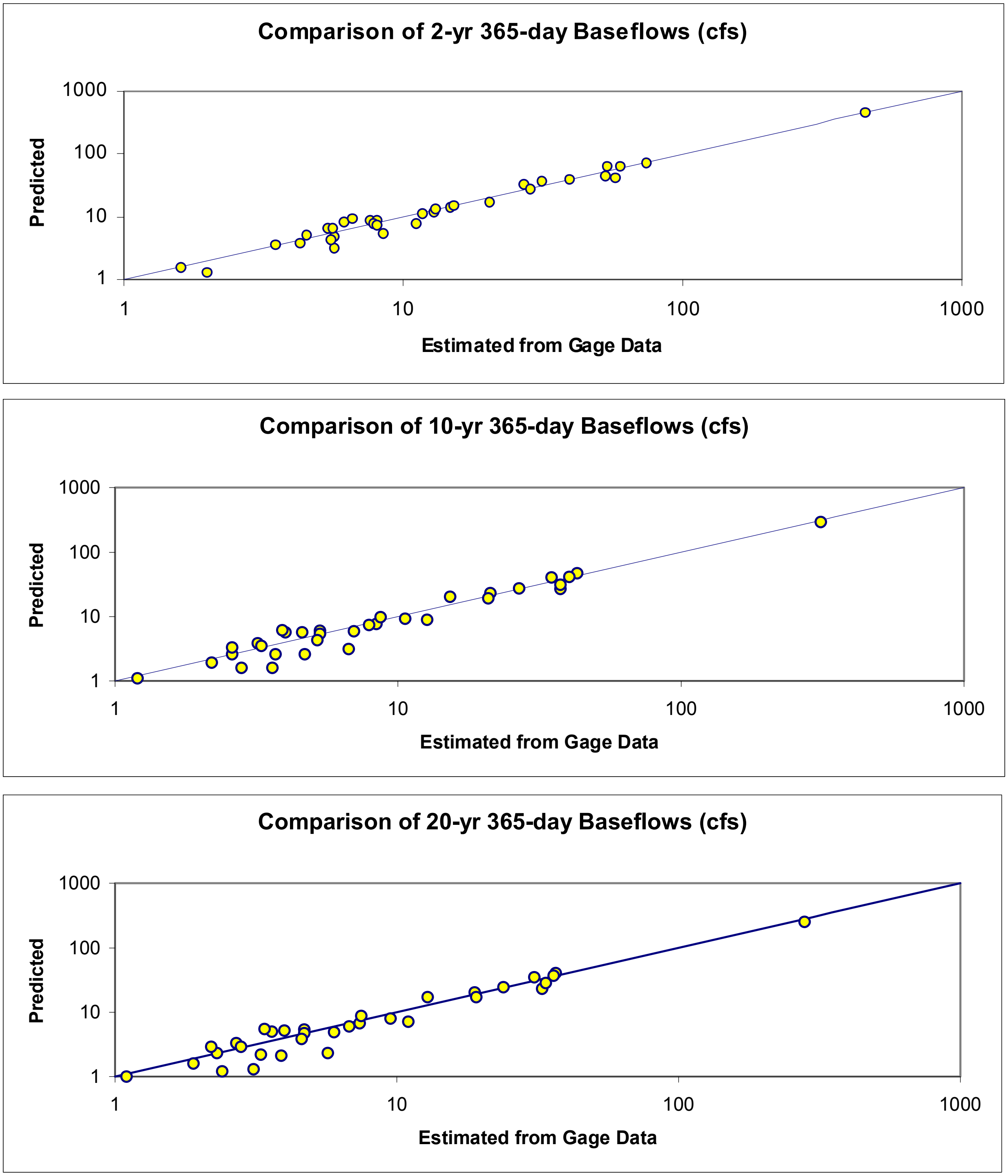


Figure 6. Regression Equation Predictions of Annual Baseflow Versus Values Estimated from Flow Data

Not surprisingly, drainage area was found to be the most significant explanatory variable (Table 5). The effect of drainage area on annual baseflow appears to be approximately multiplicative, because in all of the regression equations, the drainage area coefficient is close to 1. This result is similar to that of several low flow investigations (Carpenter and Hayes, 1996; Ries, 1994b; Flynn, 2002).

The percent of Mesozoic Lowland HGMR underlying the drainage basin, ML, is significant at the 95% confidence level for all of the equations (Table 5). The negative coefficient associated with the variable, ML, suggests that the Mesozoic Lowland produces less flow than other HGMRs. This result is consistent with a study of the Chesapeake Bay (Bachman et. al, 1998) that found that percent Mesozoic Lowland HGMR underlying a basin is correlated (though not to a strong degree) with a lower baseflow index (average baseflow divided by average total streamflow) relative to other HGMRs. The same study showed that the baseflow index in basins that are predominantly underlain by the Mesozoic Lowland HGMR have significantly lower baseflow than basins underlain by other HGMRs. The negative Mesozoic Lowland coefficent is also consistent with a report on the Water Resources of Frederick County (Duigon and Dine, 1987) which observed that the lowest 7Q10s per square mile in the county are in the Triassic Gettysburg Shale and New Oxford Formations that form the Mesozoic Lowland HGMR.

The percent of Blue Ridge HGMR underlying the drainage basin, BR, is significant at the 95% confidence level for the 2-year and 10-year annual baseflows, but is only significant at the 90% confidence level for the 20-year baseflow (Table 5). The coefficient suggests that Blue Ridge has a moderate but positive influence on flow. A study of the Chesapeake Bay (Bachman et. al, 1998), did not find the percentage of Blue Ridge HGMR underlying a gaged basin to be significantly correlated to baseflow index, nor did it find the baseflow index of basins underlain predominantly by the Blue Ridge HGMR to be significantly different than the baseflow index of basins underlain primarily by the Piedmont Crystalline HGMR. It is possible that the effect of the Blue Ridge HGMR on baseflow appeared to be more significant in this study because the area of Blue Ridge examined in this study is much smaller than that studied by the Bachman (1998) study. Therefore, precipitation, relief and other non-geologic factors that may affect baseflow may have been more uniform.

The percent of the drainage basin underlain by the Piedmont Carbonate HGMR, PCA, is significant at the 95% confidence level for the 10-year and 20-year baseflow recurrence intervals, but is only significant at the 85% confidence level for the 2-year recurrence interval (Table 5). The carbonate geology appears to have the greatest positive effect on flow relative to the other HGMRs. This is consistent with Bachman et. al, (1998), who found that the percentage of Piedmont Carbonate HGMR underlying a drainage basin is strongly correlated with greater baseflow indexes relative to other HGMRs. A low flow study of Maryland (Carpenter and Hayes, 1996) found that although the percentage of carbonate geology did not appear to be linearly related to low flow characteristics (and therefore was not used as a predictor variable), the predicted flows of gages underlain by carbonate rock were on average many times greater than predicted values based on the regression equations developed for areas underlain by non-carbonate rock. Interestingly, based on the t statistics, the influence of carbonates on flow appears to be greater as the recurrence intervals increase. That is, during times of increasing drought, the Piedmont Carbonate HGMR influences flow more than other HGMRs. A study of the Frederick and Hagertown Valleys in Maryland (Nutter, 1973) attributed greater average summer flow in a basin dominated by carbonate geology than metamorphic geology to 1) carbonates have greater secondary porosity than the metamorphic rock, which allows carbonates to store greater amounts of water and 2) the slope of the water table in carbonates is often flatter than the water table in metamorphic rocks, resulting in a lower groundwater gradient. These characteristics of carbonate rocks may result in the Piedmont Carbonate HGMR having a greater influence on flow during times of drought than the other HGMRs.

Table 8 shows baseflow predictions for hypothetical 60 square mile basins underlain by 100% of each HGMR. The table also includes 90% confidence intervals for the predictions (see Appendix A). The predicted 2-year baseflows were similar to the median baseflows calculated by Bachman et al., 1998 for the period between 1980 and 2000. In that study, median baseflows calculated for basins underlain predominantly by the Mesozoic Lowland, Blue Ridge, and Piedmont Crystalline HGMRs were 5.9 inches, 9.0 inches and 8.5 inches, respectively; in this study, the 2-year annual baseflows predicted for a 60 square mile basin that was composed entirely of Mesozoic Lowland, Blue Ridge, and Piedmont Crystalline HGMRs were 5.3, 12.2, and 8.5 inches. The Mesozoic Lowland HGMR predictions produced the least flow and the Piedmont Carbonate HGMR produced the most flow in all recurrence intervals. One surprising result of the analysis is that when the carbonates comprise 100% of the drainage basin area, the regression equations predicts that baseflow does not decrease between the 2- and 20-year recurrence intervals, a result which seems to contradict the hypothesis used in this study that baseflow statistics are a measure of ground water recharge. However, the range of the confidence intervals for the predicted Piedmont Carbonate baseflows was quite wide. Also, many studies warn that using regression equations to predict flow at basins that have characteristics outside of the range of characteristics of basins used to develop the regression equations may result in large errors (Flynn, 2002; Ries, 1994a; Ries, 1994b). The basins used to develop the regression equations were underlain by zero to 42% Piedmont Carbonates (see Table 3), so this is likely to be the cause of the inconsistency.

Table 8. Predicted flows, with 90% confidence intervals, for hypothetical 60 square mile basins underlain by 100% of a given HGMR

HGMR	Units	Predicted 2-year 365-day baseflow (90% lower, upper confidence levels)	Predicted 10-year 365-day baseflow (90% lower, upper confidence levels)	Predicted 20-year 365-day baseflow (90% lower, upper confidence levels)
100% Piedmont Crystalline (PCR)	inches/year	8.5 (5.6, 11.7)	5.8 (3.1, 8.8)	5.2 (2.6, 8.2)
	gpd/acre	630 (420, 870)	430 (230, 660)	390 (190, 610)
100% Mesozoic Lowland (ML)	inches/year	5.3 (3.4, 7.5)	2.9 (1.5, 4.6)	2.4 (1.2, 4)
	gpd/acre	390 (250, 560)	220 (110, 340)	180 (90, 300)
100% Blue Ridge (BR)	inches/year	12.2 (8, 17)	7.8 (4.1, 12)	6.8 (3.3, 11)
	gpd/acre	910 (600, 1300)	580 (310, 910)	510 (250, 820)
100% Piedmont Carbonate (PCA)	inches/year	14 (7.2, 24)	14 (5.3, 30)	14 (4.8, 32)
	gpd/acre	1000 (540, 1800)	1000 (400, 2200)	1000 (360, 2400)

Potential improvements to the model

Although adequate gage coverage of the study area was attempted when selecting the gages used for the regression analysis, the upper part of the Monocacy basin is still not well represented relative to the other parts of the basin (Figure 5). Few gages in this area exist, and many that do exist were eliminated because the data were collected outside the base period of record, did not appear to be taken during a period of low flow, or did not adequately match up with data taken at a continuous gage station. More gage data in this area would certainly improve baseflow estimates in this part of the basin.

The fact that the average model error is greater than the average sampling error in all of the models (Table 6) suggests that the model could be most improved by minimizing the average model error. As described earlier, the average model error variance represents the error inherent in the model. Average model error can be reduced by improving the measurement of site characteristics that are used as explanatory variables in the regression, choosing explanatory variables that better predict flow statistics, or adding new sites to the regression analysis (Ries, 1994b).

III.3 Seasonal Water Budget Analysis

Annual ground water recharge estimates provide a starting point for developing an understanding of water availability in a sub-basin. However, a water budget based on annual averages does not take into account a number of factors that may play a significant role in determining availability. In our region of interest, water availability is generally only an issue during the summer months, but the annual water budget does not provide information on seasonal variability. Also, in the Monocacy/Catoctin basin it is evident that sub-basins vary significantly in their ability to store recharge (see discussion below), but the annual water budget approach does not incorporate information on changes in storage. Therefore, an understanding of the seasonal water budget, including seasonal changes in storage, is desirable.

In a seasonal water budget, the equation that describes changes in storage in a sub-basin aquifer, (1), requires knowledge of water budget components for each season of the year. For a number of sub-basins in the study area, sufficient data are available to obtain good estimates of several quantities useful for computing the seasonal water budget, namely, total quarterly precipitation, P_i, total quarterly stream baseflow, $q_{BF\,i}$, and total quarterly stream storm flow, $q_{SF\,i}$. Data are also available for the time period, 1980-2001, to make some rough estimates of total net ground water withdrawals, W_i, in order to evaluate the relative importance of this quantity. However, it is very difficult to obtain reliable estimates of two important component of the seasonal water budget, storage, S_i, and ground water recharge, R_i , or, alternatively, net recharge, $R_{net\,i}$. If reliable estimates can be obtained for just one of these quantities, the other can be computed via equation (1).

For regional scale water balance studies, recharge is often computed via equation (2) or some similar equation, using estimates of unsaturated zone evapotranspiration based on climate data, soil characteristics, and other basin characteristics (Thornthwaite, 1948; Sophocleous and McAllister, 1987; Alley, 1984; Bauer and Vaccaro, 1990). But estimates of evapotranspiration are subject to considerable uncertainty. They are sensitive to soil and vegetation parameters, which are difficult to accurately measure (Finch, 1998). Also, parameters governing evapotranspiration are difficult to estimate at the regional scale (Milly and Dunne, 2002).

As an alternative to estimating recharge through evapotranspiration, some researchers have estimated recharge via equation (1) by estimating changes in aquifer storage obtained from analyses of the recession characteristics of stream hydrographs. In most studies it's assumed that, if a sufficiently long time has elapsed since the last recharge event, stream discharge is equivalent to ground water discharge (i.e. stream baseflow) and can be approximated by an exponentially decaying function of time. This function can be used to estimate the aquifer storage associated with any given value of baseflow. The storage volume, or "total potential ground water discharge", was used by Meyboom (1961) to estimate annual recharge volumes from 1951 through 1958 for a river basin in Alberta, Canada. In a study of stream-aquifer properties in eastern Kansas, Bevans (1986) estimated recharge by computing aquifer storage volumes at the critical time defining the onset of exponentially decaying baseflow for several distinct recharge periods. Rutledge and Daniel (1994) used an automated computer program incorporating equations for baseflow recession developed by Rorabaugh (1964) to analyze stream hydrographs and compute accumulated recharge for a given time interval of interest. Dias and Kan (1999) computed mean monthly evapotranspiration by using recharge estimates found for recession periods within or near the month of interest. Wittenberg and Sivapalan (1999), assuming a nonlinear relationship between storage and discharge which leads to a non-exponential form of the function describing recession, have used estimates of daily baseflow to construct a daily time series of water budget components.

In this study we use analyses of baseflow recession to help obtain estimates of seasonal changes in storage and develop a seasonal water budget time series for the period, 1960 through 2002. Rather than computing changes in storage for a series of recharge and recession periods of varying length, a simple estimate of "beginning-of-quarter" baseflow, based on means of logarithms of daily baseflow, is used to compute "beginning-of-quarter storage". The resulting predictions for the time series of storage volumes are found to compare well with quarterly means of observed ground water levels. Storage predictions are also compared with predictions of seasonal storage based on the USGS's automated computer program, RORA (Rutledge, 1992; 1998).

The seasonal water budget time series are used to investigate summertime water availability by using components of the water budget to construct a volume of water representing summer availability, consisting of the sum of beginning-of-summer storage and summer recharge. The frequency distribution of this volume, over the study period, 1960 through 2002, is examined to obtain estimates of summer availability in typical years and in dry years.

Methods

Seasonal water budget time series have been constructed for the following four gaged sub-basins in the Monocacy/Catoctin drainage area: Bennett Creek above the gage at Park Mills, MD; Big Pipe Creek above the gage at Bruceville, MD; upper Monocacy River above the gage at Bridgeport, MD; and, Catoctin Creek above the gage near Middletown, MD. These sub-basins were chosen because they have continuous periods of record over all or most of the study period of interest, 1960 through 2002. This study period includes two periods of serious drought: the drought of the 1960's and the drought of 1999-2002. The sub-basin drainage areas are depicted in Figure 7 and given in Table 9. The time series were computed for the water years 1960 through 2002, that is, beginning in October 1959 and ending September 2002 (with the exception of the Catoctin Creek sub-basin, where the continuous record of daily discharge data began in 1966). Seasons were defined as follows: 1st Quarter (Winter): January through March; 2nd Quarter (Spring): April through June; 3rd Quarter (Summer): July through September; and 4th Quarter (Fall): October through December.

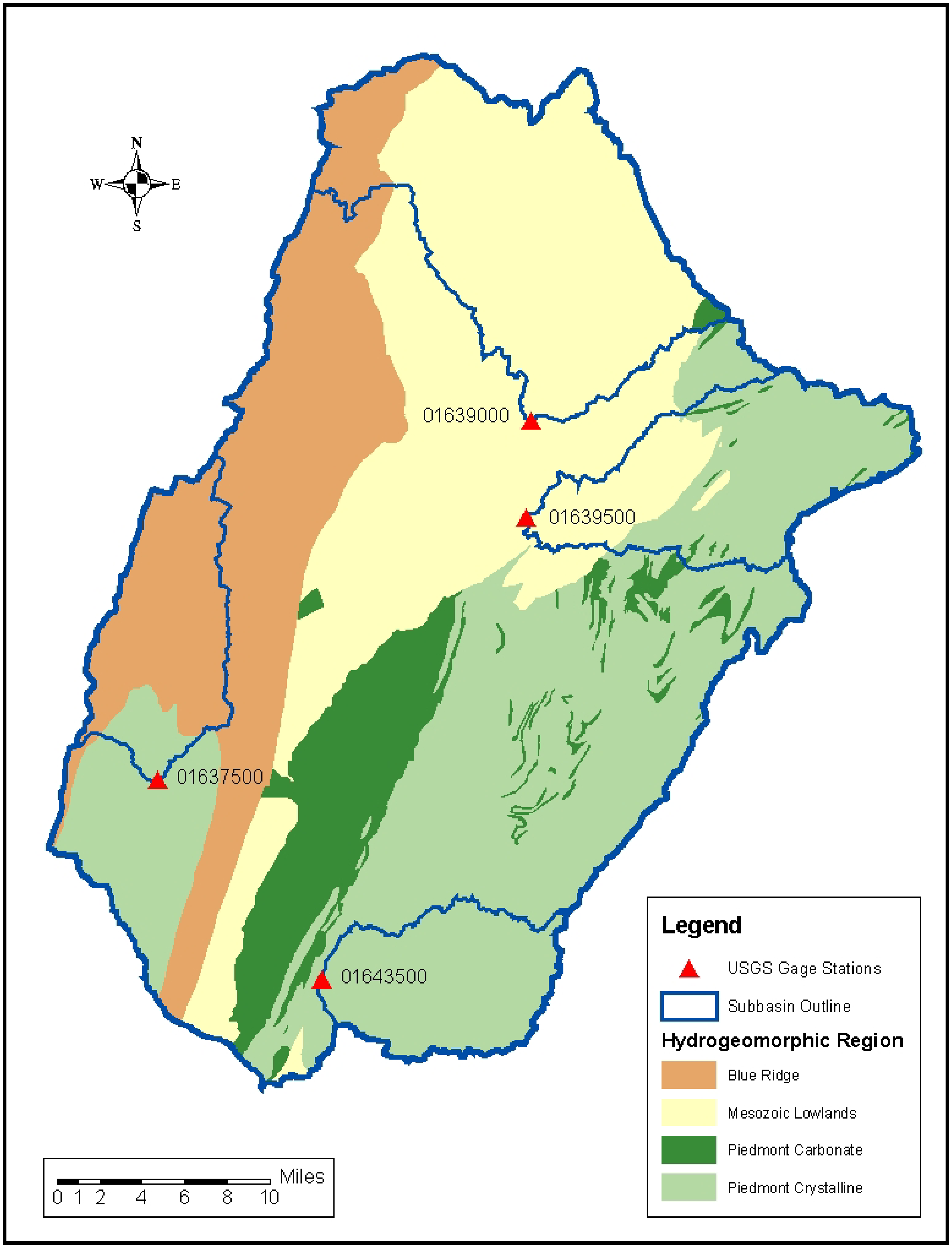


Figure 7. Gage stations defining four sub-basins of interest

Table 9. Sub-Basins for Seasonal Water Budget Analysis

	Catoctin Creek	Upper Monocacy	Big Pipe Creek	Bennett Creek
USGS gage station	01637500	01639000	01639500	01643500
Drainage area (mi^2)	66.9	173	102	62.8
Beginning of daily flow record	8/1/47	5/1/42	10/1/47	7/29/48*
End of daily flow record	9/30/03	9/30/03	9/30/03	9/30/03

* Flow data is not available for Bennett Creek for the time period, 10/1/58 to 7/31/66.

Analysis of baseflow recession

In this study, several important seasonal water budget components, storage, recharge, and evapotranspiration, are computed by using baseflow recession analyses to estimate aquifer storage. If sufficient time has elapse since the last recharge event, stream discharge is assumed to be equivalent to stream baseflow, and its change over time of can often be approximated by a simple exponential decay function (Barnes, 1939)

$$q(t) = q_0 \, e^{-k(t-t_0)} \qquad \textbf{(9)}$$

where

q(t)	=	discharge at time t
q_0	=	discharge at initial time, t_0
k	=	decay rate

For any portion of the stream hydrograph approximated by equation (9), a plot of the logarithm of flow versus time should be approximately a straight line with slope, -k, and therefore, analyses of stream hydrographs can be used to estimate the decay rate, k. The decay rate is often expressed in terms of the "recession index", $K = \ln(10)/k \cong 2.303/k$, where K can be defined as the length of time it takes for discharge to decrease to $1/10^{th}$ of its initial value.

Equation (9) can be integrated to obtain the volume of water which would be discharged over a given period of time, assuming that no additional ground water recharge were to occur. In particular, equation (9) can be integrated from t_0 to ∞ to estimate, for a given initial discharge value, q_0, the "total potential ground water discharge", that is, the volume of water that is stored in the aquifer above the zero-streamflow level (Meyboom, 1961; Rorabaugh, 1964),

$$\textit{volume stored above zero flow level} = \frac{q_0 \, K}{2.303} \qquad \textbf{(10)}$$

In a stream basin where a minimum low-flow requirements has been determined, or where low-flow requirements have been established by regulatory agencies, equation (9) can be integrated to estimate the volume of water stored in a sub-basin aquifer above the minimum low-flow level, q_{min}, that is

$$\textit{volume stored above minimum flow level} = \frac{(q_0 - q_{min}) \, K}{2.303} \qquad \textbf{(11)}$$

Baseflow recession indices, K, were estimated for each of the four gaged sub-basins of interest using the USGS's automated computer program, RECESS (Rutledge, 1992; 1998) The flow records used in the computations were restricted to the period, October through March, representing the portion of the year with relatively low evapotranspiration. From the daily flow record, RECESS identifies periods of continuous recession, and for each period identified, allows the user to examine the semi-log plot of daily flow, identify the segment of the curve which best represents conditions of linear recession, and specify this segment to be used for calculation of the recession index. In general, it is recommended that segments be chosen which fall outside an initial time period defined by a critical time, t_c, which is approximately 1/5 of the value of the recession index. In all but very few of the recession analyses, two linear segments in each recession curve were found to be present, and the second of the segments, generally beginning after the critical time, was chosen for calculation of the recession index.

Computation of seasonal water budget time series

The change in the volume of water stored in a sub-basin aquifer over a given quarter, $\Delta t_i = t_{i+1} - t_i$, is given by equations (1) and (2), where S_i is now the volume stored at t_i, the beginning of quarter i, and R_i , $q_{BF\,i}$, RET_i , W_i , P_i , $q_{SF\,i}$, and UET_i all represent quarterly totals. Equation (10) is used to estimate values for "beginning of the quarter" storage volumes, S_1 , S_2 , S_3 , …for all quarters of the water years 1960 through 2002. Then the S_i, can be used with equations (1) and (3) to compute estimates for net recharge, that is,

$$R_{net\,i} = \Delta S_i + q_{BF\,i} + W_i \qquad \textbf{(12)}$$

Also, once the ΔS_i are known, total evapotranspiration, ET = (RET + UET), can be computed, using equations (1), (2), and (3), as

$$ET_i = RET_i + UET_i = P_i - q_{BF\,i} - q_{SF\,i} - W_i - \Delta S_i \qquad \textbf{(13)}$$

Most components of the seasonal water budget are readily estimated from available data. Daily stream flow data is available from the USGS gage stations located at the discharge point of each of the four sub-basins of interest for periods of record noted in Table 9. These data were used to compute total quarterly baseflow and stormflow, $q_{BF,i}$, and $q_{SF,i}$, using the USGS hydrograph separation program, PART (Rutledge, 1992; 1998) Quarterly precipitation totals for each sub-basin, P_i, were estimated using the Thiessen polygon method and daily precipitation data for 16 stations within or near the Monocacy/Catoctin drainage area obtained from the National Climatic Data Center. A list of the precipitation gage stations and the periods of record for daily precipitation are given in Table 10 and depicted in Figure 8.

In order to use equation (10) to obtain the storage time series, S_i, appropriate values must be obtained for the initial baseflow at the beginning of each quarter, $q_{0\,i}$, and baseflow recession indices, K. In this study, daily time series of sub-basin baseflows were used to estimate "beginning-of-quarter" baseflow, $q_{0\,i}$, by computing means of the logs of daily baseflows over a two-month time period centered around the beginning of the quarter of interest. For example, the beginning of any given first quarter baseflow was computed from the mean of the logs of December and January daily baseflows, the beginning of a second quarter baseflow was computed from the mean of the logs of March and April daily baseflows, etc. Mean values of baseflow recession indices for each of the four sub-basins were substituted for K.

Table 10. Precipitation Gage Stations

Precipitation Gage Station Name	State	Period of record begin	Period of record end	Station ID	Latitude	Longitude
Biglerville	PA	1971	2003	360656	39:56:00	77:15:00
Catoctin	MD	1968	2003	181530	39:39:00	77:29:00
Damascus 2SW	MD	1973	1992	182335	39:16:00	77:14:00
Damascus 3SSW	MD	1993	2003	182336	39:16:00	77:14:00
Eisenhower NHS	PA	1982	2003	362537	39:48:00	77:14:00
Emittsburg	MD	1948	1956	182905	39:41:00	77:21:00
Emmitsburg 2SE	MD	1956	2003	182906	39:41:00	77:18:00
Frederick Police Barracks	MD	1948 1973	1962 2002	183348	39:25:00	77:26:00
Frederick WFMD	MD	1948	1972	183350	39:25:00	77:28:00
Frederick 3E	MD	1948	1990	183355	39:24:00	77:22:00
Millers 4NE	MD	1987	2003	185934	39:43:00	76:48:00
Rockville 1NE	MD	1948	2003	187705	39:06:00	77:09:00
South Mountain	PA	1948	2003	368308	39:51:00	77:30:00
Spring Grove	PA	1948	2003	368379	39:52:00	76:52:00
Westminister 2 SSE	MD	1948	1979	189435	39:33:00	76:59:00
Westminister Police Barracks	MD	1979	1999	189440	39:33:00	76:58:00

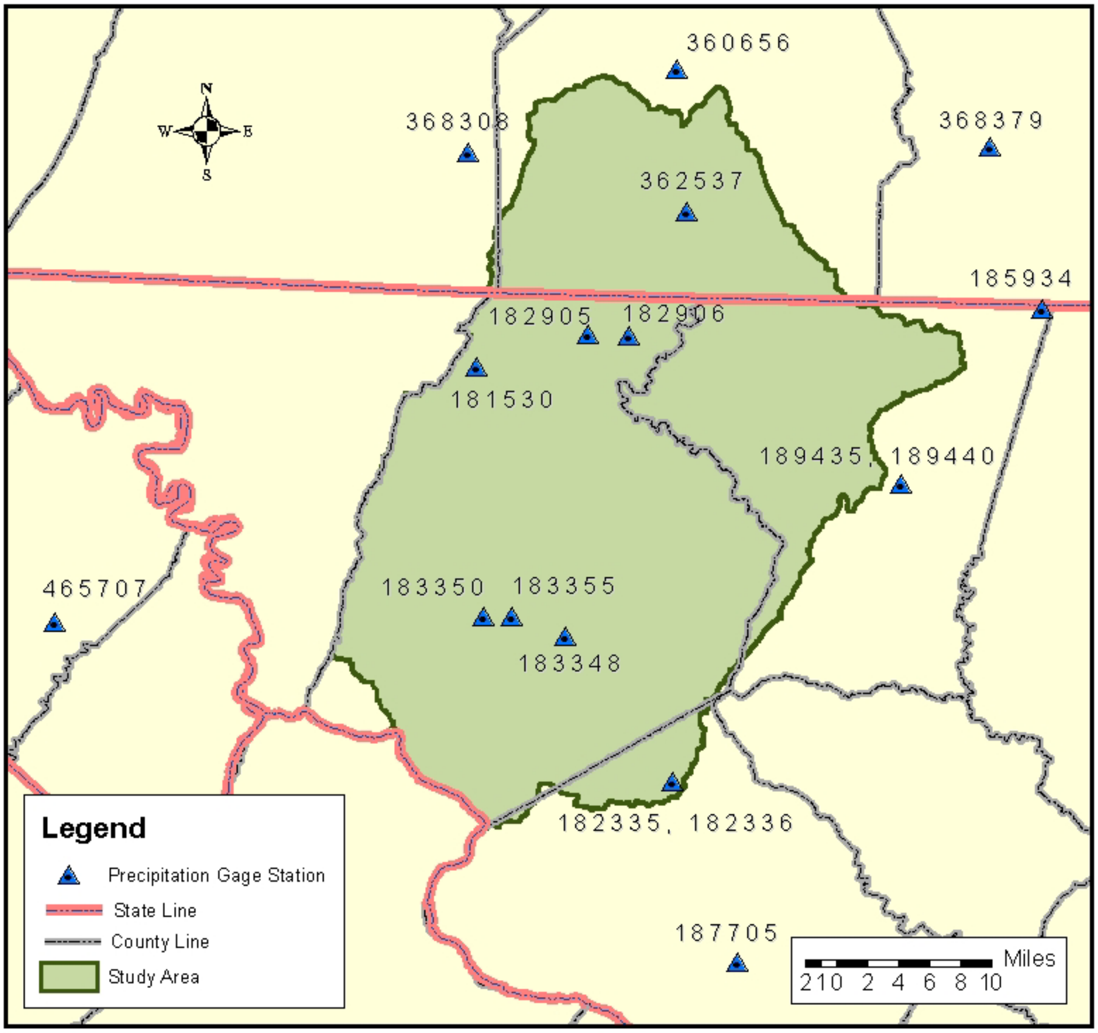


Figure 8. Location of precipitation gage stations

Estimates of ground water withdrawals

Estimates were made for seasonal net ground water withdrawals, W_i, for the time period of interest, 1960 through 2002, based on available data. For the Maryland portion of the study area, estimates of monthly ground water withdrawals from major water users are available for the time period, 1980 thru 2001, from the USGS's Site-Specific Water-Use Data System (SWUDS) for Maryland, prepared by the USGS District Office in Baltimore (private communication, Judy Wheeler). These estimates were based on data collected by the Maryland Department of the Environment under its water appropriation permit program, which requires monthly water use totals from all water users who withdraw more than 10,000 gallons per day (gpd). Appendix C lists the major water users that withdraw ground water from locations upstream of the flow gages in the Bennett Creek, Catoctin Creek, and Big Pipe Creek sub-basins, as given in the SWUDS database for Maryland. Total seasonal ground water withdrawals in this time period for the sub-basins of interest ranged from 0.00 to 0.08 inches per quarter.

The Pennsylvania Department of Environmental Protection (PADEP) has collected data on net ground water withdrawals from significant users, including detailed yearly data from public water supply systems. Recently, under the Water Use Planning Act of 2002 (Act 220), PADEP has initiated a program to register and collect information on all water users withdrawing more than 10,000 gallons per day. However, little time series data is currently available for the Pennsylvania portion of the Monocacy/Catoctin drainage area for most types of users. Based on an analysis of available data, primarily from the 1990's, available from the USGS District Office in Pennsylvania (private communication, Russell Ludlow) and the Pennsylvania Department of Environmental Protection (private communication, David Jostenski), net ground water withdrawals from significant users in recent years has been on the order of 0.04 inches per quarter, and consumptive use of ground water by domestic users served by individual wells has been on the order of 0.01 inches per quarter.

In addition to the estimates of ground water withdrawals from major users, an estimate is made of net ground water withdrawals, i.e. consumptive use, by domestic users served by individual wells, from information contained in the 1985, 1990, 1995, and 2000 USGS Aggregated Water Use Data System (AWUDS). From the information available in AWUDS, consumptive use of ground water by households relying on individual wells and septic was estimated at an approximately constant value of 0.01 inch per quarter throughout the time period of interest, 1980 - 2002. This estimate was made based on available information from AWUDS on the population of self-served domestic users in the Monacacy basin and in Adams, Frederick and Carroll Counties. The estimate also assumes a per capita use of 80 gpd for self-served domestic users, and a consumptive use, i.e. net ground water withdrawal, of 25%. Though the value of 0.01 inch per quarter throughout Monocacy/Catoctin watersheds throughout the time period of interest is a fairly crude estimate, it was judged to be sufficient for use in the seasonal water budget time series for the pilot study area since it is usually at least an order of magnitude smaller than other water budget components.

For the Maryland sub-basins, Catoctin, Big Pipe, and Bennett Creeks, the 1960 through 2002 time series for W_i were constructed using 1980-2001 seasonal withdrawal estimates based on monthly ground water withdrawals by major users available from the Maryland SWUDS. Based on review of data from the early 1980s, a constant value of $W_i = 0.01$ inches per quarter was used for Bennett and Big Pipe, and $W_i = 0.02$ per quarter for Catoctin for years earlier than 1980. Added to each of these withdrawal estimates was the estimate of 0.01 inches per quarter for consumptive use by domestic users served by individual wells. Seasonal ground water withdrawals for 2002 were assumed to equal their 2001 values. To obtain a withdrawal time series for the upper Monocacy basin, the mean of the time series for the three Maryland sub-basins was used. The resulting upper Monocacy time series is consistent with the limited information available for the Pennsylvania portion of the study area.

Summer water availability

Water supply in the Monocacy and Catoctin drainage area tends to be lowest in the summer months (3rd quarter, that is, July, August and September) when both well levels and stream flow are often at their lowest. Therefore, a quantitative measure of summer availability may be a more relevant indicator of potential water supply problems than the measure of annual availability given by the annual recharge approach. A simple and intuitively appealing estimate of the volume of ground water available during summer months, V_{Q3} , is the sum of beginning of summer storage plus summer recharge, that is,

$$V_{Q3} = S_{Q3} + R_{Net,Q3} \quad \textbf{(14)}$$

where, as before, S_i represents the volume of water stored in the aquifer above the level of zero stream discharge at the beginning of quarter, i, and $R_{net,\,i}$ represents the total net recharge for quarter, i. In equation (14), we are only considering summer, that is, 3rd quarters of the water budget time series. Therefore, V_{Q3} represents an estimate of the total volume of water available in a sub-basin for both human consumption and stream baseflow requirements during the summer quarter.

Estimates of summer water availability, V_{Q3} , for each of the four sub-basins of interest are computed from the water budget time series for each summer in the study period, 1960 through 2002. Frequency curves are constructed for these series in order to obtain estimates of the frequency of occurrence of summers with “low availability”. The frequency curves are obtained by constructing the cumulative probability functions for V_{Q3} using the USGS’s “graphical method” (Riggs, 1968), where the recurrence interval, or return period, T, in years, is related to the probability of non-exceedence in any one year, p, by the formula, $T = 1/p = (n+1)/m$, where n is the sample size and m is the order number of the sample value. For comparison with the results of the annual water budget approach, values for V_{Q3} for the 2-year, 10-year, and 20-year recurrence intervals are computed.

Results

Sub-basin recession indices

Baseflow recession indices were computed using the automated computer program, RECESS, with a summary of results appearing in Table 11. Though there is a fair amount of variability in the computed recession index, results imply that storage is relatively poor in these upper fractured bedrock aquifers, and that these aquifers’ “memory” of past hydrologic conditions is quite poor. For example, in the portion of the Monocacy River basin upstream of the gage at Bridgeport, median value results in Table 11 imply that if no recharge were to occur, aquifer storage (as well as discharge to streams) would drop to 10% of its original value in only approximately 33 days.

Table 11. Summary of Results for Baseflow Recession Index, K (days)

	Catoctin Creek 01637500	Upper Monocacy 01639000	Big Pipe Creek 01639500	Bennett Creek 01643500
Count	30	16	14	16
Maximum	137	51	119	139
Minimum	26	24	52	53
Mean	57	35	80	87
Std. Deviation	31	8	20	29
90th Percentile	111	45	104	128
75th Percentile	59	37	94	105
Median	45	33	71	80
25th Percentile	35	32	66	57
10th Percentile	31	26	64	56

Results in Table 11 are reasonably consistent with values of recession indices reported by Rutledge and Mesko (1996), who analyzed recession rates for 89 stream basins in the Appalachian Valley and Ridge, the Piedmont, and the Blue Ridge Physiographic Provinces for the time period, 1961 to 1990, restricting their analysis to recession segments that began in the time period, October through May. For sub-basins in the Piedmont Province they found a median recession index of approximately 70 to 80 days, consistent with the results in Table 11 for Bennett and Big Pipe Creeks. For the Blue Ridge, they found a median recession index of around 90 days, considerably larger than the value of 45 days in Table 11 for Catoctin Creek, though Catoctin Creek, Station 01637500, is a sub-basin in their sample set, with a recession index reported as 48.3 days. Recession index results for the Monocacy River gage at Bridgeport, also in the Piedmont Province, are significantly lower than values typically found by Rutledge and Mesko, implying that the shales and sandstone of the Mesozoic lowlands have particularly poor storage properties.

Seasonal water budget time series

Components of the seasonal water budget time series from October 1959 through September 2002 for the four sub-basins are given in Appendix B. Long-term averages of the seasonal water budget components appear in Table 12. As expected, total evapotranspiration (ET = UET + RET) is highest in all sub-basins in the spring and summer (Q2 and Q3). Increase in aquifer storage, ΔS, is greatest in the fall and winter (Q4 and Q1). However, net recharge is greatest in the winter months (Q1). The aquifers underlying the upper portion of the Monocacy River basin, above the gage at Bridgeport, and Catoctin Creek appear to have significantly poorer ability to store ground water than the other sub-basins, as reflected by the low values of beginning of the quarter storage, S, for all seasons. This is consistent with the low values of the recession coefficient estimated for these sub-basins (see Table 11). Long-term averages of seasonal ground water withdrawals are less than 0.05 inches per quarter for all seasons for all of the four sub-basins.

As a means of checking the validity of the approach used in this study, storage predictions, S_i , for the four sub-basins were compared with ground water level data from ten wells within or near the Monocacy/Catoctin drainage area. Changes in well water level, Δh, can be used to estimate changes in aquifer storage in the vicinity of the well when aquifer specific yield, S_y, is a known constant, since in this case the change in storage per unit area is simply

$$\Delta S = \Delta h \; S_y \qquad \textbf{(15)}$$

Therefore, under the assumption that S_y is approximately constant in a given sub-basin, plots of the storage time series, S_i, after an appropriate rescaling, should approximately resemble plots of mean well water levels, h_i, in that sub-basin.

Wells used in this comparison are shown in Figure 9 and listed in Table 13. Wells selected for use in the analysis satisfied the following three criteria: 1) at least 36 water level observations, 2) at least three years of reasonably continuous observation records within the time period of interest, 1960 through 2002, and 3) location within the sub-basin of interest, or near the sub-basin of interest and within the predominant HGMR of the sub-basin of interest. Thus, selected wells generally had monthly data for at least several years within the study period. At least two wells satisfying these criteria were found for each of the four sub-basins, as indicated in Table 13. Water level data for each well (measured in feet below ground surface) was downloaded from the USGS's NWIS web-site. Well data was normalized by subtracting water level from mean water level (where mean water level was computed for the entire period of record of the well).

Table 12. Average Seasonal Water Budgets for Four Gaged Sub-Basins for Time Period, 1960 – 2002 (inches per quarter)

	Precip	q_{SF}	q_{BF}	ET	R_{net}	ΔS	S	W
Catoctin (01637500)								
Q1	9.9	1.9	4.4	2.8	5.2	0.7	0.7	< 0.05
Q2	11.7	1.3	3.7	7.7	2.7	-1.1	1.4	< 0.05
Q3	11.2	0.6	0.7	10.0	0.6	-0.1	0.3	< 0.05
Q4	9.8	1.0	1.8	6.4	2.4	0.5	0.2	< 0.05
Annual	42.5	4.8	10.7	26.9	10.8	0.0		0.1
Bridgeport (01639000)								
Q1	10.0	4.5	2.9	2.3	3.1	0.2	0.3	< 0.05
Q2	12.0	2.5	1.7	8.2	1.3	-0.4	0.5	< 0.05
Q3	11.5	1.0	0.4	10.1	0.4	0.0	0.1	< 0.05
Q4	9.9	2.2	1.2	6.2	1.5	0.2	0.1	< 0.05
Annual	43.4	10.3	6.2	26.8	6.3	0.0		0.1
Big Pipe (01639500)								
Q1	9.7	2.2	3.6	3.4	4.1	0.5	1.0	< 0.05
Q2	11.4	1.3	3.0	8.0	2.1	-0.9	1.5	< 0.05
Q3	11.4	0.8	1.2	9.5	1.1	-0.2	0.6	< 0.05
Q4	9.8	1.1	1.9	6.2	2.5	0.5	0.4	< 0.05
Annual	42.3	5.4	9.7	27.1	9.7	0.0		0.1
Bennett (01643500)								
Q1	9.9	1.7	3.7	3.9	4.3	0.6	1.1	< 0.05
Q2	11.8	1.4	3.3	8.1	2.3	-1.0	1.7	< 0.05
Q3	11.6	0.8	1.2	9.8	1.0	-0.2	0.7	< 0.05
Q4	10.4	1.0	2.0	6.7	2.6	0.6	0.5	< 0.05
Annual	43.8	4.9	10.2	28.6	10.3	0.0		0.1

Before making any comparisons with storage estimates, well data were smoothed both temporally and spatially. Temporal smoothing of the well water level data was done by computing three-month means of observed water levels, with each three month averaging period centered around the beginning of a quarter. Thus, for each well, all available data from November 16 through February 15 was averaged to obtain the beginning of the first quarter means, all available data from February 16 through May 15 was averaged to obtain beginning of second quarter means, all available data from May 16 through August 15 was averaged to obtain beginning of second quarter means, and all available data from August 16 through November 15 was averaged to obtain beginning of fourth quarter means. Spatial smoothing was done by averaging the time series of the groups of well data for each sub-basin, as given in Table 13. For example, time series for the three wells, MOCc14, FREh11, and FRDf35, were averaged to obtain a single water level time series for comparison with the Bennett Creek recession-based storaged estimates.

The smoothed water level time series, h_i (in feet above mean water level) are compared with the predicted time series for storage, S_i (in inches), for each of the four sub-basins of interest in Figure 10 and Figure 11. In these figures, the scales of the vertical axes on the right-hand-side of each graph were adjusted to obtain the best visual fit for each pair of plots. The time series are also compared by means of a linear regression analysis, assuming the linear relationship, $S_i = \beta_0 + \beta_1 h_i$. The results of the regression analysis, given in Table 14, show that the storage time series predicts aquifer water levels in the four sub-basins with R^2's ranging from 0.61 to 0.81, and p-values for the regression coefficients all approaching zero. Both the visual comparisons and the regression analyses indicate that the computed aquifer storage time series match changes in aquifer water levels quite well.

Figures 9 and 10 include plots of storage predictions computed using results from the USGS automated computer program, RORA (Rutledge, 1992; 1998; 2000), which is based on baseflow recession analyses of stream hydrographs using Rorabaugh's model. RORA can be used to compute quarterly recharge estimates for a gaged sub-basin, using as input the daily flow record and an estimate of the recession coefficient for the sub-basin. RORA was used to analyze daily flow records for the study period, 1960 through 2002, for the Catoctin Creek, upper Monocacy at Bridgeport, Bennett Creek, and Big Pipe Creek gage stations, and using the mean values of the baseflow recession indices given in Table 11. Storage predictions were then computed from the RORA recharge estimates with the help of equation (12). Using the assumption that RORA calculates a net recharge defined by $R_{RORA} = R - RET - W$, equation (12) becomes $\Delta S_{RORA\ i} = R_{RORA\ i} - q_{BF\ i}$, where $\Delta S_{RORA\ i} = (S_{RORA\ i+1} - S_{RORA\ i})$. The storage time series, $S_{RORA\ i}$, was initialized by computing the storage at the beginning of the first quarter of 1960, S_0, from the corresponding beginning-of-quarter baseflow, q_0, from equation (10). Because recharge estimates over the 42-year study period computed by RORA exceeded long-term baseflow estimates computed by PART by an average amount, r_err, which ranged from r_err = 1.5 in/yr for Bennett Creek to r_err = 2.4 in/yr for the upper Monocacy at Bridgeport, RORA results were normalized by subtracting the quantity r_err/4 from each quarterly recharge estimate from RORA. Rutledge and Mesko (1996) hypothesized that this quantity represents an estimate of average annual riparian evapotranspiration in a sub-basin, that is, that r_err = RET, and that RORA gives an estimate of sub-basin recharge, R, rather than net recharge. However, in later work (Rutledge, 2000), it is determined that RORA seems to compute estimates for a net recharge, as assumed above. In this case, r_err may represent a systematic bias in the hydrograph separation estimates of stream baseflow.

When RORA predictions were used to estimate long-term averages for seasonal water budget components, results corresponded qualitatively to those appearing in Table 12. However, storage predictions computed from RORA did not match the well level time series data very well in portions of the study period and were poor for the upper Monocacy Bridgeport gage (Figures 9 and 10). These comparisons indicate that quarterly storage and recharge estimates from the simple storage-based approach developed in this study, based on baseflow recession analyses using beginning-of-quarter baseflow estimates, provide more accurate results for the purposes of frequency analyses.

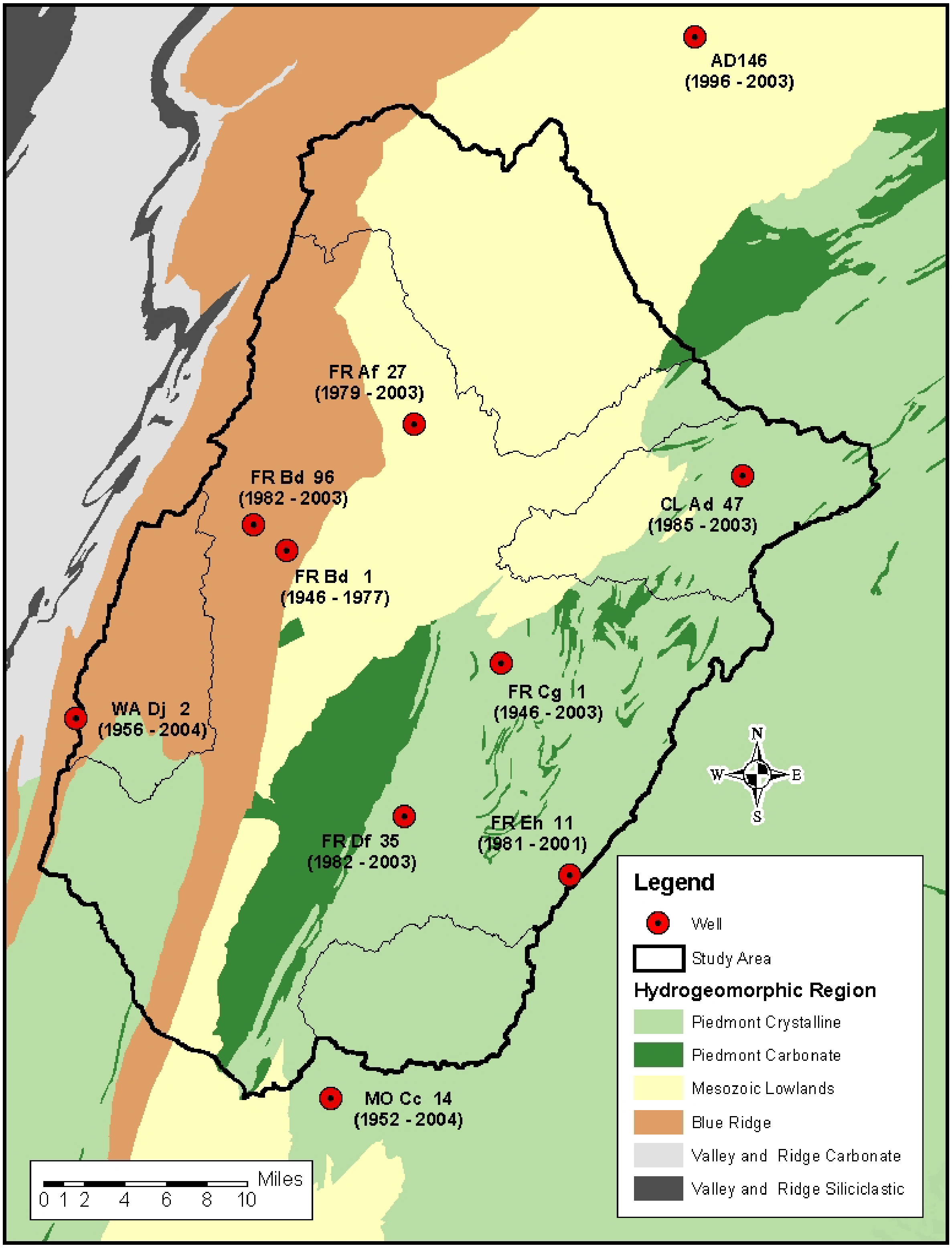


Figure 9. Wells used for comparisons of storage predictions and water levels.

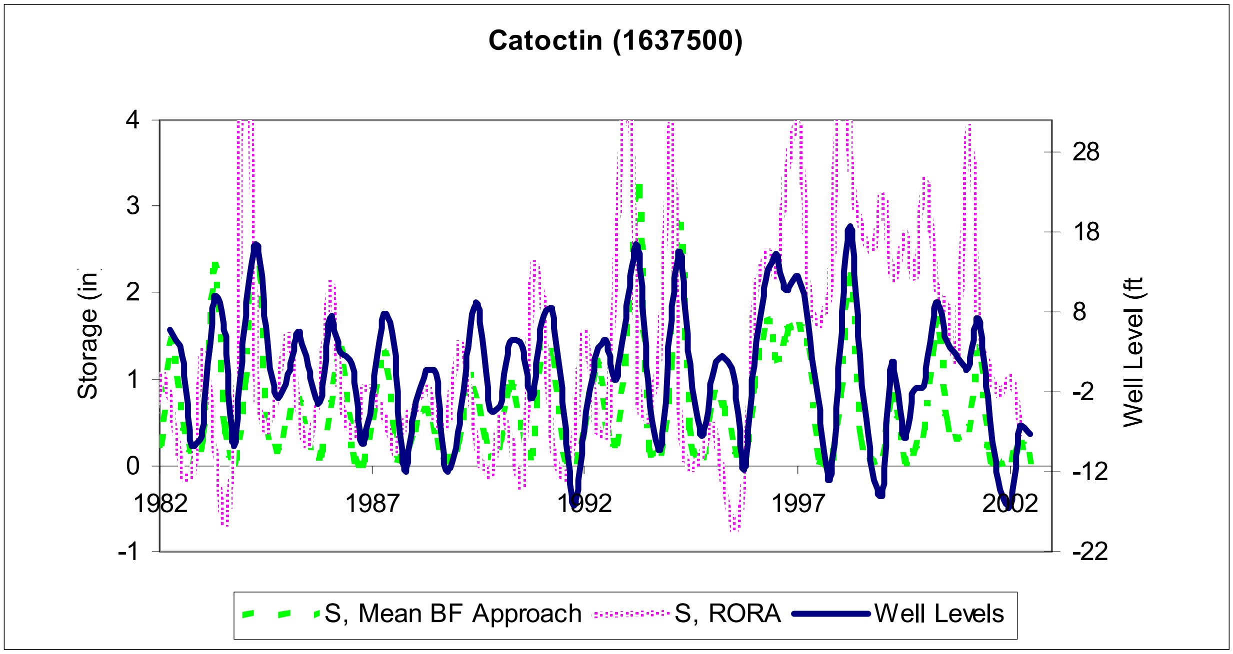
Table 13. Well Data Used for Comparison with Baseflow Recession-Based Storage Estimates

USGS Well Number	Well ID	Depth (ft)	HGMR	Observation Begin Date	Observation End Date	Observation Count
Catoctin (01637500)						
393628077255501	FR Bd 1	NA	BR	10/01/1946	07/21/1977	393
392904077371501	WA Dj 2	61	BR	12/18/1956	11/28/2003	418
393733077274801	FR Bd 96	189	BR	04/05/1982	10/29/2003	885
Upper Monocacy (01639000)						
394200077190701	FR Af 27	365	ML	08/29/1979	11/28/2003	256
395846077040601	AD 146	100	ML	10/18/1996*	09/07/2004	94
Big Pipe (01639500)						
393156077135701	FR Cg 1	43	PCR	06/28/1946	11/28/2003	743
394008077005601	CL Ad 47	310	PCR	08/07/1985	11/18/2003	218
Bennett (01643500)						
391314077224201	MO Cc 14	46	PCR	11/12/1952	08/23/2004	553
392257077095601	FR Eh 11	103	PCR	11/06/1981	11/05/2001	226
392517077190401	FR Df 35	302	PCR	05/06/1982	10/28/2003	255

*One additional well level observation was made on 6/12/67.

Table 14. Linear Regression Analysis Predicting Well Water Levels from Recession-Based Storage Estimates

		Coefficients	t-value	p-value	R^2
Catoctin (01637500)	β_0	-5.7	-7.8	2×10^{-11}	0.65
	β_1	9.2	12.3	4×10^{-20}	
Upper Monocacy (01639000)	β_0	-1.2	-8.1	5×10^{-08}	0.76
	β_1	4.2	8.3	3×10^{-08}	
Big Pipe (01639500)	β_0	-1.3	-13.3	2×10^{-20}	0.81
	β_1	1.5	16.9	8×10^{-26}	
Bennett (01643500)	β_0	-3.0	-9.8	2×10^{-15}	0.70
	β_1	3.2	13.8	8×10^{-23}	



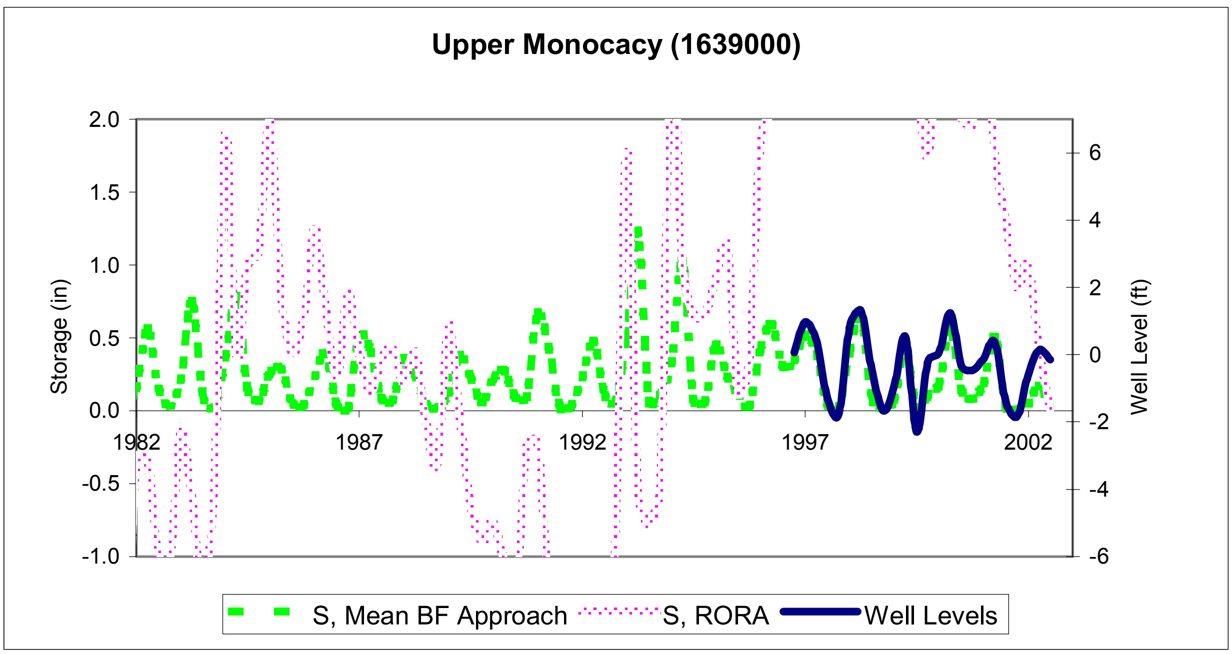
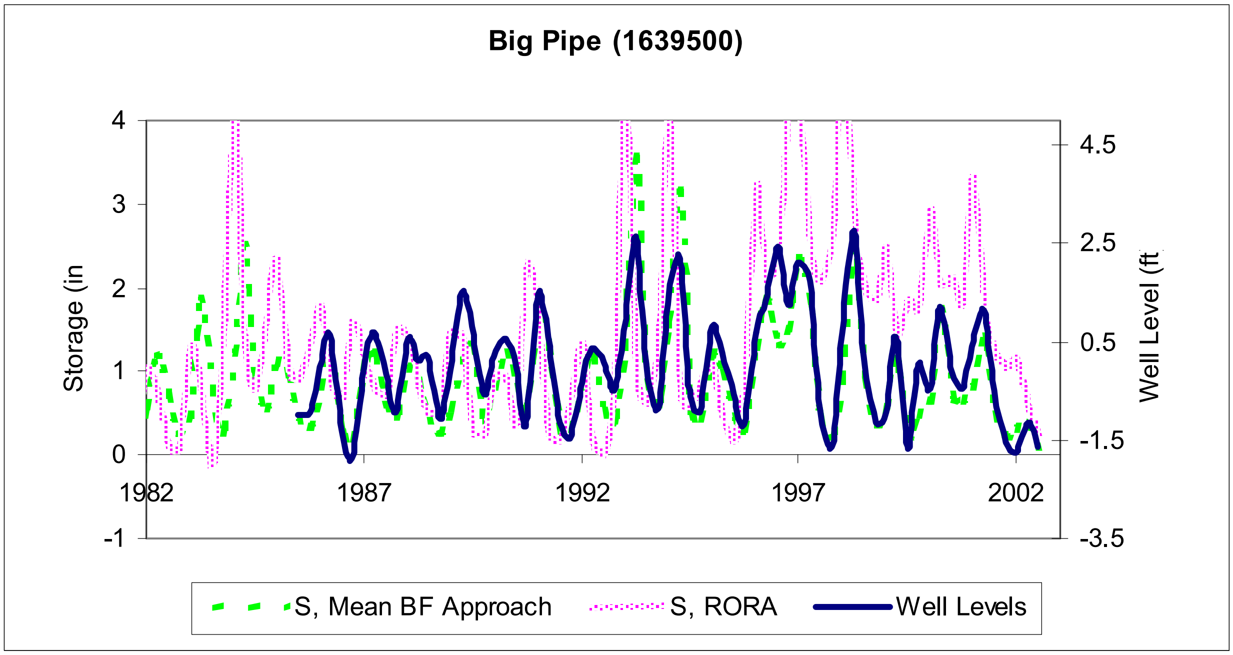


Figure 10. Comparison of storage predictions from mean baseflow method, and from RORA, with mean well levels, for upper Monocacy above Bridgeport gage and Catoctin Creek.



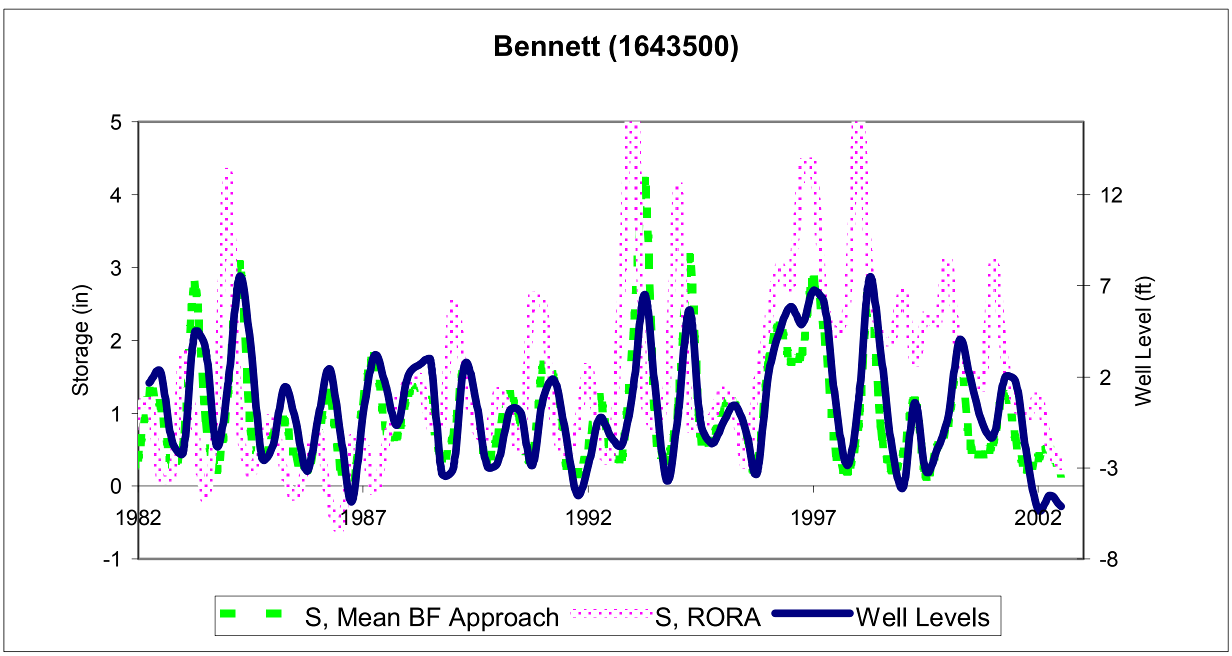


Figure 11. Comparison of storage predictions from mean baseflow method, and from RORA, with mean well levels, Big Pipe and Bennett Creeks.

Water availability estimates

Summertime, or third quarter, water availability has been defined in this study as the sum of beginning-of-summer storage and summer recharge, that is, $V_{Q3} = (S_{Q3} + R_{net\,Q3})$, where aquifer storage is measured from the level of zero stream discharge. In this analysis, "availability" is a measure of the total amount of water available to be apportioned for the purpose of providing water supply for human use and maintaining adequate stream baseflow. Results for the seasonal water budget time series, Appendix B, indicate that summer water availability is lowest in the upper Monocacy sub-basin, above the gage at Bridgeport. In this sub-basin, summer availability, $(S_{Q3} + R_{Q3})$, drops to below 0.10 inches during the drought period of the mid-1960's and also in 2001. Summertime availability is also low in the Catoctin sub-basin, dropping to below 0.15 inches in 1965 and in 2002.

Values for the quantity, V_{Q3}, were computed from third quarter values of S_i and $R_{net\,i}$ in the seasonal water budget time series, Appendix B, for each of the years 1960 through 2002 for each of the four sub-basins. The resulting time series for V_{Q3} were used to construct empirical frequency curves, shown in Figure 12, and to estimate recurrence intervals for V_{Q3}, given in Table 15. For the purpose of comparison, recurrence intervals for water availability obtained with the annual water budget approach are given in Table 16.

A comparison of seasonal and annual water budget results in Table 15 and Table 16, shows some significant differences in predictions of summer water availability. Results for Bennett and Big Pipe sub-basins, both predominately Piedmont Crystalline Rock, are similar. In a typical year (2-year recurrence interval) availability in these sub-basins is roughly 600 gpd/acre based on annual averages, whereas summer availability is around 400 gpd/acre from the seasonal approach. Annual average availability in dry years is around 400 gpd/acre (10-year recurrence) and in the range of 350 to 400 gpd/acre (20-year recurrence), but summer availability from the seasonal water budget drops down to around 200 gpd/acre (10-year recurrence) and around 150 gpd/acre (20-year recurrence).

Differences between annual and seasonal water budget results are more pronounced for the Catoctin and upper Monocacy sub-basins. Annual water budget availability results for the Catoctin sub-basin are very similar to results for Bennett and Big Pipe. However, the summer availability estimates from the seasonal water budget are significantly lower, only 210, 65, and 60 gpd/acre for the 2-year, 10-year, and 20-year recurrence intervals, respectively. For the upper Monocacy sub-basin, above the gage at Bridgeport, annual availability estimates are roughly 25-30% lower than estimates for the other sub-basins. However, summer availability estimates from the seasonal water budget are much lower, with predictions of only 120, 42, and 30 gpd/acre for the 2-year, 10-year, and 20-year recurrence intervals, respectively.

The last columns of Table 15 and Table 16 contain third quarter ground water withdrawal estimates for the four sub-basins for the year 2001. For the annual water budget, 2001 withdrawals are less than 4% of predicted water availability in an average year (2-year recurrence interval)., and less than 7% of predicted availability in a dry year (20-year recurrence interval) for all four sub-basins. However, if availability estimates from the seasonal water budget are used, current ground water withdrawals are much closer to dry year water availability predictions. Ground water withdrawals in 2001 were approximately 40% of predicted dry year water availability in the Catoctin Creek sub-basin and approximately 50% of predicted dry year water availability in the upper Monocacy sub-basin, above the gage at Bridgeport, MD.

Provided that seasonal water budget components can be reliably computed, they should give more accurate predictions of summer water availability than analyses based on annual averages, since they include the effects of seasonality and aquifer storage. The simple approach to computing seasonal water budget components developed in this study appears to give reasonably reliable results, based on comparisons with available well data. It is not surprising that the seasonal water budget analysis predicts considerably lower summertime water availability than annual recharge estimates, since water supply problems in the region typically occur only in summer and early fall. The seasonal water budget's extremely low predictions for dry-year summer water availability for the Catoctin and upper Monocacy sub-basins appear in part to be the result of these aquifers' poor ability to store recharge, as indicated by their low recession indices. For this type of sub-basin, it appears that the annual recharge estimates, which include the significant recharge which occurs in fall and winter, can mask the presence of potential water supply problems in the summer months. It should be noted that the Catoctin and upper Monocacy sub-basins, which primarily represent the BR and ML hydrogeomorphic regions, respectively, have both experienced significant water availability problems during times of drought.

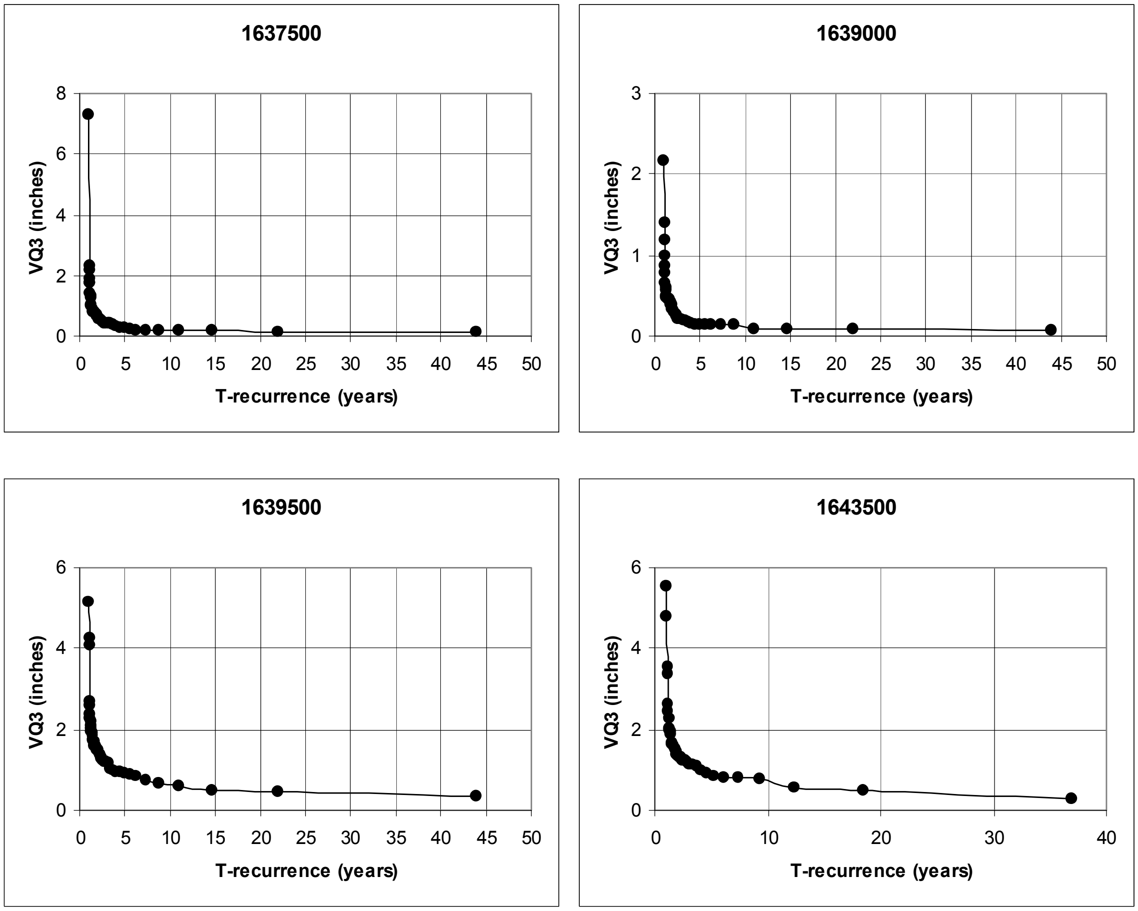


Figure 12. Frequency curves for third quarter water availability, $V_{Q3} = S_{Q3} + R_{net\ Q3}$

Table 15. Seasonal water budget predictions of summer water availability, V_{Q3} (gpd/acre)

Station	2-year V_{Q3} (gpd/acre)	10-year V_{Q3} (gpd/acre)	20-year V_{Q3} (gpd/acre)	2001 Q3 GW Withdrawal Estimate (gpd/acre)
Catoctin Creek (01637500)	210	65	60	24
Upper Monocacy (01639000)	120	42	30	15
Big Pipe Creek (01639500)	460	190	150	16
Bennett Creek (01643500)	420	220	160	6

Table 16. Annual water budget predictions of annual recharge (gpd/acre)

Station	2-year 365-day baseflow (gpd/acre)	10-year 365-day baseflow (gpd/acre)	20-year 365-day baseflow (gpd/acre)	2001 Q3 GW Withdrawal Estimate (gpd/acre)
Catoctin Creek (01637500)	630	400	350	24
Upper Monocacy (01639000)	410	270	230	15
Big Pipe Creek (01639500)	620	400	350	16
Bennett Creek (01643500)	640	440	390	6

III. Conclusions

In this study, water availability in the Monocacy River and adjoining Catoctin Creek drainage areas was investigated by two water budget analyses, the first based on an annual water budget and the second on a seasonal water budget. The goal of the study was 2-fold: first, to assess availability at the sub-basin scale in order to provide water resource managers with estimates of water availability, in units of mgd/mi^2 or gpd/acre, for water supply planning purposes; and second, to evaluate and compare the two methodologies. The annual water budget analysis was applied to the entire study area. However, the seasonal water budget analysis was only applied to four sub-basins in the study area. The seasonal water budget analysis, believed to be more appropriate for the fractured bedrock aquifers of the Monocacy/Catoctin drainage area, was found to give drastically lower predictions of availability for some sub-basins than the annual approach.

In the first analysis, annual ground water recharge was estimated from annual baseflow estimates for 34 sub-basins where discharge data was available. Annual baseflow statistics were extrapolated to ungaged sub-basins of the Monocacy/Catoctin drainage area based on sub-basin hydrogeomorphology using multiple regression techniques. The explanatory variables considered in the study were drainage area and percent of sub-basin in each of the four hydrogeomorphic regions represented in the study area, Piedmont crystalline (PCR), mesozoic lowlands (ML), Blue Ridge (BR), and Piedmont carbonates (PCA). Each of the HGMRs were found to have significant predictive value for most of the baseflow statistics considered. Annual recharge rates for PCR, ML, BR, and PCA were estimated to be 8.5, 5.3, 12.2, and 13.7 inches, respectively, for the 2-year recurrence interval, and 5.2, 2.4, 6.8, and 14 inches, respectively, for the 20-year recurrence interval.

In the second water budget analysis, time series of seasonal water budget components for the time period, 1960 through 2002, were constructed for four sub-basins in the study area: Catoctin Creek, the upper Monocacy basin (above gage at Bridgeport, MD), Big Pipe Creek and Bennett Creek. The seasonal water budget included seasonal changes in ground water storage, computed using information from ground water recession analyses. Median and mean recession coefficients were computed for the four sub-basins and were found to range from 33 to 87 days, indicating fairly poor storage properties for the fractured bedrock aquifers, especially in the upper Monocacy and Catoctin Creek sub-basins. Daily time series of sub-basin baseflows were used to estimate beginning-of-quarter baseflows used to compute beginning-of-quarter storage. A quantity representing summer water availability, defined as the sum of beginning-of-summer storage and summer recharge, was computed for each of the 42 years of the seasonal water budget time series, and was used to predict summer availability in average years and in dry years.

Water availability predictions from the annual and the seasonal water budget approaches were found to differ significantly. Predictions of water availability in dry years, based on estimates of annual recharge, ranged from almost 400 gpd/acre in the Bennett Creek sub-basin to somewhat over 200 gpd/acre for the upper Monocacy sub-basin. However, predictions of dry-year summer availability from the seasonal water budget ranged from approximately 150 gpd/acre for the Bennett and Big Pipe sub-basins, to only 30 gpd/acre for the upper Monocacy sub-basin. The dry year summer availability prediction for the Catoctin Creek sub-basin was also extremely low, only 60 gpd/acre. These availability predictions are uncomfortably close to ground water withdrawals in the year 2001, estimated to be 15 and 24 gpd/acre for the upper Monocacy and Catoctin sub-basins, respectively.

It is not unreasonable that summer water availability estimates in the study area are lower than availability estimates obtained from annual averages, since water supply problems in the region typically occur only in summer and early fall. The seasonal water budget's extremely low predictions for dry-year summer water availability for the Catoctin and upper Monocacy sub-basins appear in part to be the result of these aquifers' poor ability to store recharge, as indicated by their unusually low recession indices. It should be noted that these two sub-basins have both experienced significant water supply problems during times of drought. During the drought year, 2002, the Town of Middletown in the Catoctin Creek sub-basin experienced significant problems with its system of public supply wells, and reported that streams in the area were dry or very low (private communication, Drew Bowen, Water and Sewer Manager, Town of Middletown). Records for the gage at Bridgeport, Md, which measures stream flow from the upper Monocacy basin, indicate that flow fell to zero for several summer days during the drought of 1966.

Provided that seasonal water budget components can be reliably computed, they should give more accurate predictions of summer water availability than analyses based on annual averages, since seasonal analyses include the effects of seasonality and aquifer storage. The approach to computing seasonal water budget components developed in this study, based on a baseflow recession analysis and beginning-of-quarter baseflow estimates, appears to give reasonably reliable results when compared with available well data. In order to extend this approach beyond gaged sub-basins, multiple regression analyses must be conducted to see whether the quantities used in summer availability predictions, that is, recession indices, beginning-of-summer baseflow, and summer recharge, can be estimated for ungaged sub-basins. Results from the regression analyses for baseflow characteristics, carried out for the annual water budget, indicate that hydrogeomorphic regions may be useful predictors of sub-basin flow characteristics.

Estimates of water availability made in this report, in both the annual and the seasonal analyses, were computed from stream flow data collected at USGS stream gage stations. Daily flow values from continuous record gage stations provide the most useful data, allowing the computation of baseflow recession indices and more accurate estimates of annual and seasonal baseflow. However, at this time only a handful of these stations are still in operation in the study area. Continuation of stream gage data collection programs is crucial for developing a better understanding of water availability in the Potomac River basin.

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Appendix A – Computation of Confidence Limits for Baseflow Recurrence Intervals

Confidence intervals express the uncertainty associated with the use of regression equation and are calculated at a percent confidence level for a given regression estimate. The method used in this study and described below is adapted from Flynn (2002) and Ries (2000).

The confidence interval of a streamflow statistic for an ungaged site corrected for bias can be calculated by the following equation (Tasker and Driver, 1988):

$$1/(TQ/BCF) < Q < TQ/BCF$$

where

Q = streamflow statistic for the site
BCF = bias correction factor
T = $10^{(t(\alpha/2,n-p)*Si)}$

and where

$t(\alpha/2,n-p)$ = the critical value from the student's t-distribution at a certain alpha level divided by 2 (e.g. a 90% confidence interval is associated with an $\alpha/2$ of 0.05)
n = number of degrees of freedom
= number of stream-gaging stations used in the regression analysis;
p = 1 + number of basin characteristics in the equation
Si = the standard error of prediction at site i , calculated as the square root of the sum of the average model error variance and the sampling error variance at site i (Flynn, 2002): (average model error variance+$X_iUX_i^T$)^$^{0.5}$

where

average model error variance is given as output by GSLnet
X_i is a row vector for the study site i containing a 1 and the logarithm base 10 of the basin characteristics used in the regression
U is the covariance matrix for the seasonal and annual regression coefficients (given as an output of GLSnet) and
X_i^T is the matrix algebra transpose of X_i

$X_iUX_i^T$ represents the sampling error at site i, and represents the error due to estimating the true model parameters from a sample of data (Feaster and Guimaraes, 2004). Model error variance is the error due to an imperfect model (Tasker and Stedinger, 1989) and is a function of time sampling error and cross correlations at the gaging stations. For more information regarding the calculation of U and the model error variance, see Stedinger and Tasker (1989).

Example
Provided below is an example of baseflow recurrence interval estimation and confidence interval calculation for the 2-year recurrence interval for gage 01643000. The method is adapted from

Flynn, 2002 and Ries, 2000. The same calculations would apply to estimating baseflow recurrence intervals and confidence intervals at an ungaged site.

Bias correction factor:

The bias correction factor (BCF) for the model is given by

$$BCF = \exp^{(0.5(S*S)*5.302)}$$

Where

$$S^2 = \text{average model error variance + average sampling error variance}$$

Using Table 6 for the average model error variance and average sampling variance:

$$S^2 = 0.0073 + 0.0019 = 0.0092$$

Therefore, the model bias correction factor is

$$BCF = \exp^{(0.5(0.0092)*5.302)} = 1.02$$

Baseflow recurrence interval:

The bias-corrected regression equation for the 2-year recurrence interval, from equation (6) and values of the regression coefficients from GLSnet, given in Table 5, is:

$$= 1.02*10^{-0.20177}*DA^{0.99318}*(ML*0.01+1)^{-0.68803}\ (BR*0.01+1)^{0.52134}\ (PCA*0.01+1)^{0.68408}$$

where:

DA = drainage area
ML = % of basin that is Mesozoic Lowland HGMR
BR = % of basin that is Blue Ridge HGMR
PCA = % of basin that is Piedmont Carbonate HGMR

For station 01643000, the values of the explanatory variables are given by (from Table 3):

DA (drainage area) = 817 square miles
ML = 43.1%
BR = 18.3%
PCA = 8.0%

Therefore, the estimated 2-year recurrence interval at 1643000 is:

$$= 1.02*10^{-0.20177}*(817)^{0.99318}*(43.1*0.01+1)^{-0.68803}\ (18.3*0.01+1)^{0.52134}\ (8.8*0.01+1)^{0.68408}$$

= 451 cfs

Confidence limits:

The confidence limits for the 2-year baseflow recurrence interval for site 01643000 is calculated as follows:

Lower and upper confidence limits are 1/(TQ/BCF) and TQ/BCF, where $T = 10^{(t(\alpha/2,n-p)*Si)}$, and $S_i = [\text{model error variance} + X_i U X_i^T]^{0.5}$, with

- model error variance for site 01643000 is given in Table 6 as 0.0073,
- row vector, X_i is given by (1.0, log (817), log (43.1*0.01+1), log (18.3*0.01+1), log (8.0*0.01+1)),
- X_i^T is the algebraic matrix transpose of X_i ,
- the U matrix is given in the GLSnet 2yr recurrence interval output (see Table 7).

Therefore, the value of the matrix product, X_iUX_i , can be computed:

X_iUX_i = 0.0030 (note this value for site 01643000 can also be obtained from the GLSnet model output)

Then,

$$S_i = [0.0073+ 0.0030]^{0.5} = 0.101387$$

Also, the t-statistic for the 90-percent confidence interval, n = 35, and p = 4, is

t(alpha/2, n-p) = 1.7

These results can be substituted into the expression giving the quantity, T:

$$T = 10^{[1.7*0.101387)} = 1.49$$

Finally, the confidence limits can be computed:

Lower confidence limit:

1/T(Q/BCF) =1/1.49*440/1.02 = 289 cfs

Upper confidence limit:

T(Q/BCF) =1*1.49*440/1.02 = 640 cfs

Therefore, there is a 90% probability that the true value of the 2-year recurrence interval at site 01643000 is between 289 and 640 cfs.

Appendix B – Seasonal Water Budget Time Series for Four Monocacy/Catoctin Sub-basins (units = inches/quarter)

Subbasin	Year	Quarter	Precip	qSF	qBF	ET	Rnet	DS	S	W
1637500	1959	4	10.24	0.41	0.99	8.27	1.56	0.55	0.07	0.02
1637500	1960	1	8.46	1.21	3.61	3.10	4.16	0.53	0.62	0.02
1637500	1960	2	13.40	2.31	4.48	7.19	3.90	-0.60	1.15	0.02
1637500	1960	3	10.55	0.24	0.74	10.02	0.29	-0.47	0.55	0.02
1637500	1960	4	5.24	0.06	0.31	4.82	0.36	0.03	0.08	0.02
1637500	1961	1	11.45	1.56	3.64	4.49	5.40	1.74	0.11	0.02
1637500	1961	2	12.88	1.65	4.83	7.97	3.26	-1.59	1.85	0.02
1637500	1961	3	8.82	0.15	0.39	8.46	0.21	-0.20	0.26	0.02
1637500	1961	4	8.46	0.29	0.56	7.30	0.87	0.29	0.06	0.02
1637500	1962	1	9.50	2.49	4.98	0.36	6.65	1.65	0.34	0.02
1637500	1962	2	10.01	0.53	3.00	8.35	1.13	-1.89	2.00	0.02
1637500	1962	3	5.68	0.07	0.15	5.51	0.10	-0.07	0.11	0.02
1637500	1962	4	9.33	0.29	0.61	8.12	0.92	0.29	0.03	0.02
1637500	1963	1	8.08	2.37	3.37	1.71	4.00	0.61	0.32	0.02
1637500	1963	2	8.88	0.52	1.61	7.45	0.91	-0.72	0.93	0.02
1637500	1963	3	8.35	0.15	0.24	8.13	0.07	-0.19	0.21	0.02
1637500	1963	4	8.94	0.31	0.49	7.63	1.00	0.49	0.02	0.02
1637500	1964	1	10.12	2.24	5.62	0.88	6.99	1.35	0.51	0.02
1637500	1964	2	6.59	0.93	4.03	3.35	2.31	-1.74	1.86	0.02
1637500	1964	3	9.95	0.34	0.20	9.47	0.13	-0.09	0.11	0.02
1637500	1964	4	7.36	0.24	0.34	6.57	0.55	0.19	0.03	0.02
1637500	1965	1	10.84	1.95	3.64	4.21	4.68	1.02	0.21	0.02
1637500	1965	2	6.33	0.25	2.11	5.08	1.00	-1.13	1.23	0.02
1637500	1965	3	8.98	0.04	0.11	8.88	0.06	-0.07	0.10	0.02
1637500	1965	4	4.93	0.06	0.17	4.66	0.21	0.02	0.02	0.02
1637500	1966	1	8.88	1.02	1.55	5.75	2.11	0.54	0.05	0.02
1637500	1966	2	8.71	0.58	2.16	6.46	1.67	-0.51	0.58	0.02
1637500	1966	3	15.07	1.08	0.37	13.64	0.35	-0.04	0.08	0.02
1637500	1966	4	6.70	0.38	1.72	3.73	2.59	0.85	0.04	0.02
1637500	1967	1	7.76	1.47	5.10	0.88	5.41	0.29	0.89	0.02
1637500	1967	2	6.79	0.40	2.39	4.98	1.41	-1.00	1.17	0.02
1637500	1967	3	12.15	0.59	0.64	10.90	0.66	0.00	0.17	0.02
1637500	1967	4	8.47	1.01	2.47	4.06	3.40	0.91	0.17	0.02
1637500	1968	1	5.14	1.76	4.72	-1.19	4.56	-0.18	1.08	0.02
1637500	1968	2	12.12	0.87	2.79	8.95	2.30	-0.51	0.90	0.02
1637500	1968	3	7.05	0.26	0.49	6.61	0.18	-0.33	0.39	0.02
1637500	1968	4	9.41	0.45	1.16	7.54	1.42	0.24	0.07	0.02
1637500	1969	1	4.88	0.34	1.55	2.72	1.81	0.24	0.31	0.02
1637500	1969	2	6.54	0.30	1.41	5.25	0.98	-0.45	0.55	0.02
1637500	1969	3	13.70	0.73	0.65	12.21	0.75	0.08	0.10	0.02
1637500	1969	4	11.53	0.56	1.35	9.21	1.76	0.39	0.19	0.02
1637500	1970	1	7.44	1.99	4.65	-0.45	5.90	1.23	0.57	0.02

Subbasin	Year	Quarter	Precip	qSF	qBF	ET	Rnet	DS	S	W
1637500	1970	2	13.48	1.55	4.63	8.57	3.36	-1.29	1.80	0.02
1637500	1970	3	12.99	0.99	1.22	11.17	0.82	-0.42	0.51	0.02
1637500	1970	4	10.76	1.00	2.05	6.86	2.91	0.84	0.09	0.02
1637500	1971	1	9.54	2.26	6.15	0.88	6.40	0.23	0.93	0.02
1637500	1971	2	9.40	0.91	3.24	6.09	2.40	-0.86	1.16	0.02
1637500	1971	3	15.62	0.37	0.58	14.72	0.53	-0.07	0.30	0.02
1637500	1971	4	10.94	1.79	3.62	4.59	4.56	0.92	0.23	0.02
1637500	1972	1	9.70	2.50	6.71	-0.51	7.71	0.98	1.15	0.02
1637500	1972	2	24.67	7.01	7.63	11.11	6.55	-1.10	2.13	0.02
1637500	1972	3	5.09	0.27	1.79	3.96	0.87	-0.94	1.03	0.02
1637500	1972	4	17.26	2.29	3.15	10.39	4.59	1.42	0.09	0.02
1637500	1973	1	9.73	1.45	5.48	2.70	5.58	0.08	1.51	0.02
1637500	1973	2	16.73	1.79	5.74	10.28	4.66	-1.10	1.58	0.02
1637500	1973	3	10.65	0.27	0.65	10.08	0.30	-0.37	0.48	0.02
1637500	1973	4	10.59	1.41	1.45	6.78	2.40	0.93	0.11	0.02
1637500	1974	1	9.55	1.14	3.84	4.60	3.81	-0.05	1.05	0.02
1637500	1974	2	12.33	1.05	3.96	8.05	3.23	-0.75	1.00	0.02
1637500	1974	3	10.05	0.32	0.54	9.27	0.47	-0.09	0.25	0.02
1637500	1974	4	9.53	1.33	1.71	5.64	2.57	0.84	0.15	0.02
1637500	1975	1	12.63	1.88	6.04	4.18	6.57	0.51	0.99	0.02
1637500	1975	2	16.04	1.70	4.91	10.16	4.18	-0.75	1.50	0.02
1637500	1975	3	20.26	4.44	1.67	14.14	1.68	-0.01	0.75	0.02
1637500	1975	4	10.07	1.26	4.60	3.76	5.04	0.42	0.75	0.02
1637500	1976	1	9.21	1.69	5.15	2.51	5.01	-0.16	1.17	0.02
1637500	1976	2	12.04	0.63	2.40	9.75	1.66	-0.76	1.01	0.02
1637500	1976	3	12.89	0.32	0.67	11.69	0.88	0.19	0.24	0.02
1637500	1976	4	14.02	4.98	4.43	4.51	4.54	0.09	0.43	0.02
1637500	1977	1	6.97	1.21	3.44	1.18	4.58	1.12	0.52	0.02
1637500	1977	2	8.56	2.01	2.87	5.10	1.45	-1.44	1.64	0.02
1637500	1977	3	8.64	0.13	0.47	8.14	0.37	-0.12	0.20	0.02
1637500	1977	4	15.31	1.88	3.57	8.43	5.00	1.41	0.07	0.02
1637500	1978	1	10.37	3.50	5.29	1.86	5.01	-0.30	1.49	0.02
1637500	1978	2	13.66	1.98	4.32	8.06	3.62	-0.72	1.19	0.02
1637500	1978	3	9.44	0.45	0.91	8.45	0.55	-0.38	0.46	0.02
1637500	1978	4	9.65	0.47	0.72	7.78	1.39	0.65	0.08	0.02
1637500	1979	1	14.84	5.19	6.91	1.62	8.03	1.10	0.73	0.02
1637500	1979	2	10.55	0.53	3.72	7.78	2.23	-1.51	1.83	0.02
1637500	1979	3	21.11	2.05	1.30	17.08	1.99	0.67	0.33	0.02
1637500	1979	4	10.68	2.44	4.80	3.51	4.72	-0.10	0.99	0.02
1637500	1980	1	9.32	1.34	4.00	3.42	4.56	0.53	0.90	0.03
1637500	1980	2	13.56	1.14	4.70	8.79	3.63	-1.11	1.43	0.03
1637500	1980	3	6.83	0.13	0.45	6.48	0.22	-0.27	0.32	0.04
1637500	1980	4	7.13	0.22	0.41	6.42	0.49	0.05	0.05	0.03
1637500	1981	1	9.10	0.96	1.63	5.73	2.41	0.74	0.10	0.04
1637500	1981	2	14.08	1.08	2.95	10.43	2.57	-0.42	0.84	0.04
1637500	1981	3	10.74	0.28	0.71	10.04	0.41	-0.32	0.41	0.02

Subbasin	Year	Quarter	Precip	qSF	qBF	ET	Rnet	DS	S	W
1637500	1981	4	7.35	0.26	0.68	6.20	0.89	0.18	0.09	0.03
1637500	1982	1	9.78	1.47	4.18	2.92	5.39	1.19	0.27	0.02
1637500	1982	2	14.09	1.11	3.47	10.49	2.49	-1.00	1.46	0.02
1637500	1982	3	8.23	0.37	0.68	7.55	0.31	-0.39	0.47	0.02
1637500	1982	4	7.18	0.19	0.65	6.11	0.88	0.21	0.07	0.02
1637500	1983	1	9.61	0.96	3.66	2.93	5.72	2.04	0.29	0.02
1637500	1983	2	18.00	2.48	6.75	10.69	4.83	-1.94	2.32	0.02
1637500	1983	3	6.02	0.10	0.43	5.81	0.11	-0.33	0.38	0.01
1637500	1983	4	16.78	2.02	2.27	11.63	3.13	0.85	0.05	0.01
1637500	1984	1	14.82	3.61	6.91	2.65	8.56	1.62	0.90	0.03
1637500	1984	2	12.64	1.14	6.88	6.71	4.79	-2.13	2.51	0.04
1637500	1984	3	15.48	0.90	1.25	13.50	1.08	-0.20	0.39	0.03
1637500	1984	4	8.68	0.59	1.46	6.20	1.89	0.40	0.18	0.03
1637500	1985	1	7.88	1.45	2.87	3.35	3.07	0.17	0.58	0.03
1637500	1985	2	7.98	0.42	2.00	6.02	1.55	-0.49	0.75	0.03
1637500	1985	3	10.34	0.63	0.77	9.04	0.67	-0.13	0.27	0.03
1637500	1985	4	12.86	1.47	3.49	7.31	4.08	0.56	0.14	0.03
1637500	1986	1	7.95	1.35	4.89	1.03	5.58	0.66	0.70	0.03
1637500	1986	2	7.73	0.47	2.44	6.03	1.23	-1.24	1.36	0.03
1637500	1986	3	5.43	0.09	0.15	5.26	0.09	-0.10	0.12	0.03
1637500	1986	4	13.27	0.61	0.86	11.22	1.44	0.55	0.02	0.03
1637500	1987	1	9.28	0.65	3.02	4.85	3.78	0.74	0.57	0.02
1637500	1987	2	10.63	1.30	4.00	6.44	2.89	-1.14	1.31	0.02
1637500	1987	3	11.62	0.30	0.28	11.11	0.21	-0.11	0.17	0.04
1637500	1987	4	9.02	0.49	0.86	7.26	1.27	0.37	0.06	0.04
1637500	1988	1	6.20	0.79	2.49	2.67	2.74	0.21	0.43	0.04
1637500	1988	2	14.20	4.00	4.45	6.07	4.12	-0.36	0.65	0.04
1637500	1988	3	10.96	0.24	0.36	10.54	0.18	-0.22	0.28	0.04
1637500	1988	4	6.51	0.24	0.54	5.47	0.80	0.23	0.07	0.03
1637500	1989	1	9.13	0.79	3.14	4.43	3.91	0.74	0.29	0.04
1637500	1989	2	16.82	2.82	5.29	9.05	4.96	-0.37	1.03	0.04
1637500	1989	3	7.31	0.22	1.16	6.43	0.66	-0.54	0.66	0.04
1637500	1989	4	8.21	0.34	0.73	6.89	0.98	0.21	0.12	0.04
1637500	1990	1	8.23	0.81	3.22	3.55	3.87	0.62	0.33	0.04
1637500	1990	2	11.23	1.07	3.82	6.90	3.25	-0.60	0.95	0.04
1637500	1990	3	12.49	0.36	0.57	11.72	0.40	-0.20	0.34	0.04
1637500	1990	4	13.97	1.45	2.46	8.73	3.79	1.29	0.14	0.04
1637500	1991	1	9.95	1.01	5.74	3.37	5.57	-0.21	1.43	0.04
1637500	1991	2	6.52	0.25	2.28	5.09	1.18	-1.14	1.23	0.04
1637500	1991	3	8.54	0.23	0.15	8.15	0.16	-0.03	0.09	0.04
1637500	1991	4	8.45	0.59	0.89	6.51	1.35	0.42	0.06	0.04
1637500	1992	1	8.45	0.82	2.99	3.87	3.76	0.73	0.48	0.04
1637500	1992	2	12.04	1.77	3.42	7.58	2.69	-0.77	1.20	0.04
1637500	1992	3	13.82	1.32	1.49	11.13	1.37	-0.16	0.44	0.05
1637500	1992	4	11.66	3.23	4.52	2.31	6.12	1.56	0.28	0.04
1637500	1993	1	12.37	3.26	6.96	0.76	8.35	1.35	1.83	0.04

Subbasin	Year	Quarter	Precip	qSF	qBF	ET	Rnet	DS	S	W
1637500	1993	2	12.30	1.56	6.19	7.52	3.22	-3.01	3.18	0.04
1637500	1993	3	11.77	0.39	0.39	10.97	0.41	-0.02	0.17	0.05
1637500	1993	4	11.33	2.65	2.58	5.07	3.61	0.99	0.15	0.04
1637500	1994	1	13.46	4.51	8.31	-1.06	10.01	1.65	1.14	0.04
1637500	1994	2	9.24	0.63	3.95	7.20	1.41	-2.59	2.79	0.05
1637500	1994	3	14.41	0.31	0.53	13.61	0.49	-0.09	0.20	0.04
1637500	1994	4	9.19	0.47	1.36	6.63	2.09	0.69	0.11	0.04
1637500	1995	1	6.87	0.72	3.42	2.77	3.37	-0.09	0.80	0.04
1637500	1995	2	11.28	0.34	1.54	9.89	1.05	-0.54	0.71	0.05
1637500	1995	3	5.91	0.12	0.23	5.66	0.14	-0.14	0.17	0.05
1637500	1995	4	13.12	0.65	1.75	9.77	2.70	0.90	0.03	0.04
1637500	1996	1	16.13	4.56	6.38	4.41	7.17	0.74	0.93	0.05
1637500	1996	2	16.78	3.79	5.62	7.77	5.23	-0.44	1.68	0.05
1637500	1996	3	23.59	4.55	5.97	12.71	6.33	0.31	1.23	0.05
1637500	1996	4	13.68	3.16	7.74	2.66	7.87	0.08	1.54	0.05
1637500	1997	1	7.56	0.88	4.85	2.08	4.60	-0.30	1.62	0.05
1637500	1997	2	5.87	0.17	2.15	4.70	0.99	-1.21	1.32	0.05
1637500	1997	3	10.77	0.15	0.15	10.49	0.13	-0.07	0.11	0.05
1637500	1997	4	11.75	0.84	1.19	8.82	2.09	0.85	0.04	0.05
1637500	1998	1	19.92	6.75	10.47	1.32	11.86	1.34	0.88	0.05
1637500	1998	2	16.20	2.41	5.69	10.00	3.79	-1.95	2.22	0.05
1637500	1998	3	7.22	0.12	0.32	6.95	0.14	-0.23	0.27	0.06
1637500	1998	4	3.89	0.05	0.22	3.46	0.39	0.11	0.04	0.06
1637500	1999	1	13.95	0.97	1.95	10.31	2.67	0.66	0.15	0.06
1637500	1999	2	7.50	0.26	1.63	6.29	0.94	-0.75	0.81	0.06
1637500	1999	3	16.42	0.78	0.21	15.20	0.44	0.17	0.06	0.06
1637500	1999	4	7.80	0.56	1.85	5.13	2.11	0.20	0.24	0.06
1637500	2000	1	10.08	1.55	4.02	3.19	5.33	1.25	0.44	0.06
1637500	2000	2	14.73	1.10	3.68	11.09	2.54	-1.20	1.69	0.06
1637500	2000	3	16.20	0.67	1.49	14.16	1.37	-0.18	0.49	0.06
1637500	2000	4	5.97	0.61	1.46	3.71	1.65	0.13	0.31	0.06
1637500	2001	1	12.01	1.02	3.81	6.18	4.81	0.94	0.44	0.06
1637500	2001	2	8.48	0.32	2.75	6.61	1.55	-1.27	1.38	0.07
1637500	2001	3	8.18	0.13	0.17	7.89	0.16	-0.09	0.12	0.08
1637500	2001	4	4.32	0.08	0.21	3.91	0.33	0.06	0.02	0.07
1637500	2002	1	6.80	0.27	0.54	5.77	0.76	0.16	0.08	0.06
1637500	2002	2	9.46	0.31	0.98	8.29	0.86	-0.19	0.24	0.07
1637500	2002	3	11.85	0.26	0.08	11.44	0.15	-0.01	0.05	0.08
1639000	1959	4	10.30	0.80	0.60	8.66	0.84	0.23	0.02	0.01
1639000	1960	1	9.64	3.47	2.29	3.70	2.46	0.16	0.25	0.01
1639000	1960	2	13.50	3.47	1.81	8.52	1.51	-0.31	0.41	0.01
1639000	1960	3	10.40	1.22	0.41	8.81	0.37	-0.05	0.10	0.01
1639000	1960	4	5.59	0.19	0.39	4.91	0.48	0.08	0.05	0.01
1639000	1961	1	12.15	8.02	3.36	0.20	3.94	0.57	0.13	0.01
1639000	1961	2	12.60	3.28	2.15	7.81	1.51	-0.65	0.70	0.01
1639000	1961	3	10.54	0.26	0.15	10.16	0.12	-0.04	0.06	0.01

Subbasin	Year	Quarter	Precip	qSF	qBF	ET	Rnet	DS	S	W
1639000	1961	4	8.92	0.44	0.31	8.05	0.43	0.11	0.02	0.01
1639000	1962	1	10.50	6.83	2.34	0.87	2.80	0.45	0.13	0.01
1639000	1962	2	9.56	1.37	1.38	7.35	0.84	-0.55	0.57	0.01
1639000	1962	3	9.72	0.08	0.08	9.56	0.08	-0.01	0.02	0.01
1639000	1962	4	10.77	1.49	0.81	8.31	0.97	0.15	0.02	0.01
1639000	1963	1	8.77	5.32	3.23	-0.03	3.48	0.24	0.17	0.01
1639000	1963	2	10.04	0.53	0.82	9.02	0.49	-0.34	0.40	0.01
1639000	1963	3	7.61	0.06	0.13	7.46	0.09	-0.05	0.06	0.01
1639000	1963	4	7.98	0.45	0.28	7.11	0.42	0.13	0.01	0.01
1639000	1964	1	11.24	5.65	2.89	2.26	3.33	0.43	0.14	0.01
1639000	1964	2	9.02	2.48	1.82	5.26	1.29	-0.54	0.57	0.01
1639000	1964	3	8.92	0.19	0.08	8.66	0.07	-0.02	0.03	0.01
1639000	1964	4	7.00	0.29	0.25	6.34	0.37	0.11	0.01	0.01
1639000	1965	1	11.93	5.12	2.30	4.22	2.59	0.28	0.12	0.01
1639000	1965	2	5.45	0.14	0.82	4.86	0.45	-0.38	0.40	0.01
1639000	1965	3	8.24	0.10	0.07	8.06	0.08	0.00	0.02	0.01
1639000	1965	4	5.97	0.07	0.19	5.67	0.23	0.03	0.02	0.01
1639000	1966	1	10.11	3.27	1.70	4.89	1.96	0.25	0.04	0.01
1639000	1966	2	6.14	1.10	1.13	4.18	0.85	-0.29	0.29	0.01
1639000	1966	3	14.30	2.47	0.19	11.61	0.23	0.03	0.01	0.01
1639000	1966	4	8.73	1.51	1.03	5.87	1.35	0.31	0.03	0.01
1639000	1967	1	8.46	4.64	2.72	1.04	2.78	0.05	0.34	0.01
1639000	1967	2	9.67	0.95	1.52	7.51	1.21	-0.32	0.40	0.01
1639000	1967	3	14.47	1.12	0.42	12.95	0.40	-0.03	0.08	0.01
1639000	1967	4	11.85	2.27	1.33	7.90	1.68	0.34	0.04	0.01
1639000	1968	1	7.10	3.24	2.36	1.61	2.25	-0.12	0.39	0.01
1639000	1968	2	13.69	2.78	1.26	9.79	1.12	-0.15	0.26	0.01
1639000	1968	3	10.33	0.47	0.24	9.69	0.17	-0.08	0.11	0.01
1639000	1968	4	9.37	1.36	0.77	7.14	0.87	0.09	0.03	0.01
1639000	1969	1	4.55	1.26	1.21	1.92	1.37	0.15	0.12	0.01
1639000	1969	2	8.76	0.46	0.82	7.70	0.61	-0.22	0.27	0.01
1639000	1969	3	12.70	1.13	0.28	11.28	0.29	0.00	0.05	0.01
1639000	1969	4	11.92	2.00	1.01	8.68	1.25	0.23	0.05	0.01
1639000	1970	1	8.50	5.56	3.05	-0.52	3.46	0.40	0.28	0.01
1639000	1970	2	15.11	4.61	2.22	8.82	1.68	-0.55	0.68	0.01
1639000	1970	3	14.88	2.49	0.57	11.92	0.47	-0.11	0.13	0.01
1639000	1970	4	13.25	3.32	1.68	7.92	2.01	0.32	0.03	0.01
1639000	1971	1	10.82	5.61	4.22	0.96	4.26	0.03	0.35	0.01
1639000	1971	2	12.14	1.12	1.32	9.99	1.03	-0.30	0.37	0.01
1639000	1971	3	12.35	0.47	0.30	11.57	0.32	0.01	0.08	0.01
1639000	1971	4	10.71	4.81	2.16	3.38	2.52	0.35	0.08	0.01
1639000	1972	1	11.08	5.64	3.17	2.14	3.31	0.13	0.43	0.01
1639000	1972	2	27.39	9.67	2.59	15.43	2.29	-0.31	0.56	0.01
1639000	1972	3	8.59	0.40	0.83	7.56	0.63	-0.21	0.25	0.01
1639000	1972	4	17.20	3.91	2.29	10.43	2.87	0.57	0.03	0.01
1639000	1973	1	9.59	3.60	3.22	2.76	3.23	0.00	0.60	0.01

Subbasin	Year	Quarter	Precip	qSF	qBF	ET	Rnet	DS	S	W
1639000	1973	2	18.08	4.02	2.76	11.75	2.31	-0.46	0.60	0.01
1639000	1973	3	13.33	0.91	0.41	12.07	0.35	-0.07	0.14	0.01
1639000	1973	4	11.10	2.89	1.63	6.04	2.17	0.53	0.07	0.01
1639000	1974	1	9.30	2.73	2.85	3.89	2.68	-0.18	0.60	0.01
1639000	1974	2	12.94	1.64	1.91	9.75	1.55	-0.37	0.42	0.01
1639000	1974	3	9.78	0.16	0.19	9.44	0.18	-0.02	0.05	0.01
1639000	1974	4	8.33	1.22	0.82	5.92	1.19	0.36	0.03	0.01
1639000	1975	1	12.69	4.11	3.92	4.60	3.98	0.05	0.39	0.01
1639000	1975	2	15.53	3.64	2.45	9.60	2.29	-0.17	0.44	0.01
1639000	1975	3	19.25	6.87	0.94	11.46	0.93	-0.02	0.27	0.01
1639000	1975	4	10.41	3.74	2.63	3.93	2.75	0.11	0.25	0.01
1639000	1976	1	8.68	3.72	2.70	2.24	2.72	0.01	0.35	0.01
1639000	1976	2	10.91	1.51	1.21	8.44	0.97	-0.25	0.36	0.01
1639000	1976	3	12.52	0.31	0.31	11.88	0.33	0.01	0.11	0.01
1639000	1976	4	14.49	5.58	2.13	6.75	2.15	0.01	0.12	0.01
1639000	1977	1	8.15	3.29	1.65	2.84	2.02	0.36	0.13	0.01
1639000	1977	2	8.96	2.08	1.26	6.07	0.81	-0.46	0.50	0.01
1639000	1977	3	11.79	0.13	0.14	11.51	0.15	0.00	0.03	0.01
1639000	1977	4	14.84	4.33	2.19	7.81	2.70	0.50	0.03	0.01
1639000	1978	1	12.97	6.35	3.86	2.83	3.79	-0.08	0.53	0.01
1639000	1978	2	10.61	2.00	1.45	7.49	1.12	-0.34	0.45	0.01
1639000	1978	3	10.38	0.75	0.43	9.27	0.36	-0.08	0.11	0.01
1639000	1978	4	9.42	1.12	0.62	7.33	0.96	0.33	0.03	0.01
1639000	1979	1	16.05	8.05	4.74	2.98	5.02	0.27	0.37	0.01
1639000	1979	2	9.99	1.55	1.93	7.03	1.41	-0.53	0.64	0.01
1639000	1979	3	19.05	4.64	1.03	13.10	1.31	0.27	0.11	0.01
1639000	1979	4	9.35	2.91	2.73	3.75	2.70	-0.04	0.38	0.01
1639000	1980	1	9.19	2.95	1.90	4.19	2.06	0.14	0.34	0.02
1639000	1980	2	12.97	2.76	2.35	8.25	1.96	-0.41	0.48	0.02
1639000	1980	3	4.96	0.06	0.18	4.75	0.15	-0.05	0.07	0.02
1639000	1980	4	7.56	0.42	0.34	6.75	0.39	0.04	0.01	0.02
1639000	1981	1	8.56	3.40	1.53	3.35	1.81	0.26	0.05	0.02
1639000	1981	2	11.68	1.59	1.21	9.10	0.99	-0.24	0.31	0.02
1639000	1981	3	10.55	0.24	0.22	10.11	0.19	-0.04	0.07	0.01
1639000	1981	4	6.80	0.46	0.57	5.63	0.71	0.12	0.03	0.02
1639000	1982	1	8.93	4.92	2.69	0.89	3.12	0.41	0.15	0.01
1639000	1982	2	12.80	2.73	2.09	8.38	1.69	-0.41	0.56	0.01
1639000	1982	3	6.92	0.10	0.28	6.65	0.17	-0.12	0.15	0.01
1639000	1982	4	6.81	0.46	0.66	5.49	0.85	0.18	0.03	0.01
1639000	1983	1	11.10	4.46	2.79	3.29	3.35	0.54	0.21	0.01
1639000	1983	2	19.91	6.52	3.02	11.01	2.37	-0.66	0.75	0.01
1639000	1983	3	5.15	0.05	0.18	4.98	0.11	-0.08	0.09	0.01
1639000	1983	4	16.09	4.81	1.72	9.20	2.08	0.35	0.02	0.01
1639000	1984	1	12.81	8.01	3.75	0.61	4.19	0.42	0.36	0.02
1639000	1984	2	14.43	4.07	2.89	8.09	2.27	-0.64	0.79	0.02
1639000	1984	3	14.05	2.78	0.92	10.41	0.86	-0.08	0.15	0.02

Subbasin	Year	Quarter	Precip	qSF	qBF	ET	Rnet	DS	S	W
1639000	1984	4	8.51	1.28	1.33	5.68	1.54	0.19	0.07	0.02
1639000	1985	1	7.71	2.73	1.70	3.24	1.74	0.03	0.26	0.02
1639000	1985	2	9.22	0.88	1.18	7.38	0.96	-0.24	0.29	0.02
1639000	1985	3	12.16	0.87	0.29	11.00	0.29	-0.01	0.05	0.02
1639000	1985	4	11.96	3.06	2.05	6.64	2.26	0.20	0.04	0.02
1639000	1986	1	8.06	3.67	2.94	1.28	3.11	0.16	0.24	0.02
1639000	1986	2	9.52	0.98	1.02	7.86	0.68	-0.36	0.39	0.02
1639000	1986	3	9.84	0.17	0.13	9.53	0.13	-0.01	0.03	0.02
1639000	1986	4	13.85	3.34	1.34	8.66	1.86	0.50	0.02	0.02
1639000	1987	1	6.28	2.37	2.77	1.23	2.68	-0.11	0.52	0.01
1639000	1987	2	10.62	1.81	1.73	7.39	1.42	-0.33	0.41	0.02
1639000	1987	3	12.64	1.44	0.32	10.87	0.33	-0.01	0.08	0.02
1639000	1987	4	9.19	2.97	1.61	4.30	1.92	0.29	0.07	0.02
1639000	1988	1	6.24	2.66	2.31	1.36	2.22	-0.11	0.36	0.02
1639000	1988	2	9.79	3.06	1.54	5.37	1.36	-0.20	0.25	0.02
1639000	1988	3	8.91	0.15	0.12	8.65	0.12	-0.02	0.04	0.02
1639000	1988	4	6.23	0.25	0.37	5.49	0.49	0.10	0.02	0.02
1639000	1989	1	9.04	2.39	2.03	4.35	2.31	0.26	0.12	0.02
1639000	1989	2	18.88	7.04	2.79	9.18	2.66	-0.15	0.38	0.02
1639000	1989	3	9.06	0.88	0.73	7.60	0.58	-0.17	0.23	0.02
1639000	1989	4	8.54	1.12	0.88	6.37	1.06	0.16	0.06	0.02
1639000	1990	1	7.61	2.72	2.55	2.26	2.63	0.06	0.22	0.02
1639000	1990	2	10.77	2.24	1.52	7.17	1.36	-0.18	0.28	0.02
1639000	1990	3	12.58	0.96	0.41	11.19	0.43	0.00	0.09	0.02
1639000	1990	4	15.21	5.52	2.17	6.93	2.77	0.58	0.09	0.02
1639000	1991	1	8.54	3.25	3.65	1.85	3.44	-0.23	0.67	0.02
1639000	1991	2	5.03	0.39	1.18	3.85	0.79	-0.42	0.44	0.02
1639000	1991	3	13.56	0.50	0.11	12.92	0.14	0.01	0.02	0.02
1639000	1991	4	8.84	1.52	0.78	6.32	1.00	0.20	0.03	0.02
1639000	1992	1	9.07	3.45	2.26	3.09	2.53	0.25	0.23	0.02
1639000	1992	2	10.47	1.50	1.64	7.68	1.29	-0.37	0.48	0.02
1639000	1992	3	13.16	0.85	0.38	11.95	0.36	-0.05	0.11	0.02
1639000	1992	4	11.77	4.51	2.09	4.68	2.58	0.47	0.06	0.02
1639000	1993	1	15.40	6.28	5.20	3.19	5.92	0.70	0.53	0.02
1639000	1993	2	11.87	3.73	2.70	6.59	1.55	-1.18	1.23	0.02
1639000	1993	3	15.53	0.93	0.34	14.18	0.43	0.06	0.05	0.03
1639000	1993	4	11.69	5.32	1.92	4.21	2.16	0.21	0.11	0.02
1639000	1994	1	14.84	10.23	5.70	-1.82	6.43	0.71	0.32	0.02
1639000	1994	2	10.34	1.02	1.82	8.45	0.87	-0.97	1.03	0.02
1639000	1994	3	12.45	0.55	0.40	11.48	0.42	0.00	0.06	0.03
1639000	1994	4	8.75	2.43	1.44	4.46	1.86	0.40	0.06	0.02
1639000	1995	1	7.52	3.52	2.52	1.68	2.33	-0.22	0.45	0.02
1639000	1995	2	13.68	1.23	0.82	11.72	0.73	-0.12	0.24	0.03
1639000	1995	3	8.86	0.74	0.53	7.64	0.48	-0.08	0.12	0.03
1639000	1995	4	10.56	2.61	1.50	6.04	1.91	0.38	0.03	0.03
1639000	1996	1	13.26	9.42	4.43	-0.80	4.64	0.18	0.42	0.03

Subbasin	Year	Quarter	Precip	qSF	qBF	ET	Rnet	DS	S	W
1639000	1996	2	21.56	7.82	2.73	11.27	2.47	-0.29	0.59	0.03
1639000	1996	3	18.74	4.85	1.82	12.00	1.89	0.04	0.30	0.03
1639000	1996	4	14.00	6.48	3.71	3.60	3.92	0.18	0.35	0.03
1639000	1997	1	7.60	2.66	2.93	2.11	2.83	-0.13	0.52	0.03
1639000	1997	2	6.57	0.30	1.00	5.59	0.69	-0.35	0.39	0.03
1639000	1997	3	10.74	0.27	0.12	10.33	0.14	-0.02	0.04	0.04
1639000	1997	4	10.75	1.68	1.04	7.61	1.47	0.40	0.02	0.03
1639000	1998	1	18.10	10.09	5.38	2.38	5.63	0.22	0.42	0.03
1639000	1998	2	15.55	3.47	2.02	10.59	1.49	-0.56	0.64	0.04
1639000	1998	3	7.48	0.19	0.19	7.12	0.18	-0.06	0.07	0.04
1639000	1998	4	3.71	0.08	0.18	3.35	0.28	0.06	0.01	0.04
1639000	1999	1	11.73	3.11	1.95	6.28	2.35	0.36	0.08	0.04
1639000	1999	2	8.38	1.11	1.23	6.41	0.86	-0.42	0.44	0.05
1639000	1999	3	16.25	1.30	0.18	14.63	0.31	0.09	0.02	0.04
1639000	1999	4	7.34	1.71	1.22	4.30	1.33	0.08	0.11	0.04
1639000	2000	1	9.64	3.61	3.13	2.48	3.55	0.38	0.18	0.04
1639000	2000	2	13.75	1.90	1.87	10.36	1.49	-0.42	0.56	0.04
1639000	2000	3	11.38	1.19	0.57	9.64	0.55	-0.06	0.14	0.04
1639000	2000	4	6.23	1.87	0.79	3.42	0.94	0.11	0.08	0.04
1639000	2001	1	8.82	2.99	2.42	3.06	2.78	0.32	0.19	0.04
1639000	2001	2	7.23	0.64	1.33	5.69	0.90	-0.48	0.51	0.05
1639000	2001	3	6.74	0.11	0.07	6.53	0.10	-0.02	0.03	0.05
1639000	2001	4	4.73	0.10	0.18	4.36	0.26	0.04	0.01	0.04
1639000	2002	1	7.45	1.15	0.65	5.52	0.78	0.12	0.05	0.04
1639000	2002	2	11.39	0.85	0.86	9.81	0.73	-0.14	0.17	0.05
1639000	2002	3	11.67	0.34	0.09	11.21	0.12	0.02	0.03	0.05
1639500	1959	4	11.24	0.55	1.27	8.86	1.83	0.55	0.26	0.01
1639500	1960	1	8.81	0.89	3.11	4.18	3.74	0.62	0.81	0.01
1639500	1960	2	12.64	1.19	2.75	9.53	1.92	-0.84	1.43	0.01
1639500	1960	3	13.81	0.84	1.34	11.82	1.15	-0.20	0.59	0.01
1639500	1960	4	5.37	0.11	0.98	4.17	1.09	0.10	0.39	0.01
1639500	1961	1	11.23	2.49	4.09	3.23	5.52	1.42	0.50	0.01
1639500	1961	2	12.51	1.32	3.52	8.94	2.25	-1.28	1.91	0.01
1639500	1961	3	7.83	0.34	1.10	6.70	0.79	-0.32	0.63	0.01
1639500	1961	4	8.01	0.36	1.08	6.28	1.38	0.29	0.31	0.01
1639500	1962	1	10.53	3.37	3.41	2.49	4.67	1.25	0.60	0.01
1639500	1962	2	10.96	0.73	2.54	9.13	1.11	-1.44	1.85	0.01
1639500	1962	3	7.06	0.16	0.73	6.31	0.59	-0.15	0.40	0.01
1639500	1962	4	11.43	0.66	1.29	9.12	1.65	0.35	0.25	0.01
1639500	1963	1	8.83	3.58	2.86	1.78	3.47	0.60	0.60	0.01
1639500	1963	2	8.24	0.30	1.55	7.29	0.65	-0.91	1.20	0.01
1639500	1963	3	7.67	0.12	0.38	7.32	0.23	-0.16	0.29	0.01
1639500	1963	4	9.07	0.36	0.82	7.39	1.32	0.49	0.13	0.01
1639500	1964	1	11.58	2.85	3.41	4.15	4.58	1.16	0.62	0.01
1639500	1964	2	7.34	0.71	2.90	5.14	1.48	-1.43	1.78	0.01
1639500	1964	3	7.16	0.23	0.57	6.52	0.41	-0.17	0.35	0.01

Subbasin	Year	Quarter	Precip	qSF	qBF	ET	Rnet	DS	S	W
1639500	1964	4	7.28	0.28	0.76	5.94	1.06	0.29	0.19	0.01
1639500	1965	1	10.67	1.66	2.39	6.20	2.82	0.42	0.48	0.01
1639500	1965	2	5.99	0.13	1.26	5.27	0.59	-0.68	0.90	0.01
1639500	1965	3	8.40	0.19	0.45	7.81	0.40	-0.06	0.22	0.01
1639500	1965	4	5.62	0.11	0.50	4.96	0.55	0.04	0.16	0.01
1639500	1966	1	10.06	1.54	1.67	6.31	2.21	0.53	0.20	0.01
1639500	1966	2	7.84	0.44	1.45	6.52	0.88	-0.58	0.72	0.01
1639500	1966	3	11.65	0.76	0.29	10.54	0.35	0.05	0.14	0.01
1639500	1966	4	8.46	0.41	1.31	6.10	1.94	0.62	0.19	0.01
1639500	1967	1	8.78	1.66	3.03	3.84	3.29	0.25	0.81	0.01
1639500	1967	2	7.03	0.25	1.64	5.84	0.93	-0.72	1.06	0.01
1639500	1967	3	15.62	2.11	1.58	11.77	1.73	0.14	0.34	0.01
1639500	1967	4	10.11	0.87	2.04	6.55	2.69	0.64	0.49	0.01
1639500	1968	1	6.58	1.11	3.09	2.41	3.06	-0.04	1.13	0.01
1639500	1968	2	10.51	0.93	2.11	8.01	1.57	-0.55	1.09	0.01
1639500	1968	3	12.36	0.82	0.92	10.80	0.74	-0.19	0.53	0.01
1639500	1968	4	10.50	0.97	1.76	7.47	2.05	0.28	0.35	0.01
1639500	1969	1	5.37	0.54	1.93	2.71	2.12	0.18	0.63	0.01
1639500	1969	2	8.69	0.32	1.33	7.53	0.84	-0.50	0.81	0.01
1639500	1969	3	15.58	1.68	1.10	12.63	1.27	0.16	0.31	0.01
1639500	1969	4	9.97	0.75	1.44	7.40	1.82	0.37	0.47	0.01
1639500	1970	1	7.78	1.65	3.59	1.67	4.47	0.87	0.84	0.01
1639500	1970	2	12.45	1.61	3.54	8.28	2.55	-1.00	1.71	0.01
1639500	1970	3	10.69	1.15	1.26	8.71	0.83	-0.44	0.71	0.01
1639500	1970	4	11.83	0.91	1.60	8.66	2.26	0.65	0.27	0.01
1639500	1971	1	10.91	2.84	4.03	3.69	4.39	0.35	0.92	0.01
1639500	1971	2	10.11	0.57	2.37	7.90	1.64	-0.74	1.27	0.01
1639500	1971	3	17.08	1.29	1.51	14.04	1.75	0.23	0.53	0.01
1639500	1971	4	9.85	2.04	3.68	3.36	4.44	0.75	0.76	0.01
1639500	1972	1	10.91	1.67	4.72	4.04	5.20	0.47	1.52	0.01
1639500	1972	2	29.36	8.97	4.93	15.46	4.93	-0.01	1.98	0.01
1639500	1972	3	5.58	0.66	3.61	2.75	2.16	-1.46	1.97	0.01
1639500	1972	4	17.42	2.72	3.63	9.37	5.33	1.69	0.51	0.01
1639500	1973	1	9.99	1.74	5.41	2.91	5.34	-0.08	2.20	0.01
1639500	1973	2	17.14	2.32	5.28	10.60	4.22	-1.07	2.12	0.01
1639500	1973	3	9.08	0.31	1.49	7.95	0.82	-0.68	1.06	0.01
1639500	1973	4	9.74	1.67	1.64	5.52	2.55	0.90	0.38	0.01
1639500	1974	1	9.45	1.66	3.50	4.11	3.68	0.17	1.28	0.01
1639500	1974	2	12.76	1.13	3.60	8.82	2.82	-0.79	1.46	0.01
1639500	1974	3	10.72	0.77	1.41	8.63	1.31	-0.11	0.66	0.01
1639500	1974	4	7.90	0.77	1.77	4.78	2.35	0.57	0.56	0.01
1639500	1975	1	11.36	1.68	4.19	5.00	4.68	0.48	1.13	0.01
1639500	1975	2	14.83	1.98	4.26	8.92	3.94	-0.33	1.61	0.01
1639500	1975	3	26.22	7.21	2.80	15.84	3.17	0.36	1.28	0.01
1639500	1975	4	8.50	1.52	4.77	2.18	4.80	0.02	1.63	0.01
1639500	1976	1	9.40	2.45	4.68	2.55	4.40	-0.29	1.65	0.01

Subbasin	Year	Quarter	Precip	qSF	qBF	ET	Rnet	DS	S	W
1639500	1976	2	11.90	0.98	2.60	9.02	1.90	-0.71	1.36	0.01
1639500	1976	3	11.74	0.35	1.19	10.25	1.13	-0.07	0.65	0.01
1639500	1976	4	10.62	1.70	2.53	6.27	2.65	0.11	0.58	0.01
1639500	1977	1	8.52	1.32	2.36	4.08	3.12	0.75	0.69	0.01
1639500	1977	2	11.60	1.23	2.48	8.95	1.42	-1.07	1.44	0.01
1639500	1977	3	7.69	0.18	0.72	6.89	0.61	-0.12	0.37	0.01
1639500	1977	4	15.08	2.05	2.42	9.23	3.80	1.37	0.26	0.01
1639500	1978	1	11.13	4.58	4.64	1.88	4.67	0.02	1.62	0.01
1639500	1978	2	9.07	0.74	3.09	6.15	2.17	-0.93	1.64	0.01
1639500	1978	3	8.42	0.48	1.29	7.02	0.92	-0.38	0.71	0.01
1639500	1978	4	9.93	0.95	1.27	6.89	2.09	0.81	0.33	0.01
1639500	1979	1	16.30	6.12	5.11	4.35	5.83	0.71	1.14	0.01
1639500	1979	2	9.07	0.60	2.93	6.76	1.71	-1.23	1.85	0.01
1639500	1979	3	19.41	1.74	1.59	15.47	2.21	0.61	0.63	0.01
1639500	1979	4	11.88	2.79	3.88	5.41	3.68	-0.21	1.23	0.01
1639500	1980	1	7.40	1.39	2.86	2.70	3.31	0.44	1.02	0.01
1639500	1980	2	14.73	1.62	3.85	9.95	3.16	-0.70	1.46	0.01
1639500	1980	3	6.18	0.11	1.09	5.47	0.59	-0.51	0.76	0.01
1639500	1980	4	6.78	0.38	0.89	5.42	0.98	0.08	0.26	0.01
1639500	1981	1	7.65	1.27	1.75	3.99	2.39	0.63	0.34	0.01
1639500	1981	2	16.46	1.46	2.43	12.84	2.15	-0.29	0.97	0.01
1639500	1981	3	8.04	0.45	1.16	6.77	0.82	-0.35	0.68	0.01
1639500	1981	4	6.02	0.29	1.02	4.46	1.27	0.24	0.33	0.01
1639500	1982	1	8.51	2.08	2.99	2.80	3.62	0.62	0.57	0.01
1639500	1982	2	12.31	1.26	2.60	8.92	2.13	-0.48	1.20	0.01
1639500	1982	3	7.43	0.21	0.93	6.73	0.49	-0.45	0.71	0.01
1639500	1982	4	6.24	0.21	0.96	4.85	1.17	0.20	0.26	0.01
1639500	1983	1	9.77	1.46	2.58	4.32	4.00	1.41	0.46	0.01
1639500	1983	2	16.21	3.23	4.51	9.54	3.43	-1.09	1.87	0.01
1639500	1983	3	5.39	0.13	1.05	4.72	0.54	-0.52	0.78	0.01
1639500	1983	4	16.66	2.70	2.12	10.87	3.09	0.96	0.26	0.01
1639500	1984	1	10.89	3.29	4.89	1.38	6.22	1.32	1.22	0.01
1639500	1984	2	11.33	1.72	5.12	6.10	3.51	-1.62	2.54	0.01
1639500	1984	3	14.42	1.60	2.09	11.07	1.74	-0.36	0.92	0.01
1639500	1984	4	10.14	1.18	2.40	6.01	2.95	0.54	0.56	0.01
1639500	1985	1	7.13	2.19	2.63	2.45	2.49	-0.15	1.10	0.01
1639500	1985	2	8.50	0.48	2.13	6.38	1.64	-0.50	0.95	0.01
1639500	1985	3	11.76	0.51	0.88	10.47	0.78	-0.11	0.45	0.01
1639500	1985	4	9.53	0.97	2.11	5.96	2.60	0.48	0.35	0.01
1639500	1986	1	7.12	1.17	3.20	2.35	3.61	0.40	0.83	0.01
1639500	1986	2	5.97	0.41	1.89	4.63	0.93	-0.97	1.23	0.01
1639500	1986	3	7.26	0.15	0.52	6.65	0.46	-0.07	0.26	0.01
1639500	1986	4	15.09	1.18	1.36	11.64	2.28	0.91	0.19	0.01
1639500	1987	1	7.98	1.13	3.34	3.37	3.49	0.14	1.10	0.01
1639500	1987	2	10.35	0.76	2.62	7.59	2.00	-0.63	1.23	0.01
1639500	1987	3	14.76	0.94	1.17	12.79	1.03	-0.15	0.60	0.01

Subbasin	Year	Quarter	Precip	qSF	qBF	ET	Rnet	DS	S	W
1639500	1987	4	9.35	1.22	1.97	5.56	2.57	0.58	0.45	0.01
1639500	1988	1	7.27	1.36	3.13	2.93	2.99	-0.16	1.03	0.01
1639500	1988	2	10.55	1.25	2.55	7.17	2.14	-0.43	0.88	0.01
1639500	1988	3	11.38	0.31	0.76	10.47	0.60	-0.18	0.45	0.01
1639500	1988	4	7.55	0.29	0.98	5.99	1.27	0.28	0.28	0.01
1639500	1989	1	7.97	1.25	2.58	3.55	3.17	0.58	0.55	0.01
1639500	1989	2	16.44	3.38	4.16	8.74	4.33	0.15	1.13	0.01
1639500	1989	3	8.52	0.54	1.91	6.93	1.05	-0.87	1.29	0.01
1639500	1989	4	8.66	0.66	1.67	5.92	2.09	0.41	0.42	0.01
1639500	1990	1	7.03	1.36	3.36	1.91	3.76	0.39	0.82	0.01
1639500	1990	2	12.70	1.76	3.50	7.81	3.12	-0.39	1.21	0.01
1639500	1990	3	10.82	0.40	1.47	9.22	1.20	-0.28	0.83	0.01
1639500	1990	4	12.27	2.40	2.72	5.91	3.96	1.22	0.55	0.01
1639500	1991	1	7.88	1.63	4.48	2.23	4.02	-0.47	1.77	0.01
1639500	1991	2	5.99	0.20	2.04	4.75	1.04	-1.02	1.30	0.02
1639500	1991	3	11.51	0.48	0.60	10.38	0.65	0.03	0.28	0.02
1639500	1991	4	9.97	0.93	1.49	7.03	2.01	0.50	0.31	0.01
1639500	1992	1	8.29	1.30	2.55	4.05	2.94	0.37	0.82	0.01
1639500	1992	2	8.47	0.42	2.15	6.53	1.52	-0.65	1.19	0.02
1639500	1992	3	12.66	0.75	1.14	10.89	1.02	-0.14	0.54	0.02
1639500	1992	4	11.16	1.83	2.22	6.23	3.10	0.86	0.40	0.02
1639500	1993	1	14.76	3.92	5.38	3.13	7.71	2.31	1.27	0.02
1639500	1993	2	15.52	3.00	5.84	9.38	3.14	-2.72	3.58	0.02
1639500	1993	3	16.11	0.73	1.58	14.04	1.34	-0.26	0.86	0.03
1639500	1993	4	13.86	2.69	2.82	7.38	3.79	0.95	0.59	0.02
1639500	1994	1	14.11	5.60	7.50	-0.61	9.13	1.61	1.54	0.01
1639500	1994	2	9.15	0.52	3.71	7.55	1.08	-2.65	3.15	0.02
1639500	1994	3	12.37	0.68	1.19	10.54	1.14	-0.07	0.51	0.02
1639500	1994	4	7.21	1.03	1.98	3.41	2.77	0.77	0.44	0.02
1639500	1995	1	6.85	1.35	3.16	2.56	2.95	-0.24	1.21	0.02
1639500	1995	2	9.64	0.25	1.57	8.31	1.08	-0.51	0.98	0.03
1639500	1995	3	13.71	0.64	0.92	12.26	0.81	-0.15	0.47	0.03
1639500	1995	4	11.87	1.41	2.26	7.19	3.26	0.97	0.32	0.03
1639500	1996	1	12.87	4.98	4.91	2.36	5.52	0.59	1.29	0.03
1639500	1996	2	15.80	2.13	4.34	9.86	3.81	-0.56	1.88	0.03
1639500	1996	3	18.98	3.38	3.81	11.57	4.04	0.20	1.32	0.03
1639500	1996	4	15.62	4.13	6.11	4.52	6.96	0.83	1.51	0.03
1639500	1997	1	9.52	1.48	4.81	3.76	4.28	-0.56	2.34	0.03
1639500	1997	2	5.63	0.29	2.71	3.95	1.39	-1.34	1.78	0.03
1639500	1997	3	8.31	0.10	0.66	7.72	0.49	-0.21	0.44	0.04
1639500	1997	4	9.36	0.67	1.19	6.78	1.91	0.69	0.22	0.03
1639500	1998	1	16.35	5.10	5.78	3.85	7.40	1.59	0.91	0.03
1639500	1998	2	16.07	2.04	4.96	10.65	3.38	-1.62	2.50	0.04
1639500	1998	3	7.38	0.33	1.39	6.13	0.92	-0.51	0.88	0.04
1639500	1998	4	5.48	0.15	1.02	4.08	1.26	0.20	0.37	0.03
1639500	1999	1	12.05	1.78	2.70	6.94	3.32	0.59	0.57	0.04

Subbasin	Year	Quarter	Precip	qSF	qBF	ET	Rnet	DS	S	W
1639500	1999	2	8.05	0.38	1.73	6.83	0.84	-0.93	1.16	0.04
1639500	1999	3	16.80	0.96	0.59	14.97	0.87	0.24	0.23	0.04
1639500	1999	4	7.75	0.85	1.82	4.86	2.03	0.18	0.48	0.03
1639500	2000	1	10.24	2.01	3.21	3.88	4.35	1.10	0.66	0.04
1639500	2000	2	12.96	1.27	3.36	9.33	2.37	-1.03	1.76	0.04
1639500	2000	3	12.99	0.96	1.78	10.29	1.74	-0.07	0.73	0.04
1639500	2000	4	5.70	0.84	1.80	2.85	2.01	0.17	0.65	0.04
1639500	2001	1	9.74	1.35	3.12	4.64	3.75	0.59	0.82	0.04
1639500	2001	2	8.64	0.68	2.56	6.29	1.67	-0.93	1.42	0.04
1639500	2001	3	7.55	0.13	0.72	6.93	0.49	-0.27	0.48	0.04
1639500	2001	4	4.36	0.09	0.70	3.43	0.84	0.11	0.21	0.04
1639500	2002	1	7.11	0.24	0.91	5.86	1.01	0.06	0.32	0.04
1639500	2002	2	9.14	0.16	0.79	8.42	0.57	-0.26	0.38	0.04
1639500	2002	3	11.22	0.13	0.19	10.78	0.30	0.07	0.11	0.04
1643500	1966	4	6.34	0.47	1.62	3.59	2.27	0.64	0.28	0.01
1643500	1967	1	7.63	1.51	3.57	2.00	4.11	0.53	0.92	0.01
1643500	1967	2	6.60	0.36	1.96	5.26	0.98	-0.99	1.46	0.01
1643500	1967	3	11.39	1.85	1.41	8.00	1.54	0.12	0.46	0.01
1643500	1967	4	7.78	0.89	1.76	4.56	2.32	0.55	0.58	0.01
1643500	1968	1	4.92	1.27	3.21	0.33	3.33	0.11	1.13	0.01
1643500	1968	2	11.56	1.18	2.21	8.68	1.70	-0.52	1.24	0.01
1643500	1968	3	6.57	0.28	0.96	5.73	0.55	-0.42	0.72	0.01
1643500	1968	4	9.30	0.52	1.51	6.90	1.88	0.36	0.30	0.01
1643500	1969	1	4.95	0.44	2.31	1.78	2.72	0.40	0.66	0.01
1643500	1969	2	6.32	0.16	1.43	5.55	0.61	-0.83	1.07	0.01
1643500	1969	3	12.66	0.91	0.81	10.80	0.95	0.13	0.24	0.01
1643500	1969	4	11.01	0.57	1.06	9.02	1.43	0.36	0.37	0.01
1643500	1970	1	7.15	1.16	3.31	1.67	4.32	1.00	0.73	0.01
1643500	1970	2	13.06	1.28	3.37	9.46	2.32	-1.06	1.72	0.01
1643500	1970	3	12.97	0.60	1.06	11.70	0.67	-0.40	0.66	0.01
1643500	1970	4	10.25	0.70	1.41	7.45	2.10	0.68	0.26	0.01
1643500	1971	1	9.45	2.36	3.82	2.76	4.34	0.51	0.94	0.01
1643500	1971	2	9.12	0.99	2.95	5.87	2.25	-0.71	1.45	0.01
1643500	1971	3	16.22	4.58	2.34	8.70	2.94	0.59	0.74	0.01
1643500	1971	4	11.03	1.87	4.53	4.11	5.05	0.51	1.33	0.01
1643500	1972	1	10.00	1.38	5.48	2.29	6.33	0.84	1.84	0.01
1643500	1972	2	24.43	8.13	5.96	10.97	5.32	-0.65	2.68	0.01
1643500	1972	3	4.88	0.19	2.92	3.30	1.39	-1.54	2.03	0.01
1643500	1972	4	16.95	2.12	3.05	10.29	4.54	1.48	0.49	0.01
1643500	1973	1	9.68	1.10	4.74	3.57	5.01	0.26	1.97	0.01
1643500	1973	2	16.47	2.08	4.97	10.63	3.77	-1.21	2.23	0.01
1643500	1973	3	11.03	0.59	1.53	9.41	1.03	-0.51	1.01	0.01
1643500	1973	4	10.40	1.18	1.57	7.05	2.17	0.59	0.50	0.01
1643500	1974	1	8.53	0.80	2.76	4.79	2.94	0.17	1.09	0.01
1643500	1974	2	11.25	1.00	3.21	7.52	2.73	-0.49	1.26	0.01
1643500	1974	3	11.89	0.33	1.18	10.69	0.87	-0.32	0.77	0.01

Subbasin	Year	Quarter	Precip	qSF	qBF	ET	Rnet	DS	S	W
1643500	1974	4	9.35	0.92	1.60	6.13	2.30	0.69	0.45	0.01
1643500	1975	1	10.53	1.12	3.69	5.29	4.13	0.43	1.13	0.01
1643500	1975	2	11.00	0.97	3.37	7.42	2.61	-0.77	1.56	0.01
1643500	1975	3	20.25	2.95	1.67	15.34	1.96	0.28	0.79	0.01
1643500	1975	4	10.07	1.02	3.55	4.94	4.11	0.55	1.07	0.01
1643500	1976	1	9.32	2.14	4.48	2.80	4.37	-0.12	1.63	0.01
1643500	1976	2	12.14	1.06	2.99	8.75	2.33	-0.67	1.51	0.01
1643500	1976	3	13.66	0.47	1.36	11.92	1.26	-0.11	0.84	0.01
1643500	1976	4	11.31	1.67	2.85	6.68	2.96	0.10	0.73	0.01
1643500	1977	1	6.36	0.73	2.35	2.66	2.96	0.60	0.83	0.01
1643500	1977	2	9.71	1.00	2.42	7.26	1.45	-0.98	1.43	0.01
1643500	1977	3	8.23	0.16	0.64	7.67	0.41	-0.24	0.45	0.01
1643500	1977	4	16.37	1.41	2.17	11.36	3.60	1.42	0.20	0.01
1643500	1978	1	11.92	3.62	4.45	3.91	4.39	-0.07	1.63	0.01
1643500	1978	2	13.98	1.89	3.50	9.18	2.91	-0.60	1.56	0.01
1643500	1978	3	11.30	0.62	1.54	9.71	0.97	-0.58	0.95	0.01
1643500	1978	4	9.65	0.63	1.29	6.80	2.22	0.92	0.37	0.01
1643500	1979	1	17.02	4.91	6.45	4.39	7.72	1.26	1.30	0.01
1643500	1979	2	12.37	0.91	3.78	9.25	2.22	-1.57	2.56	0.01
1643500	1979	3	19.41	2.58	2.66	12.79	4.04	1.37	0.99	0.01
1643500	1979	4	11.77	1.81	5.81	5.02	4.94	-0.88	2.36	0.01
1643500	1980	1	9.73	1.20	3.66	4.44	4.09	0.42	1.48	0.01
1643500	1980	2	13.93	1.55	4.29	9.10	3.28	-1.02	1.90	0.01
1643500	1980	3	7.52	0.14	1.13	6.87	0.52	-0.62	0.88	0.01
1643500	1980	4	6.88	0.26	0.79	5.74	0.87	0.07	0.25	0.01
1643500	1981	1	7.27	1.13	1.44	4.23	1.91	0.46	0.33	0.01
1643500	1981	2	11.63	0.60	1.81	9.48	1.55	-0.27	0.79	0.01
1643500	1981	3	8.70	0.20	0.68	8.13	0.37	-0.32	0.52	0.01
1643500	1981	4	6.71	0.21	0.67	5.63	0.88	0.20	0.20	0.01
1643500	1982	1	10.58	1.75	2.44	5.47	3.35	0.90	0.39	0.01
1643500	1982	2	13.80	1.40	3.37	9.22	3.19	-0.20	1.29	0.01
1643500	1982	3	9.80	0.27	1.18	9.14	0.39	-0.80	1.10	0.01
1643500	1982	4	7.75	0.26	1.08	6.12	1.36	0.27	0.30	0.01
1643500	1983	1	11.04	1.36	3.24	4.24	5.44	2.19	0.57	0.01
1643500	1983	2	19.05	2.96	5.97	11.98	4.11	-1.87	2.76	0.01
1643500	1983	3	5.23	0.13	1.00	4.76	0.34	-0.67	0.89	0.01
1643500	1983	4	17.20	1.86	1.98	12.31	3.03	1.04	0.23	0.01
1643500	1984	1	12.69	2.57	4.98	3.35	6.76	1.77	1.27	0.01
1643500	1984	2	10.71	0.91	5.38	6.70	3.09	-2.30	3.04	0.01
1643500	1984	3	12.23	0.50	1.24	10.84	0.89	-0.36	0.75	0.01
1643500	1984	4	8.48	0.45	1.54	6.07	1.96	0.41	0.39	0.01
1643500	1985	1	7.84	1.35	2.26	4.11	2.37	0.10	0.79	0.01
1643500	1985	2	8.91	0.36	1.67	7.36	1.19	-0.49	0.89	0.01
1643500	1985	3	11.27	0.35	0.60	10.48	0.44	-0.17	0.40	0.01
1643500	1985	4	10.38	0.73	1.58	7.60	2.05	0.46	0.23	0.01
1643500	1986	1	7.85	0.91	2.99	3.36	3.58	0.58	0.69	0.01

Subbasin	Year	Quarter	Precip	qSF	qBF	ET	Rnet	DS	S	W
1643500	1986	2	5.61	0.36	1.69	4.60	0.65	-1.05	1.27	0.01
1643500	1986	3	9.50	0.15	0.38	9.05	0.31	-0.08	0.23	0.01
1643500	1986	4	13.14	1.11	1.23	9.76	2.26	1.02	0.14	0.01
1643500	1987	1	8.13	0.99	4.03	2.48	4.66	0.62	1.16	0.01
1643500	1987	2	12.68	1.00	3.03	9.64	2.04	-1.00	1.79	0.01
1643500	1987	3	16.09	3.29	1.83	11.07	1.74	-0.10	0.79	0.01
1643500	1987	4	10.24	0.82	2.48	6.33	3.09	0.60	0.68	0.01
1643500	1988	1	7.85	0.99	3.50	3.26	3.60	0.09	1.28	0.01
1643500	1988	2	14.78	3.80	4.36	6.98	4.01	-0.37	1.38	0.01
1643500	1988	3	12.87	0.40	1.28	11.80	0.67	-0.62	1.01	0.01
1643500	1988	4	7.24	0.28	1.16	5.48	1.48	0.31	0.39	0.01
1643500	1989	1	10.96	1.11	3.13	5.77	4.08	0.94	0.69	0.01
1643500	1989	2	16.78	2.47	4.63	10.29	4.03	-0.61	1.64	0.01
1643500	1989	3	7.24	0.20	1.32	6.37	0.67	-0.66	1.02	0.01
1643500	1989	4	9.02	0.35	1.28	7.03	1.63	0.34	0.36	0.01
1643500	1990	1	9.21	0.74	2.66	5.24	3.23	0.56	0.71	0.01
1643500	1990	2	11.25	1.29	3.35	7.15	2.81	-0.55	1.27	0.01
1643500	1990	3	10.55	0.31	1.02	9.53	0.71	-0.32	0.72	0.01
1643500	1990	4	15.71	1.97	2.19	10.28	3.46	1.26	0.40	0.01
1643500	1991	1	9.41	1.15	4.35	4.11	4.15	-0.21	1.66	0.01
1643500	1991	2	6.79	0.21	2.18	5.52	1.06	-1.13	1.44	0.01
1643500	1991	3	8.22	0.12	0.43	7.81	0.29	-0.15	0.32	0.01
1643500	1991	4	9.28	0.38	0.81	7.69	1.20	0.38	0.17	0.01
1643500	1992	1	8.50	0.75	2.14	4.93	2.82	0.67	0.55	0.01
1643500	1992	2	8.95	0.45	2.19	7.06	1.43	-0.77	1.22	0.01
1643500	1992	3	12.81	0.46	0.88	11.52	0.83	-0.06	0.45	0.01
1643500	1992	4	13.18	2.65	3.52	5.34	5.19	1.66	0.40	0.01
1643500	1993	1	12.87	3.40	6.55	0.77	8.70	2.14	2.06	0.01
1643500	1993	2	11.86	1.74	5.78	7.87	2.24	-3.55	4.20	0.01
1643500	1993	3	11.90	0.38	0.99	10.83	0.70	-0.30	0.65	0.01
1643500	1993	4	13.56	2.28	1.84	8.66	2.61	0.76	0.35	0.01
1643500	1994	1	16.46	4.01	5.09	5.31	7.14	2.04	1.11	0.01
1643500	1994	2	7.73	0.65	4.08	5.50	1.58	-2.51	3.15	0.01
1643500	1994	3	16.15	0.89	1.71	13.56	1.70	-0.02	0.63	0.01
1643500	1994	4	7.03	0.47	1.83	4.18	2.38	0.54	0.61	0.01
1643500	1995	1	7.57	0.95	3.17	3.47	3.15	-0.03	1.15	0.01
1643500	1995	2	11.80	0.47	2.03	9.79	1.53	-0.51	1.12	0.01
1643500	1995	3	8.44	0.40	0.87	7.52	0.52	-0.36	0.61	0.01
1643500	1995	4	14.63	1.40	2.45	9.32	3.90	1.44	0.25	0.01
1643500	1996	1	13.18	4.33	5.37	2.95	5.90	0.52	1.69	0.01
1643500	1996	2	19.81	3.74	5.11	11.44	4.63	-0.49	2.21	0.01
1643500	1996	3	20.16	2.61	3.87	13.54	4.01	0.12	1.71	0.01
1643500	1996	4	16.53	4.23	6.89	4.40	7.90	1.00	1.84	0.01
1643500	1997	1	9.74	1.01	5.33	4.17	4.56	-0.78	2.83	0.01
1643500	1997	2	4.99	0.14	2.81	3.63	1.22	-1.61	2.06	0.01
1643500	1997	3	8.01	0.15	0.59	7.49	0.37	-0.25	0.45	0.03

Subbasin	Year	Quarter	Precip	qSF	qBF	ET	Rnet	DS	S	W
1643500	1997	4	11.08	0.52	1.09	8.85	1.71	0.61	0.20	0.02
1643500	1998	1	18.33	4.88	6.05	5.44	8.01	1.94	0.81	0.01
1643500	1998	2	14.19	1.57	4.67	9.89	2.73	-1.97	2.75	0.03
1643500	1998	3	5.93	0.12	0.92	5.41	0.39	-0.56	0.78	0.03
1643500	1998	4	5.68	0.10	0.71	4.63	0.95	0.22	0.22	0.02
1643500	1999	1	12.59	0.93	2.15	8.76	2.90	0.73	0.44	0.02
1643500	1999	2	6.85	0.22	1.62	6.00	0.63	-1.03	1.18	0.04
1643500	1999	3	17.54	0.92	0.44	15.76	0.86	0.39	0.15	0.03
1643500	1999	4	8.37	0.73	2.05	5.24	2.40	0.33	0.53	0.02
1643500	2000	1	11.17	1.26	3.21	5.75	4.15	0.93	0.86	0.01
1643500	2000	2	11.91	0.57	2.76	9.82	1.53	-1.26	1.79	0.03
1643500	2000	3	17.64	0.65	1.15	15.93	1.07	-0.10	0.53	0.02
1643500	2000	4	5.48	0.44	1.22	3.64	1.41	0.17	0.43	0.01
1643500	2001	1	10.07	1.14	2.61	5.55	3.38	0.76	0.61	0.02
1643500	2001	2	10.84	1.05	2.49	7.99	1.80	-0.73	1.36	0.04
1643500	2001	3	11.12	0.36	0.80	10.34	0.42	-0.40	0.63	0.02
1643500	2001	4	5.07	0.14	0.79	3.96	0.97	0.16	0.23	0.02
1643500	2002	1	6.79	0.26	1.10	5.30	1.23	0.12	0.39	0.02
1643500	2002	2	11.62	0.46	1.06	10.39	0.76	-0.33	0.51	0.04
1643500	2002	3	9.98	0.14	0.18	9.69	0.15	-0.06	0.17	0.02

Appendix C – Major Ground Water Users* in Maryland Sub-basins of Interest

MDE Permit Number	Owner	Use Type
Bennett Creek:		
FR60G011	AT&T COMPANY	INDUSTRIAL
FR78G010	FR CO BOARD OF EDUCATION (KEMPTOWN ES)	COMMERCIAL
FR93G015	FR CO BUREAU WATER & SEWER (URBANA HIGH SCHOOL)	COMMERCIAL
FR90G031	FREDERICK COUNTY BUREAU (KNOLLS OF WINDSOR)	PUBLIC WATER SUPPLY
FR80G009	LILYPONS WATER GARDENS	AGRICULTURE
FR97G017	P.B. DYE GULF CLUB	IRRIGATION
FR96G008	ROBERT STURGES (WORTHINGTON MANOR GOLF COURSE)	IRRIGATION
Big Pipe Creek:		
CL89G002	BEAR CREEK GOLF CLUB, LLC	IRRIGATION
CL75G004	BLEVINS, INC., HENRY L. (INAC NOW SEE CL66G112)	PUBLIC WATER SUPPLY
CL95G053	CARROLL COUNTY BOARD OF COMMISSIONERS (PLEASANT VALLEY)	PUBLIC WATER SUPPLY
CL92G004	LIPPY BROTHERS, INC.	AGRICULTURE
CL66G112	MANCHESTER, TOWN OF (BACHMAN RD&BLEVINS CLAIM)	PUBLIC WATER SUPPLY
CL87G082	MAYS, JOHN E. (KINGSDENE NURSERIES)	IRRIGATION
CL79G068	SHELBURNE COMPANY, THE	IRRIGATION
CL00G004	SKW FARM, INC.	IRRIGATION
CL78G179	TANEYTOWN, CITY OF	PUBLIC WATER SUPPLY
CL87G107	WALDEN REAL ESTATE, INC. (BOWLING BROOK SCH FOR BOYS)	COMMERCIAL
CL77G436	WESTMINSTER, CITY OF (KRIDERS CHURCH RD WELL)	PUBLIC WATER SUPPLY
CL77G236	WESTMINSTER, CITY OF (MAINTENANCE FACILITY WELL)	PUBLIC WATER SUPPLY
CL77G836	WESTMINSTER, CITY OF (MGS KOONTZ WELL)	PUBLIC WATER SUPPLY
Catoctin Creek:		
FR66G012	FR CO DEPT OF PUB WORKS (FOUNTAINDALE/BRADDOCK HTS)	PUBLIC WATER SUPPLY
FR70G014	FR CO WATER & SEWER DEPT (BRIERCREST & CAMBRIDGE)	PUBLIC WATER SUPPLY
FR87G034	FR CO WATER & SEWER DEPT (COPPERFIELD SUBD)	PUBLIC WATER SUPPLY
FR66G013	MARYLAND STATE HIGHWAY (I-70 REST STOP)	COMMERCIAL
FR74G025	MIDDLETOWN, TOWN OF	PUBLIC WATER SUPPLY
FR98G022	MUSKET RIDGE DEVELOPMENT (MUSKET RIDGE GOLF CLUB)	IRRIGATION
FR87G104	MYERSVILLE, TOWN OF (ASHLEY HILLS WELLS)	PUBLIC WATER SUPPLY
FR88G035	MYERSVILLE, TOWN OF (CANADA HILL SUBDIVISION)	PUBLIC WATER SUPPLY
FR87G204	MYERSVILLE, TOWN OF (DEER WOODS SUPPLY)	PUBLIC WATER SUPPLY
FR97G034	MYERSVILLE, TOWN OF (RESERVOIR WELL)	PUBLIC WATER SUPPLY
FR87G020	MYERSVILLE, TOWN OF (SPRING SUPPLY)	PUBLIC WATER SUPPLY
FR95G022	MYERSVILLE, TOWN OF	PUBLIC WATER SUPPLY
FR87G004	MYERSVILLE, TOWN OF	PUBLIC WATER SUPPLY
FR43G101	U.S. ARMY GARRISON	COMMERCIAL

* Well owners in Maryland with permits to withdraw 10,000 gallons or more per day, as listed in the USGS Site-Specific Water-Use Data System for the time period 1980-2001, prepared by the USGS Baltimore District Office from information provided by the Maryland Department of Environment.