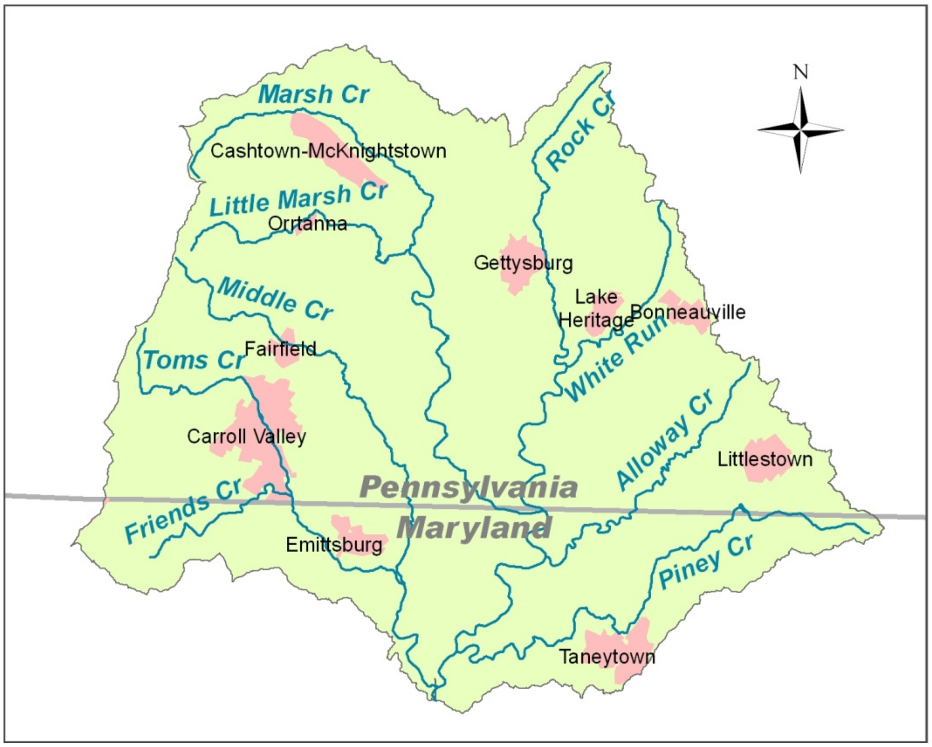
Seasonal Steady-State Ground Water/Stream Flow Model of the Upper Monocacy River Basin



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Executive Summary

The upper Monocacy River basin, located in the northeastern corner of the Potomac River basin, includes much of the southern portion of Adams County, Pennsylvania, and parts of Frederick and Carroll Counties in Maryland. Rapid population growth and development is occurring in this region, and there is growing concern regarding future water availability and the potential impact of growth on the area's water resources. The basin is drained by a dense network of streams, including the upper Monocacy River tributaries: Marsh, Rock, Alloway, Piney, and Toms Creeks. The fractured bedrock aquifers which underlie this basin continually discharge ground water into streams, leading to a close interconnection between surface water and ground water resources, with recharge to aquifers supplying water to basin residents via ground water wells and stream intakes, and also supplying stream flow necessary to sustain healthy aquatic ecosystems. Because evapotranspiration rates are highest in the summer, and water from the bedrock aquifers drains to basin streams relatively rapidly, both aquifer levels and stream flows tend to be highest in the wintertime and lowest in the summertime. Water availability problems most typically occur in the months of July, August and September.

This study investigates water resources in the upper Monocacy basin by means of a regional steady-state ground water/stream flow simulation model, with a focus on summertime conditions. Results from a past study indicate that a steady-state model may provide a reasonable approximation to average summertime conditions in the upper Monocacy basin, because ground water storage at the beginning of the summer is small due to rapid base flow recession rates. Thus, summertime aquifer levels in this basin are largely determined by summertime recharge. The model constructed for this study simulates typical summertime (July, August, September) aquifer levels and mean stream flow in the basin over a 43-year study period, from 1960 through 2002. Because of limitations in available data, well observations and stream flow measurements from the study period were categorized and combined into five different data sets for model calibration and verification, representing "dry", "average-dry", "average", "average-wet", and "wet" summertime hydrologic conditions. Net recharge estimated from stream flow data are used to construct model recharge inputs.

The model is calibrated with a data set of water level observations from summers in the study period representing "average" hydrologic conditions. To further test the model's ability to simulate summertime aquifer levels, four verification runs were done, with data sets corresponding to dry, average-dry, average-wet, and wet summers. Results of the verification runs were good, though aquifer levels were over-estimated for wet summers. Model calibration and verification runs indicate that for dry to average-wet hydrologic conditions, the model can predict mean aquifers levels in the upper Monocacy basin to within 2 or 3 meters. However, at any given location in the basin, predicted aquifer levels are only likely to be within 20 to 30 meters of observed levels. Though the match between simulated and observed aquifer levels in the calibration run was quite good, the scale and the inherent variability of the multi-year calibration data set is expected to limit the accuracy and predictive capabilities of the model.

The model was used to predict dry stream reaches and “losing” stream reaches, that is, stretches of streams where the underlying aquifer has dropped to a level below the bottom of the stream bed, causing the stream to lose water due to leakage to the aquifer below. Model runs were done to predict dry and losing stream reaches for each of the five categories of summertime hydrologic conditions defined in this study. Three additional runs were done to predict potential increases in dry and losing stream reaches during “dry” summers due to future increases in ground water withdrawals throughout the basin. These runs simulate increased ground water withdrawals by reducing net recharge rates uniformly throughout the model domain, with reductions corresponding to increases in ground water withdrawals of approximately 0.5 mgd, 1.0 mgd, and 1.5 mgd in the combined Marsh/Rock/Alloway Creek watershed.

Model predictions indicate that during “dry” summers, which represent approximately the driest 20% of summers in the study period, a significant percentage of represented stream reaches are dry or losing, primarily in head water areas. The model also predicts that the simulated increases in ground water withdrawals would significantly increase the percentage of dry or losing reaches during dry summers. For stream reaches represented in the model, the basin-wide percentage of dry or losing stream miles during dry summers is predicted to increase from approximately 40% to approximately 50% for the scenario in which withdrawals increase by 1.5 mgd.

The accuracy of the upper Monocacy ground water/stream flow model is expected to be limited, especially in its predictions of local conditions. These limitations in accuracy stem from the regional scale of the model and the lack of detailed information on geologic structure. In addition, there is a lack of water level observation data and little information or data to verify the stream flow predictions of the model calibration and verification runs. However, the predicted increases in total miles of dry and losing reaches in the upper Monocacy basin shown in may be indicative of the impact that future increases in ground water withdrawals will have on basin streams.

Seasonal Steady-State Ground Water/Stream Flow Model of the Upper Monocacy River Basin

Introduction

The upper Monocacy River basin, located in the northeastern corner of the Potomac River basin, includes much of the southern portion of Adams County, Pennsylvania, and parts of Frederick and Carroll Counties in Maryland. Rapid population growth and development is occurring in this region, largely due to proximity to the Washington, DC metropolitan area. Citizens, planners, and local water authorities are all expressing concern regarding future water availability and the potential impact of growth on the area's water resources.

The 309 square mile (mi^2) land area of the upper Monocacy basin is drained by a dense network of streams, including the upper Monocacy River tributaries: Marsh, Rock, Alloway, Piney, and Toms Creeks. The fractured bedrock aquifers which underlie this basin continually discharge water into the basin streams, leading to a close interconnection between surface water and ground water resources, with recharge to aquifers supplying water to basin residents via ground water wells and stream intakes, and also helping to supply stream flow necessary to sustain healthy aquatic ecosystems.

The hydrology of the aquifer/stream system of the upper Monocacy basin, as in other areas in the northeastern United States, is highly seasonal. Because evapotranspiration rates are highest in the summer, and water from the bedrock aquifers drains to basin streams relatively rapidly, both aquifer levels and stream flows tend to be highest in the wintertime and lowest in the summertime. Water availability problems most typically occur in the months of late summer and early fall. A seasonal water budget study done for four Monocacy River basin watersheds found that summertime water availability for the Marsh/Rock/Alloway Creek drainage area was on the order of only twice the rate of current ground water withdrawals (Schultz et al., 2005).

This study investigates water resources in the upper Monocacy basin by means of a regional steady-state ground water/stream flow simulation model, with a focus on summertime conditions. Ground water/stream flow models incorporate available geologic, hydrologic and meteorological data and make use of our understanding of the physical processes responsible for the movement of water through the ground to simulate ground water flow patterns, aquifer levels, and stream flow rates. Regional models are based on regional data sets and are constructed to help answer questions at a fairly coarse scale. Unlike smaller-scale models, which may incorporate detailed local data and can address questions concerning an individual well or the interaction between nearby wells, regional models can provide information on how significant and widespread increases in ground water withdrawals may affect aquifer levels and stream flow throughout the basin.

The model constructed for this study simulates typical summertime (July, August, September) aquifer levels and mean stream flow in the upper Monocacy River basin over a 43-year study period, from 1960 through 2002, for a range of hydrologic conditions. It is based on a steady-state ground water/stream flow model for the entire Monocacy River basin, constructed for a previous study (Palmer et al., 2007). Results from the study by Schultz et al. (2005) indicate that a steady-state model may provide a reasonable approximation to average summertime conditions in the upper Monocacy basin, because ground water storage at the beginning of the summer is small due to rapid base flow recession rates (where storage is measured from the level associated with zero stream flow). Thus, summertime aquifer levels in this basin are largely determined by summertime recharge. The current model incorporates a number of new features, including a denser network of simulated streams, a refinement of the vertical grid spacing to ten layers, and a new calibration. Net recharge estimated from stream flow data are used to construct model recharge inputs, therefore incorporating the impact of ground water withdrawals as averages over each recharge zone. In order to construct data sets for model calibration and verification, summers in the 43-year study period were categorized into five roughly equally-sized groups based on summertime hydrologic conditions: “dry”, “average-dry”, “average”, “average-wet”, and “wet”. The model is calibrated with a data set representing summers that have occurred during the study period with “average” hydrologic conditions. It is then successfully verified using the four other data sets.

Model stream flow simulations include predictions of dry stream reaches and “losing” stream reaches, that is, stretches of streams that are discharging water to the underlying aquifer because the aquifer level has dropped below the bottom of the stream bed. The model is used to predict increases in the number of dry and losing stream reaches under hypothetical future increases in basin ground water withdrawals. Because the scale of the model is regional and the water level and stream flow data sets used to construct the model are averaged over a large number of years, its predictions of dry and losing reaches are not likely to be reliable at the small watershed scale, that is, for individual streams. However, model predictions of the basin-wide percentage increases in dry or losing stream miles may give a reasonable estimate of the significant impact that potential future increases in ground water withdrawals will have on basin streams.

This study was conducted with funding provided by the National Fish and Wildlife Foundation under Grant No. 2006-0100-031, and with additional funding from the signatory states of the Interstate Commission on the Potomac River Basin (ICPRB), Maryland, Pennsylvania, Virginia, West Virginia, and the District of Columbia. Views expressed in this report reflect the opinions of the authors, and should not be construed as representing the signatory states or the Commissioners of ICPRB.

Location

The study area is the upper portion of the Monocacy River basin, an approximately 309 square mile (mi^2) drainage area covering portions of Adams County in Pennsylvania and Frederick and Carroll Counties in Maryland (see Figure 1). The area is drained by tributaries of the upper Monocacy River: Marsh Creek, Rock Creek, Tom’s Creek, Alloway Creek, and Piney Creek, as shown in Figure 2.

The upper Monocacy basin lies in two major physiographic provinces, the Blue Ridge province and the Piedmont province as described in Fenneman (1938). The surface physiography varies from gently rolling hills of the Piedmont in the central and eastern parts of the basin, to the relatively steep topography of the eastern edge of the Blue Ridge Mountains, located in the western portion of the basin.

Geology

Approximately 79% of the upper Monocacy River basin is in the Western Piedmont physiographic province, which forms most of the eastern part of the basin (Figure 3). The Western Piedmont province is from 9 to 17 miles wide in the basin and is present in Adams County, Pennsylvania and Frederick and Carroll Counties in Maryland. It forms a gently rolling upland with an average elevation of 700 to 800 feet (ft), with relief generally less than 500 ft, and is incised by many deep narrow stream valleys (Stose and Stose, 1946). The Western Piedmont within the Upper Monocacy River basin includes the Piedmont Upland section of the Piedmont Province. The Piedmont Upland is present in the eastern corner of portion of the basin in Adams County, Pa. and Carroll County, Md. and makes up approximately 4% of the basin area. The Piedmont Upland is underlain by Precambrian and Cambrian metamorphic and igneous rocks and Cambrian age carbonate rocks similar in composition and structure to the Great Valley carbonates in western Maryland, Virginia and West Virginia (Vokes and Edwards, 1974).

The central portion of the upper Monocacy River basin is underlain by rocks of the Mesozoic Lowland section of the Piedmont Province. This section occupies the majority of the basin (approximately 74%), extending from the southern to the northern boundaries of the basin and from the Blue Ridge in the west to the low hills of the Piedmont Upland on the eastern edge of the basin. The rocks in this province include Triassic-age consolidated and compacted sedimentary layers of sandstone, shale, arkose, and conglomerate with numerous Jurassic-age igneous intrusions. These igneous intrusions are formed of diabase, a dense, fine-grained rock that is resistant to weathering. These intrusive bodies frequently form low ridges and act as impermeable barriers to ground water flow (Focazio, et al, 1997). However, there are reports from well drillers that very high-yielding wells have been installed in the altered margins between the diabase intrusions and the country rock.

The Blue Ridge province is represented in the upper Monocacy River basin in the mountain ridge formed by the joining of the ridges of Catoctin and South Mountains making up the western boundary of the basin. These ridges join in the southwest corner of the basin just south of the Maryland-Pennsylvania border forming a highland about 7 miles wide. In total, the two ridges, and thus the Blue Ridge province, make up approximately 22% of the basin. The highest point in the basin is on South Mountain in Adams County, Pa, at 1,982 ft above sea level. The rocks that form these ridges consist of Precambrian metavolcanic rocks of the Catoctin Formation, and the members of the Cambrian age Chilhowee Group; phyllite of the Loudoun Formation, quartzites of the Weverton Formation, metasiltstone of the Harpers Formation, and metasandstone of the Antietam Formation (Southworth, et al, 2002).

Overlying the fractured bedrock of the basin is a layer of overburden, or regolith, composed of weathered bedrock, soil, alluvium, and colluvium. The length of casing installed in ground water wells has been used as an indicator of the thickness of the regolith in many studies in the region (e.g. Nutter and Otton, 1969, Richardson, 1982, and Low and others, 2002). An analysis of well casing data done for this study indicates that regolith thickness in the upper Monocacy basin ranges from approximately 5 ft to 115 ft, with a mean of 31 ft and a standard deviation of 14 ft.

Figure 1. Location of study area

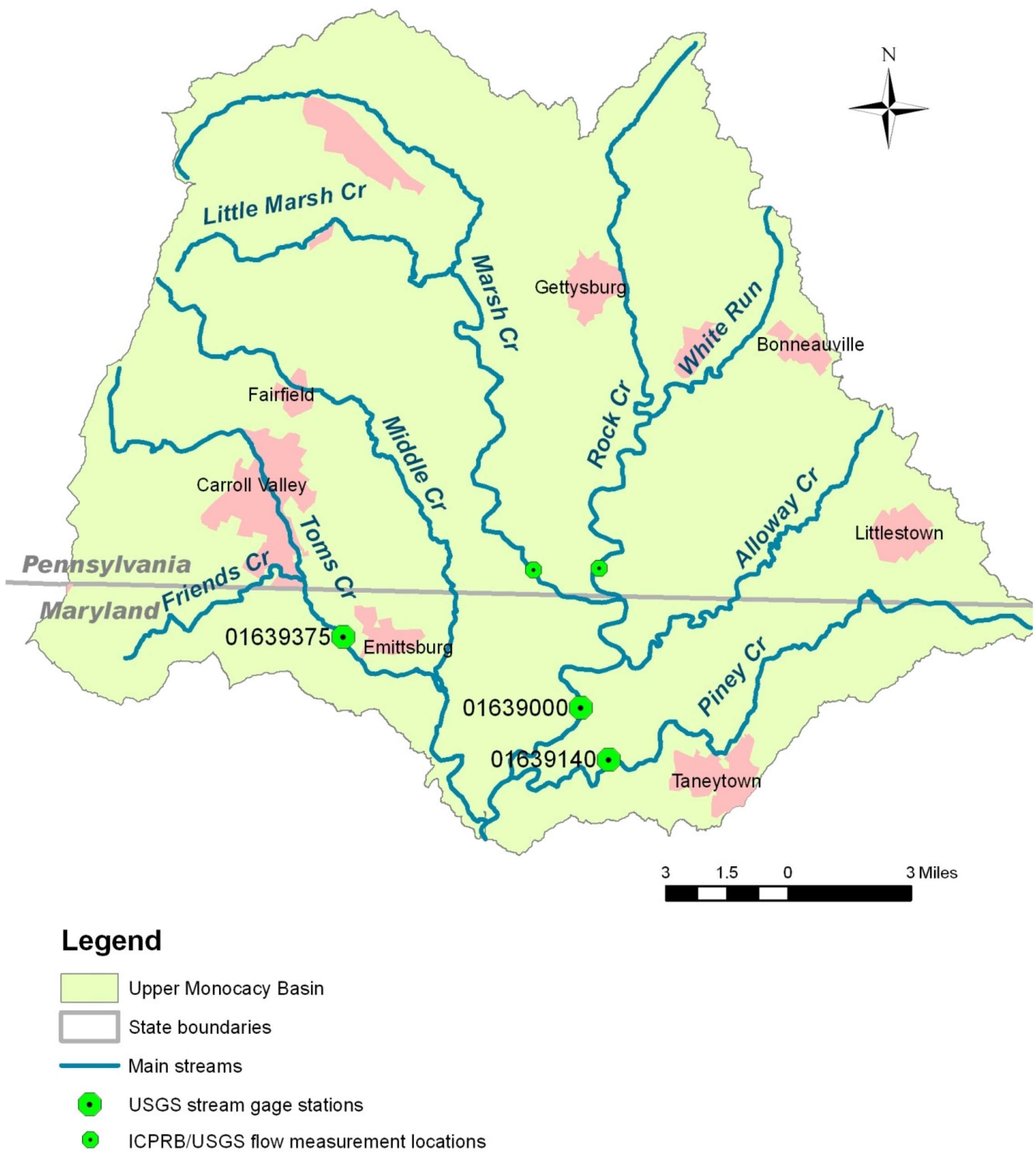

Figure 2. Upper Monocacy basin streams and municipalities

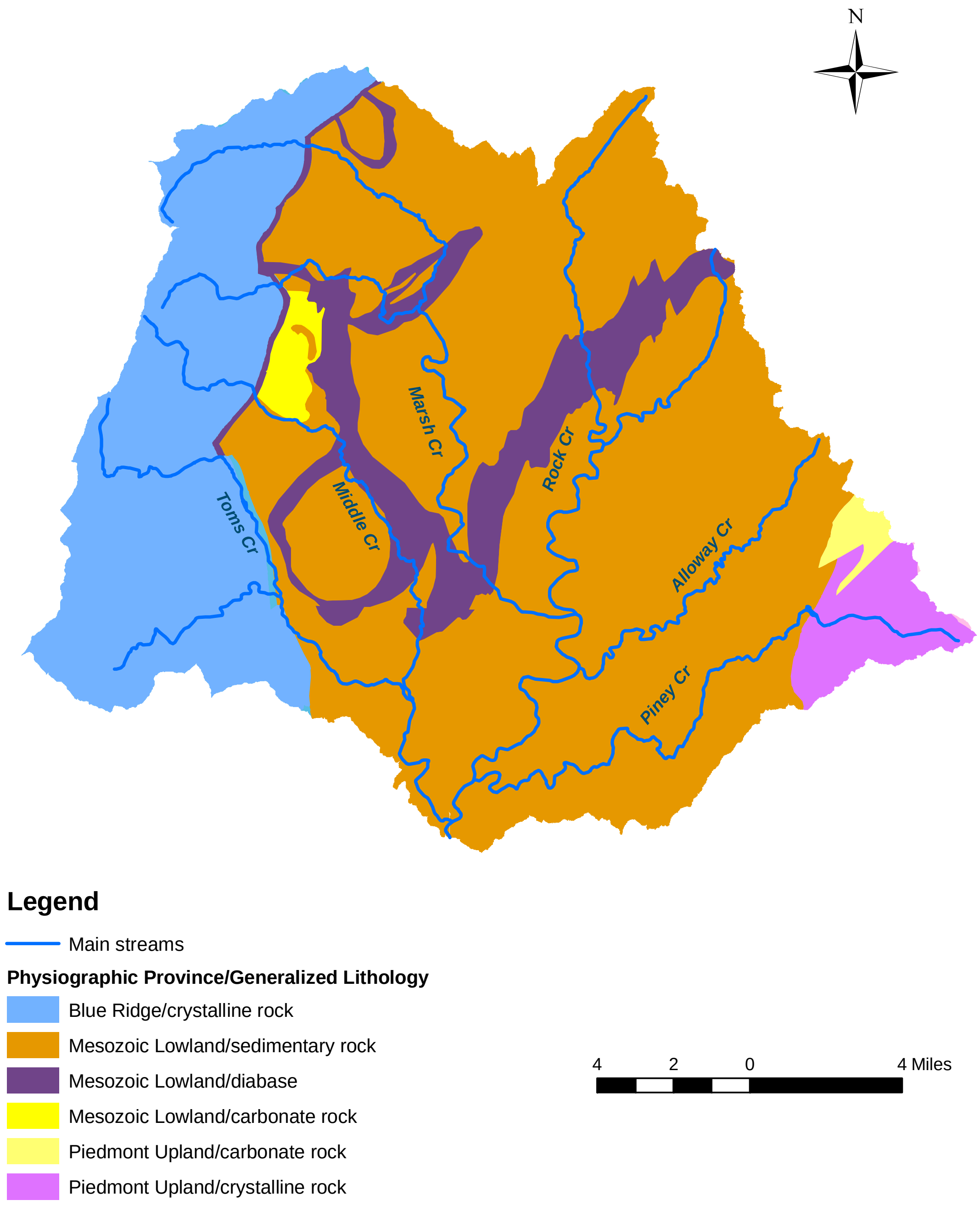

Figure 3. Physiographic Provinces and generalized lithology[1]

[1] Figure based on data from the USGS National Water-Quality Assessment (NAWQA) Program's study of the Potomac River basin (Derosier and others, 1998).

Data

Daily Stream Flow Data

Daily stream flow data are available for three USGS gage stations that have been operated within the study area. Information on these stations is given in Table 1, and their locations are depicted in Figure 2. Daily mean flow data were downloaded from the USGS National Water Information System (USGS-NWIS, 2007) website for all three stations for their respective periods of record. The gage on the Monocacy River at Bridgeport, Maryland, Station 01639000, has been operating since 1942, and current real-time instantaneous flow data for this gage are available at the USGS-NWIS website. The gages on Piney Creek near Taneytown, Maryland, Station 01639140, and Toms Creek at Emittsburg, Maryland, Station 01639375, have more limited periods of record, and are not currently in operation.

Daily flow data from these three stations were processed using the USGS's hydrograph separation software, PART (Rutledge, 1998). PART was used to compute quarterly mean baseflow for data available within the study period, and these results were used to compute model recharge inputs and stream flow targets, as described below.

Table 1. USGS stream gage stations

Station Name	Station ID	Drainage Area (sq. mi.)	Period of Record Begin Date	Period of Record End Date	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)
Monocacy River at Bridgeport, MD	01639000	173.0	5-1-1942	present	39 40 43.8	77 14 04.2
Piney Creek near Taneytown, MD	01639140	31.3	5-1-1990	1-15-2002	39 39 38.7	77 13 15.5
Toms Creek at Emittsburg, MD	01639375	41.3	3-1-1986	9-30-1990	39 42 13	77 20 41

Stream flow measurements done for this study

Instantaneous flow measurements were taken for this study by USGS staff from the Pennsylvania Water Science Center in New Cumberland, Pa. Measurements were made on both Marsh Creek and on Rock Creek on six separate days during the time period from March 2007 to March 2008. The locations of the measurements, depicted in Figure 2, were on Marsh Creek just south of the Mason Dixon Road bridge and on Rock Creek also just south of the Mason Dixon Road bridge. The data are summarized in Table A-1 of Appendix A.

The Marsh and Rock Creek flow measurements were taken at times believed to represent base flow conditions. These tributary flows were compared with instantaneous flows measured downstream at USGS Station 01639000 at Bridgeport, Maryland. The drainage areas above the Marsh Creek and Rock Creek measurement sites are 77.8 and 60.0 mi^2, respectively, representing 45% and 35%, respectively, of the 173.0 mi^2 drainage area associated with flow measurements at the Bridgeport gage. Each of the six Marsh and Rock flow measurements were compared with simultaneous instantaneous flow measurements at the Bridgeport gage as percentages. The mean percentages for each location, compared with flow at the Bridgeport gage, are given in Table A-2 of Appendix A, along with 95% confidence intervals. The flow measurements on Marsh Creek represented 39% of the flow measured at the Bridgeport gage, on average, and the flow measurements on Rock Creek represented 41% of the flow measured at the Bridgeport gage, on average. Statistical hypothesis tests were also done, and it was found that the measured flows on Marsh and Rock Creeks, as a percentage of the flow at the Bridgeport gage, did not differ significantly from the values computed using simple area adjustment factors, 45% and 35%, respectively. This lack of statistical significance is likely due to the small sample size.

Well data

Well site information and water level data are available from the USGS National Water Information System (NWIS) (USGS-NWIS, 2007) for wells throughout the nation. Site information for wells within the Monocacy River basin were downloaded from this database and reviewed. From this initial dataset, 872 wells were found to be located in the study area, the upper Monocacy basin. Of these, 432 wells had water level data available from NWIS, and are reported to be not influenced by conditions that would affect water level measurements. From these remaining wells, 361 were identified which have data in the 43 year study period, 1960 through 2002.

The resulting water level data set was found to be of limited value for characterizing mean aquifer levels at most locations in the study area, or variations in aquifer levels due to seasonal or other changes in hydrologic conditions. Of the 361 wells, 212 (59%) had only one water level measurement recorded during the 43-year study period, and 332 wells (92%) had three or less measurements. Only four wells had sufficient data to characterize seasonal variations, and all of these are located in the Toms Creek drainage area in the southwestern portion of the study area.[2] Three of these wells, FR Ad 40, FR Ae 50, and FR Af 39, have approximately monthly measurements available from June 1982 through November 1983, and one well, FR Af 27, has monthly data available from June 1982 to February 2004. The

[2] It should be noted that a real-time monitoring well, AD-808, was established in the Borough of Carroll Valley, Adams County, at a date outside of the study period. Daily water level observations for this well are available from September, 2003, to the present time.

majority of the water level observations were from the summer and fall. Averages of available water level data at each well were computed for each of the 172 quarters of the study period, and it was found that one or more water level measurements were made at 34 wells in winter months, at 111 wells in spring, at 207 wells in summer, and at 173 wells in fall.

Classification of summertime hydrologic conditions

Because of limitations in the available well data, the data set of water level observations can only be used to represent approximate average aquifer levels in the study area representative of the 43 year study period. To characterize summertime conditions, and to take into account the variations in hydrologic conditions that occur over the years, an analysis was done of upper Monocacy River mean summertime base flows, computed from daily flow data for Station 01639000 at Bridgeport, Md. Mean seasonal base flows were computed for each of the 43 years in the study period using the USGS software, PART (Rutledge, 1998). The resulting summertime (July, August, September) mean base flow values were then ordered, from lowest to highest, and divided approximately into five quintiles, with the lowest quintile representing the driest 20% of summers, and the highest quintile representing the wettest 20% of summers in the study period, from 1960 through 2002. The results are given in Table 2, and summarized in Table 3.

The summertime base flow quintiles for the upper Monocacy River were used to categorize summertime water level observations into five hydrologic conditions: dry, average-dry, average, average-wet, and wet. For example, from Table 3, all summertime water level data for the years, 1962, 1963, 1964, 1965, 1986, 1988, 1991, 1997, 2001, and 2002, in the first base flow quintile, were combined into a single dataset used to represent approximate average aquifer levels in a typical “dry” summer. All summertime water level data for the years, 1961, 1966, 1974, 1977, 1980, 1983, 1998, 1999, in the second base flow quintile, were combined to represent approximate average aquifer levels in an “average-dry” summer, etc. The locations of wells with data in each of these five categories are shown in Figure 4.

Table 2. Mean summer flows and base flows, calculated by PART, based on data from USGS stations 01639000, 01639140, and 01639375.

Year	Monocacy River summer flow, inches	Monocacy River summer base flow, inches	Monocacy River summer base flow, cfs	Monocacy River summer base flow quintile	Piney Cr summer flow, inches	Piney Cr summer base flow, inches	Toms Cr summer flow, inches	Toms Cr summer base flow, inches
1965	0.17	0.07	3.53	1	-99.99	-99.99	-99.99	-99.99
2001	0.18	0.07	3.53	1	0.18	0.05	-99.99	-99.99
1962	0.16	0.08	4.04	1	-99.99	-99.99	-99.99	-99.99
1964	0.27	0.08	4.04	1	-99.99	-99.99	-99.99	-99.99
2002	0.43	0.09	4.54	1	-99.99	-99.99	-99.99	-99.99
1991	0.61	0.11	5.55	1	0.26	0.05	-99.99	-99.99
1988	0.27	0.12	6.06	1	-99.99	-99.99	0.49	0.32
1997	0.39	0.12	6.06	1	0.09	0.05	-99.99	-99.99
1963	0.19	0.13	6.56	1	-99.99	-99.99	-99.99	-99.99
1986	0.3	0.13	6.56	1	-99.99	-99.99	0.67	0.43
1977	0.27	0.14	7.06	2	-99.99	-99.99	-99.99	-99.99
1961	0.41	0.15	7.57	2	-99.99	-99.99	-99.99	-99.99
1983	0.23	0.18	9.08	2	-99.99	-99.99	-99.99	-99.99
1980	0.24	0.18	9.08	2	-99.99	-99.99	-99.99	-99.99
1999	1.48	0.18	9.08	2	1.19	0.18	-99.99	-99.99
1974	0.35	0.19	9.59	2	-99.99	-99.99	-99.99	-99.99
1998	0.38	0.19	9.59	2	0.39	0.26	-99.99	-99.99
1966	2.66	0.19	9.59	2	-99.99	-99.99	-99.99	-99.99
1981	0.46	0.22	11.10	3	-99.99	-99.99	-99.99	-99.99
1968	0.71	0.24	12.11	3	-99.99	-99.99	-99.99	-99.99
1982	0.38	0.28	14.13	3	-99.99	-99.99	-99.99	-99.99
1969	1.41	0.28	14.13	3	-99.99	-99.99	-99.99	-99.99
1985	1.16	0.29	14.63	3	-99.99	-99.99	-99.99	-99.99
1971	0.77	0.3	15.14	3	-99.99	-99.99	-99.99	-99.99
1976	0.62	0.31	15.64	3	-99.99	-99.99	-99.99	-99.99
1987	1.76	0.32	16.15	3	-99.99	-99.99	1.33	0.73
1993	1.27	0.34	17.16	4	1.06	0.42	-99.99	-99.99
1992	1.23	0.38	19.17	4	1.29	0.55	-99.99	-99.99
1994	0.95	0.4	20.18	4	1.06	0.42	-99.99	-99.99
1973	1.32	0.41	20.69	4	-99.99	-99.99	-99.99	-99.99
1990	1.37	0.41	20.69	4	1.28	0.57	1.66	0.88
1960	1.63	0.41	20.69	4	-99.99	-99.99	-99.99	-99.99
1967	1.54	0.42	21.19	4	-99.99	-99.99	-99.99	-99.99
1978	1.18	0.43	21.70	4	-99.99	-99.99	-99.99	-99.99
1995	1.27	0.53	26.74	5	1.75	0.52	-99.99	-99.99
2000	1.76	0.57	28.76	5	1.78	0.76	-99.99	-99.99
1970	3.06	0.57	28.76	5	-99.99	-99.99	-99.99	-99.99
1989	1.61	0.73	36.84	5	-99.99	-99.99	1.85	1.22
1972	1.23	0.83	41.88	5	-99.99	-99.99	-99.99	-99.99
1984	3.7	0.92	46.42	5	-99.99	-99.99	-99.99	-99.99
1975	7.81	0.94	47.43	5	-99.99	-99.99	-99.99	-99.99
1979	5.67	1.03	51.97	5	-99.99	-99.99	-99.99	-99.99
1996	6.67	1.82	91.84	5	8.09	2.88	-99.99	-99.99

Table 3. Classification of summertime hydrologic conditions

Summertime base flow quintile	Years	Range of mean summer base flow range at USGS Station 01639000 at Bridgeport, Maryland (minimum maximum)		
		inches/quarter	cfs	mgd
Dry	1962, 1963, 1964, 1965, 1986, 1988, 1991, 1997, 2001, 2002	(0.07 0.13)	(3.6 6.6)	(2.3 4.3)
Average-Dry	1961, 1966, 1974, 1977, 1980, 1983, 1998, 1999,	(0.14 0.19)	(7.1 9.7)	(4.6 6.3)
Average	1968, 1969, 1971, 1976, 1981, 1982, 1985, 1987	(0.22 0.32)	(11.2 16.3)	(7.3 10.6)
Average-Wet	1960, 1967, 1973, 1978, 1990, 1992, 1993, 1994	(0.34 0.43)	(17.3 21.9)	(11.2 14.2)
Wet	1970, 1972, 1975, 1979, 1984, 1989, 1995, 1996, 2000	(0.53 1.82)	(27.0 92.8)	(17.5 60.0)

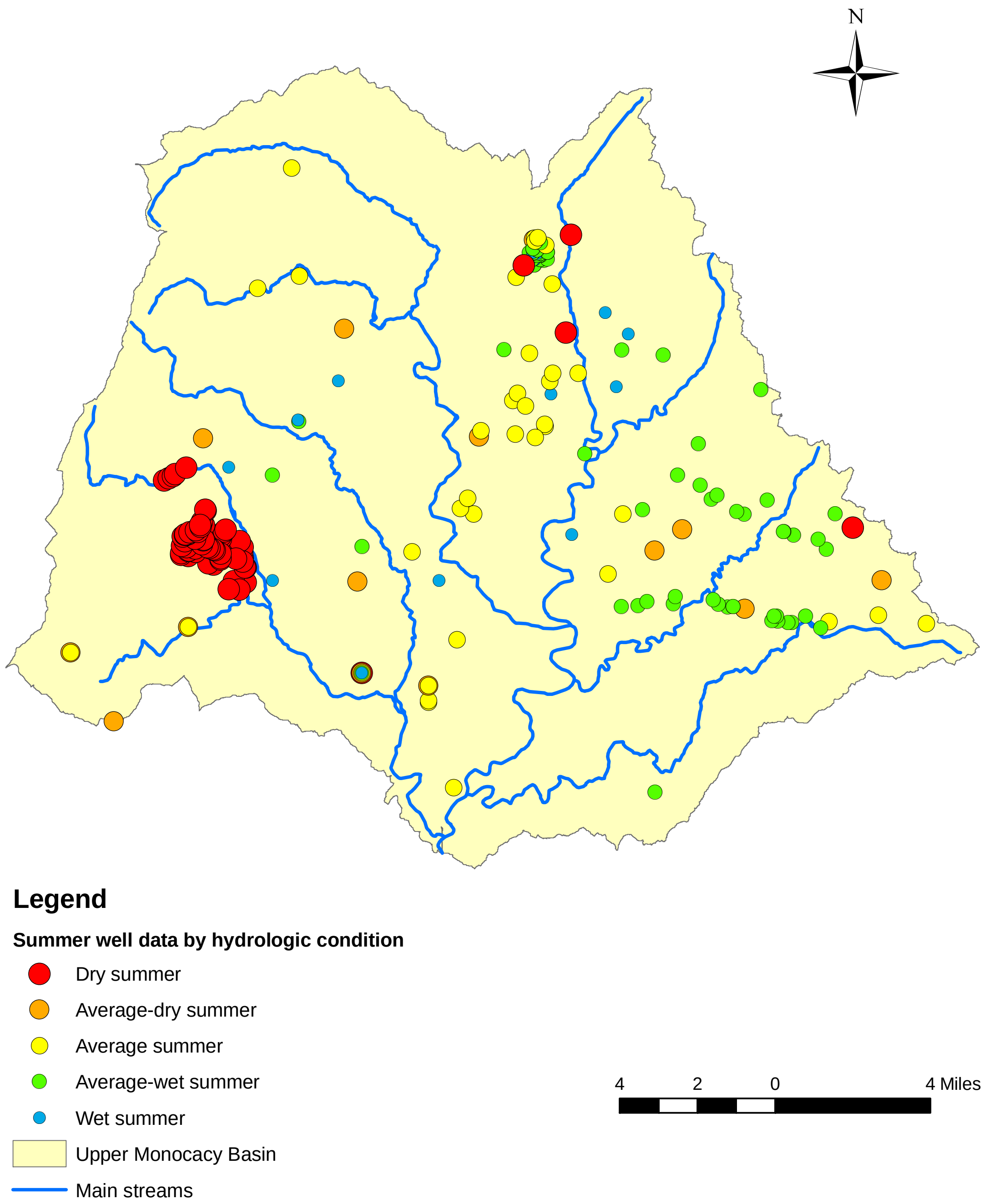

Figure 4. Location of available summertime well data

Model Design

The aquifer system in the upper Monocacy River basin consists of multiple types of fractured bedrock overlain by a mantle of regolith. The thickness of the regolith depends on the lithology of the underlying bedrock and the topographic setting. The density and size of the fractures vary with rock type, terrain, and relation to tectonic features such as faults. The primary source of recharge to the aquifer is precipitation infiltrating into the regolith and in turn recharging the network of fractures within the underlying bedrock. Ground water discharges to the surface streams through streambed seepage and via discharge from springs. The ground water divides outlining the ground water basin are assumed to coincide with the topographic divides of the upper Monocacy River basin.

An underlying assumption of ground water flow simulation models is that the aquifer material behaves as a porous permeable media. For the most part, the bedrock in the study area has practically no primary porosity and permeability. Within most, if not all, of the bedrock units essentially all flow is within the secondary porosity; bedding surfaces, joints, fractures, fault zones, and solution enhanced openings (Nutter and Otton, 1969, Low and others, 2002). However, given the scale used in the model (500 m grid spacing) and the secondary porosity demonstrated by specific capacities of wells in these no-primary-porosity bedrock units (Nutter, 1974, Duigon and Dine, 1987, Low and Dugas, 1999), the assumption seems reasonable.

The conceptual model of the ground water flow system is a layer of permeable regolith overlying impermeable bedrock with a dense fracture network (the term "fractures" is used to refer to all secondary porosity providing openings, regardless of their source). The regolith receives water in the form of infiltration from precipitation and acts as a source of recharge to the fracture network within the bedrock. The density and size of the fractures due to weathering, and therefore the transmissivity of the fractures, decrease with depth. Where the elevation of the water table is above the elevation of the streambed, water discharges from the aquifer to the streams through the streambed, resulting in a "gaining" stream reach. Where the water level in the aquifer is below the elevation of the streambed, water will flow from the stream, recharging the aquifer through the streambed and resulting in a "losing" stream reach.

The ground water/stream flow model constructed for this study represents the regolith and the upper portion of the fractured bedrock as a single layer. The upper surface of this layer represents the ground surface. Regolith thickness in the study area, estimated for this study from well casing data, varies from 1.7 to 35 meters, with a mean of 9.5 meters and a standard deviation of 4.2 meters. Processes occurring in the unsaturated zone are not represented in the model. The overall size of the modeled area requires grid cells with a large horizontal spacing, 500 meters in both the X and Y dimensions. The horizontal dimensions of the grid cells and the high topographic relief in some portions of the basin results in differences in mean ground surface elevations of up to 100 meter between adjacent grid cells. The model is discretized in the vertical, Z, dimension into 10 layers, each 50 meters in thickness. The hydraulic conductivities of the layers decrease with depth, representing the decease in fracture dimensions and density with depth. The reduction of fracture density and size is reflected in the number of wells completed at depths represented by the layers in the model. Approximately 80% of the wells in the basin are 150 m or less in depth and are represented in the upper 3 model layers.

Software tools

The ground water/stream flow model was implemented using the US Geologic Survey's MODFLOW-2000 (Harbaugh and others, 2000) finite difference model code. (References in this report to MODFLOW refer to the MODFLOW-2000 version of the USGS program.) Stream flows are simulated using MODFLOW's Stream (STR) package (Prudic, 1989). The MODFLOW code was used because it is a widely used, well-tested and verified model code. It also has a wide variety of modules available to simulate various hydrogeologic conditions for predicting ground water flow. The program Ground-water Vistas, version 4.2 (GWV), by Environmental Simulations, Inc., was used as a pre- and post-processor for MODFLOW. The parameter estimation program, PEST (Dogherty, 2004), and some of its associated utility programs were also used in the model calibration process.

Model grid

MODFLOW is a computer program that simulates ground water flow using the finite difference method. The grid used by MODFLOW is rectangular in the horizontal plane while the vertical dimension (thickness) of the layers can be varied spatially (Harbaugh and others, 2000). In the interest of minimizing the computational requirements for the model, grid spacing of 500 m in both horizontal dimensions was used, with the layer thickness selected to allow simulation of flow at depth. The horizontal dimensions of the model grid are shown in Figure 5.

The Mesozoic Lowland province within the Monocacy River basin is a half grabben with the western side dropped resulting in sedimentary layers dipping to the west-northwest. The boundary between the western Piedmont and the Blue Ridge provinces is formed by a high-angle Triassic age western border fault (Stose and Stose, 1946). The orientation of this fault and of the Mesozoic sedimentary basin in the Monocacy River basin provides a regional structural orientation to the rocks in these areas. This orientation is recreated in the flow model by the rotation of the model grid N22°E.

The grid is constructed with ten layers; the uppermost layer representing the regolith/weathered bedrock part of the fractured bedrock aquifer and the lower layers representing the part of the aquifer where the fractures are less numerous and well connected or where they pinch-out altogether with depth. The ten layers allow the model to represent this gradual decrease in hydraulic conductivity with depth.

The elevation of the top surface of the upper layer was taken from the USGS 10-m digital elevation model (DEM). The thickness of the layers was set to arbitrary constants of 50 m for all layers.

Boundary Conditions

The lateral extent of the modeled area was defined to coincide with the topographic boundary of the watershed of the upper Monocacy River above the confluence of Toms Creek with the Monocacy River. It was assumed that the ground water divide bounding the upper Monocacy basin coincides with the surface water divide of the basin. The active part of the model grid was shaped to reproduce the outline of the basin and was surrounded by inactive areas. The inactive areas within the model grid were defined with no-flow cells. By default, MODFLOW assigns a no-flow boundary to the bottom of the lowest layer.

Streams

The upper Monocacy River basin is drained by a dense network of streams. Many of these are small first- and second-order streams with very little flow, and in times of drought some may have no flow at all. The streams represented in the model, shown in Figure 5, include the main tributaries as well as a number of lower order streams. In total, approximately 271 miles of streams are represented, using the MODFLOW Stream (STR) package (Prudic, 1989). Streambed elevation data required for the STR package were estimated using USGS topographic quadrangle maps. Stream width was also estimated from the USGS topographic maps and from reconnaissance observations of several of the streams in the basin. Each stream was subdivided into segments for which constant stream characteristics such as stream width, streambed thickness, slope, etc. could be reasonably assigned. This process resulted in 101 stream segments being defined for the model, which are further subdivided into a total of 876 reaches. During several reconnaissance visits to streams within the basin, it was observed that most of the streams had little sediment covering the streambeds, with gravel or larger clast sizes dominant. In almost all streams visited, bedrock was visible in a large percentage of the streambed. As a result of this observation, a streambed thickness of 0.5 m was assumed for the majority of the tributaries and 1.0 m for the larger streams.

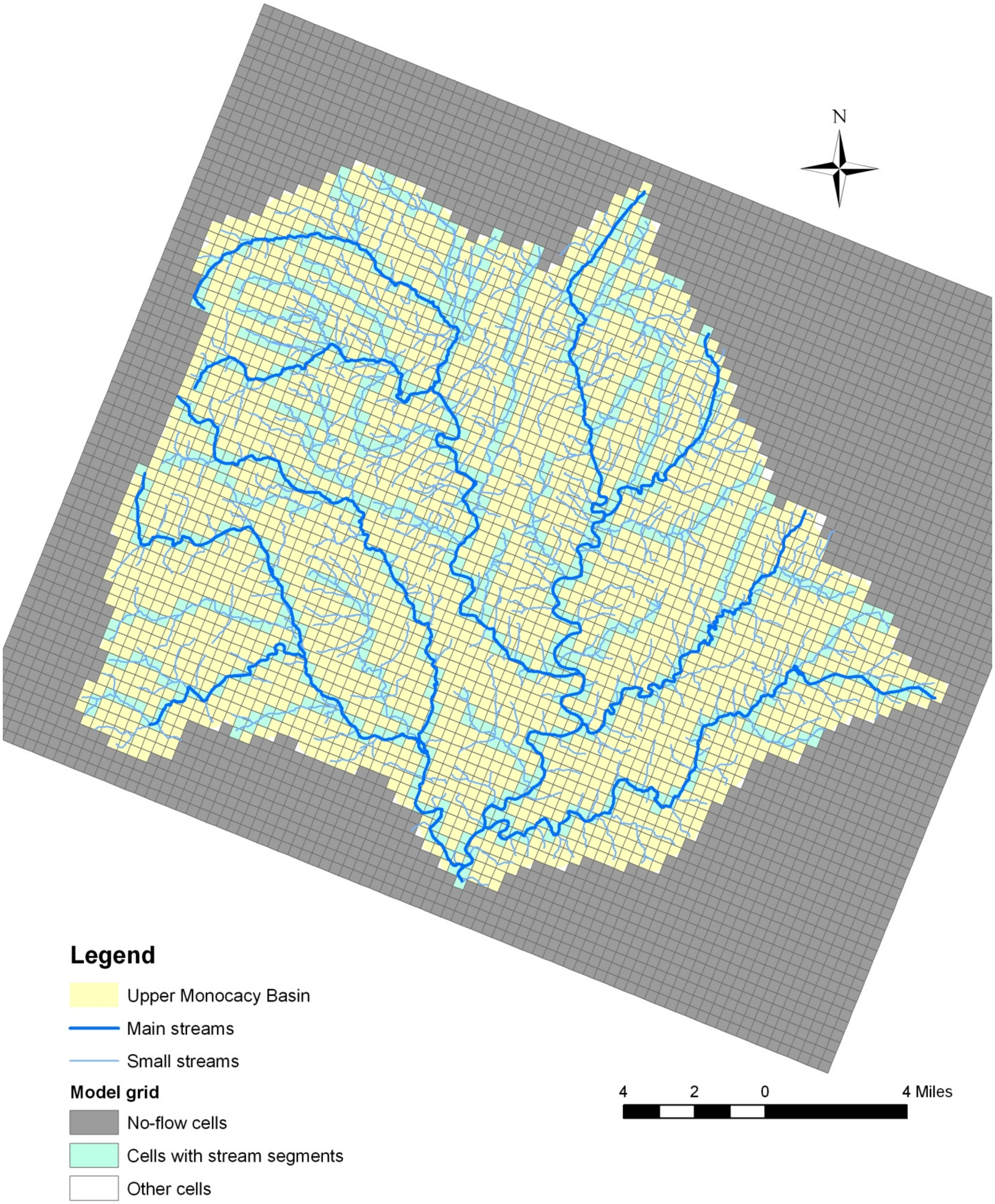

Figure 5. Model grid

Recharge

Recharge to ground water was simulated as a flux applied to the top of each cell in the top layer (Harbaugh and others, 2000). Model recharge values, given in Table 4, are based on mean summer base flow values for the upper Monocacy River, Toms Creek, and Piney Creek, computed from available data from the gages listed in Table 2, for the five hydrologic conditions of Table 3. The zones of recharge used in the model are derived, for the most part, from these three watershed boundaries, as shown in Figure 6. Recharge rates are assumed to be constant throughout each recharge zone.

Since model recharge inputs are obtained from stream base flow estimates, they represent net recharge to basin aquifers, and include the effects ground water withdrawals. Because recharge is assumed to be constant throughout each recharge zone, ground water withdrawals are represented as occurring uniformly throughout each zone, rather than at specific well locations. This representation of ground water withdrawals is not realistic, and limits the model's ability to accurately simulate aquifer levels at a local scale. However, this approach is consistent with the regional scale of the model and the data sets used for model calibration and verification, which include well data from 43 different years from locations uninfluenced by human activities.

Table 4. Model recharge by summertime hydrologic condition, in inches/quarter and meters/day

Recharge Zone	Catchment Area	Dry		Ave-dry		Ave		Ave-wet		Wet	
		in	m/day	in	m/day	in	m/day	in	m/day	In	m/day
10	Upper Monocacy River	0.10	2.79E-05	0.18	5.02E-05	0.29	8.09E-05	0.41	1.14E-04	0.83	2.32E-04
11	Piney Creek	0.05	1.40E-05	0.22	6.14E-05	0.35	9.77E-05	0.49	1.37E-04	0.76	2.12E-04
12	Toms Creek	0.38	1.06E-04	0.55	1.54E-04	0.73	2.04E-04	0.88	2.46E-04	1.22	3.41E-04

Hydraulic properties

The distribution of hydraulic conductivity assigned to the model finite difference cells was based on a combination of physiographic province, physiographic province sub-unit, and lithology type, as defined in the USGS National Water-Quality Assessment (NAWQA) Program's study of the Potomac River basin (Derosier and others, 1998) and as shown in Figure 3. Hydraulic conductivity calibration inputs were based on a grouping of these combinations into four zones, shown in Figure 7.

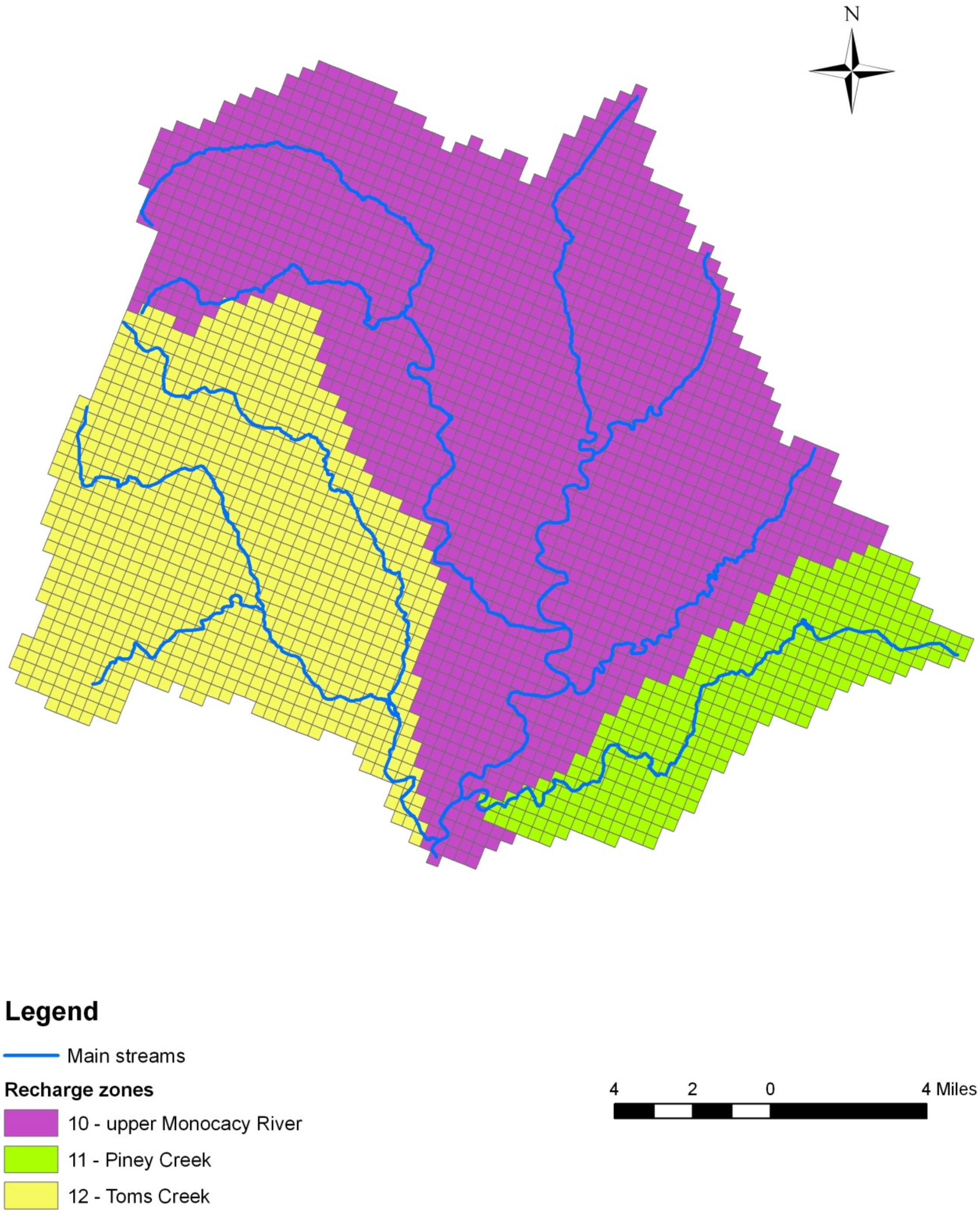

Figure 6. Model recharge zones

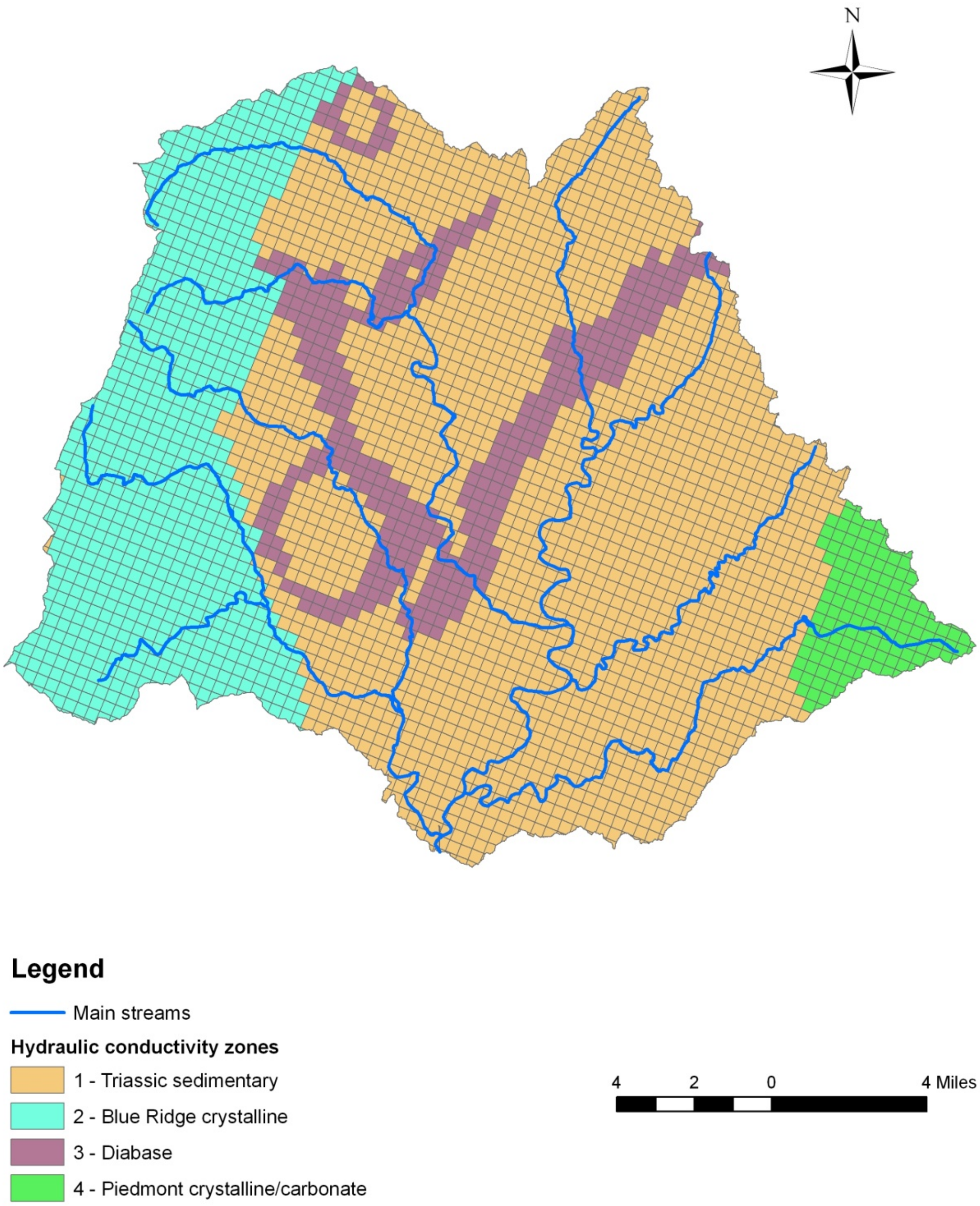

Figure 7. Model hydraulic conductivity zones

Calibration and Verification

The model was calibrated to summer (July, August , and September) well data from the years, 1968, 1969, 1971, 1976, 1981, 1982, 1985, 1987, representing summers with “average” hydrologic conditions, as given in Table 3, with well locations shown in Figure 4. To test the ability of the model to simulate summertime aquifer levels for other hydrologic conditions, four model verification runs were done, using recharge rates representing dry, average-dry, average-wet, and wet conditions, and comparing simulated aquifer levels with well data corresponding to these conditions, from other sets of years listed in Table 3.

Calibration

The model was calibrated by adjusting input parameters to provide the best match between simulated aquifer levels and a calibration dataset consisting of available water level observations for summer months (July, August and September) from years within the study period representing “average” summertime hydrologic conditions, 1968, 1969, 1971, 1976, 1981, 1982, 1985, and 1987, as given in Table 3. Model recharge inputs for the calibration runs, given in Table 4, represented average summertime recharge for the three recharge zones shown in Figure 6. During the calibration process, input parameters representing aquifer and streambed conductivities were adjusted to provide the best fit to available data by using the PEST parameter estimation program developed by John Doherty of Watermark Computing in native DOS mode and as implemented in Ground-water Vistas, and by trial-and-error methods.

Aquifer hydraulic conductivities were defined for each of the ten model layers for each of the four hydrogeologic zones listed in Table 6 and shown in Figure 7. In order to reduce the number of degrees of freedom of the model, horizontal hydraulic conductivities for each layer were assumed to be related to conductivities in layer 1 by proportionality constants that were uniform throughout the model domain. Horizontal conductivities in layer 10 were assumed to be a fixed fraction of the conductivities in layer 1, and this fraction was adjusted during model calibration. Conductivities in intermediate layers were assumed to vary linearly with distance between the values in layer 1 and in layer 10. Horizontal anisotropy was assumed to be uniform throughout each zone of hydraulic conductivity, being 1.0 in all zones except zones 1, representing the Mesozoic Lowland. The Mesozoic Lowland was assumed to have a horizontal anisotropy caused by its tilted sedimentary structure, the strike of which is in the Y-model direction through the rotation of the model grid by 22 degrees East of North. Similarly, vertical anisotropy was assumed to be uniform throughout zones 2, 3 and 4, and the Mesozoic Lowland was assigned a separate value for vertical anisotropy.

Because no data were available on stream leakage rates, streambed conductivities for tributary stream segments were initially assigned to be equal to the assumed hydraulic conductivity of the underlying lithology, and were adjusted during the calibration process. Streambed conductances were computed by MODFLOW from parameters representing streambed conductivities combined with a set of model inputs constructed from estimated values of stream reach lengths, widths, and bed thicknesses.

Final values of aquifer and stream bed conductivities for the calibrated model are given in Table 6. Horizontal conductivities in layer 10 are 1/10th of the conductivities in layer 1, and conductivities in intermediate layers were assumed to vary linearly with distance between the values in layer 1 and in layer 10. In zones 2, 3, and 4, vertical conductivities in each layer of the calibrated model are equal to horizontal conductivities, and in zone 1 they are ½ of horizontal conductivities.

Observed summertime water levels for average hydrologic conditions are compared with predictions of the calibrated model in Table 7 and in Figure 8. These model simulation results are quite good, considering the regional nature of the model. The mean residual was –1.7 m, the standard deviation of residuals was 9.8 m and the correlation was 0.948.

Model stream flow predictions were also compared with observed values at the available gaging stations on the Monocacy River, Toms Creek, and Piney Creek. Results are given in Table 5. Because model recharge inputs were derived from observed base flow for these three streams, the comparison of observed and predicted stream flow is not a true test of the predictive capabilities of the model but rather a test of the assumption, which is only expected to be approximately true, that recharge to each of these three watersheds eventually discharges solely to that watershed's stream. Results in Table 5 show that for average summertime conditions, the calibrated model simulates stream flow accurately for the Monocacy River at Bridgeport and for Toms Creek, but over-simulates flow for Piney Creek by about 7%.

Verification

The ability of the calibrated model to simulate typical aquifer levels observed in years representing other summertime hydrologic conditions was tested in four model verifications runs. In these runs, all model parameters were held at the values determined in the calibration run, with the exception of the three parameters representing net recharge. Recharge inputs for the four verification runs, given in Table 4, are estimates for typical net recharge during dry, average-dry, average-wet, and wet summers. The values were obtained by computing medians of the mean summer base flows from Table 2, for each of the four sets of years given in Table 3 representing these four hydrologic conditions.

For each verification run, simulated aquifer levels were compared with water level observations from available well data from years representing the hydrologic conditions corresponding to the recharge inputs. For example, for the dry summer verification run, recharge for zones 10, 11, and 12 were set at 2.79×10^{-5} m/day, 1.40×10^{-5} m/day, and 1.06×10^{-4} m/day, respectively, from Table 4. Simulated aquifer levels from this run were then compared with mean water levels from all available summer well data for the years, 1962, 1963, 1964, 1965, 1986, 1988, 1991, 1997, 2001, 2002, from Table 3 (with locations shown in Figure 4), which were identified to represent dry summertime conditions.

Verification run results, shown in Figure 8, Figure 9, Figure 10, and Figure 11, and summarized in Table 7, were judged to be quite good, demonstrating that the model can predict changes in aquifers levels due to changes in recharge reasonably well. Verification runs for dry, average-dry, and average-wet conditions had mean residuals, that is, mean differences between observed and simulated aquifer levels, ranging from -3.8 to 1.9 meters, and standard deviations of residuals ranging from 7.8 to 16.5 meters. The verification run for wet conditions was less successful, and over-predicted aquifer levels on average by 19.8 meters.

Stream flows predicted by the verification runs, given in Table 5, were accurate to within 3% for the Monocacy River at Bridgeport and to within 1% for Toms Creek. However, the model over-predicted stream flow for Piney Creek, with errors ranging from 6% for average-wet summers to 45% for dry summers.

Table 5. Stream base flow calibration/verification targets and model predictions

	Dry summer		Ave-dry summer		Ave summer		Ave-wet summer		Wet summer	
	cfs	m3/day	cfs	m3/day	cfs	m3/day	cfs	m3/day	cfs	m3/day
Calibration/verification targets:										
Upper Monocacy River	5.10	1.25E+04	9.18	2.25E+04	14.79	3.62E+04	20.92	5.12E+04	42.34	1.04E+05
Piney Creek	0.46	1.13E+03	2.03	4.97E+03	3.23	7.90E+03	4.52	1.11E+04	7.01	1.72E+04
Toms Creek	4.63	1.13E+04	6.70	1.64E+04	8.89	2.18E+04	10.72	2.62E+04	14.86	3.64E+04
Model predictions:										
Upper Monocacy River		1.26E+04		2.31E+04		3.70E+04		5.19E+04		1.04E+05
Piney Creek		1.64E+03		5.45E+03		8.49E+03		1.18E+04		1.85E+04
Toms Creek		1.14E+04		1.64E+04		2.17E+04		2.62E+04		3.62E+04

Table 6. Final aquifer and streambed conductivity values of calibrated model[3]

Zone	Layer	Aquifer Conductivities Kx (m/day)	Ky (m/day)	Kz (m/day)	Streambed Conductivities (m/day)	Unit
1	1	0.020	0.24	0.01	2.36	Mesozoic Lowland
2	1	0.0088	0.0088	0.0088	0.265	Blue Ridge
3	1	0.010	0.010	0.010	10.0	Diabase
4	1	0.026	0.026	0.026	0.0377	Piedmont Uplands
1	10	0.002	0.024	0.001	NA	Mesozoic Lowland
2	10	0.00088	0.00088	0.00088	NA	Blue Ridge
3	10	0.001	0.001	0.001	NA	Diabase
4	10	0.0026	0.0026	0.0026	NA	Piedmont Uplands

Table 7. Run statistics for calibration and verification run.

	Calibration Run	Verification Runs			
	Ave	Dry	Ave-dry	Ave-Wet	Wet
No. observations	40	75	13	68	16
Minimum residual	-27.3	-28.4	-36.7	-27.6	-101
Maximum residual	27.8	40.7	34.6	15	4.7
Mean residual	-1.7	1.9	-0.1	-3.8	-19.8
Standard deviation of residuals	9.8	15.8	16.5	7.8	26.6
Run statistic	-2.57	-0.69	-0.56	-2.51	NA
Correlation between ordered residuals and normal order statistics	0.948	0.985	0.906	0.977	0.769
R2	0.95	0.8	0.93	0.65	0.84

[3] Note: Kx = hydraulic conductivity in the x-direction, i.e. along model rows, Ky = hydraulic conductivity in the y-direction, along model column, and Kz = hydraulic conductivity in the vertical direction

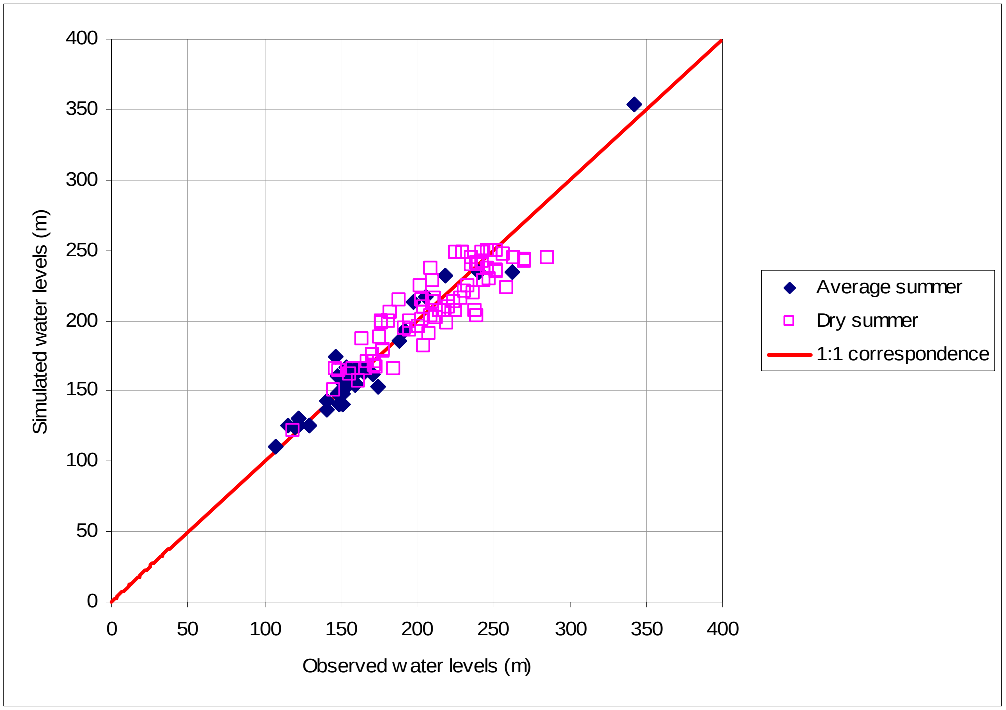

Figure 8. Simulated vs. observed aquifer levels for average and dry summers

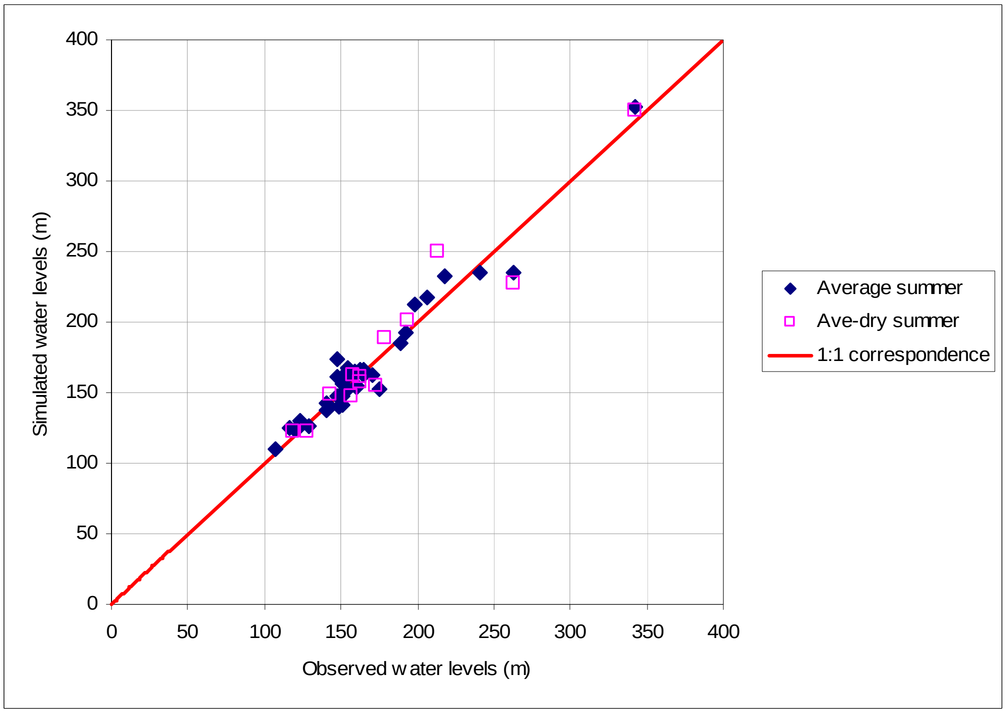

Figure 9. Simulated vs. observed aquifer levels for average and average-dry summers

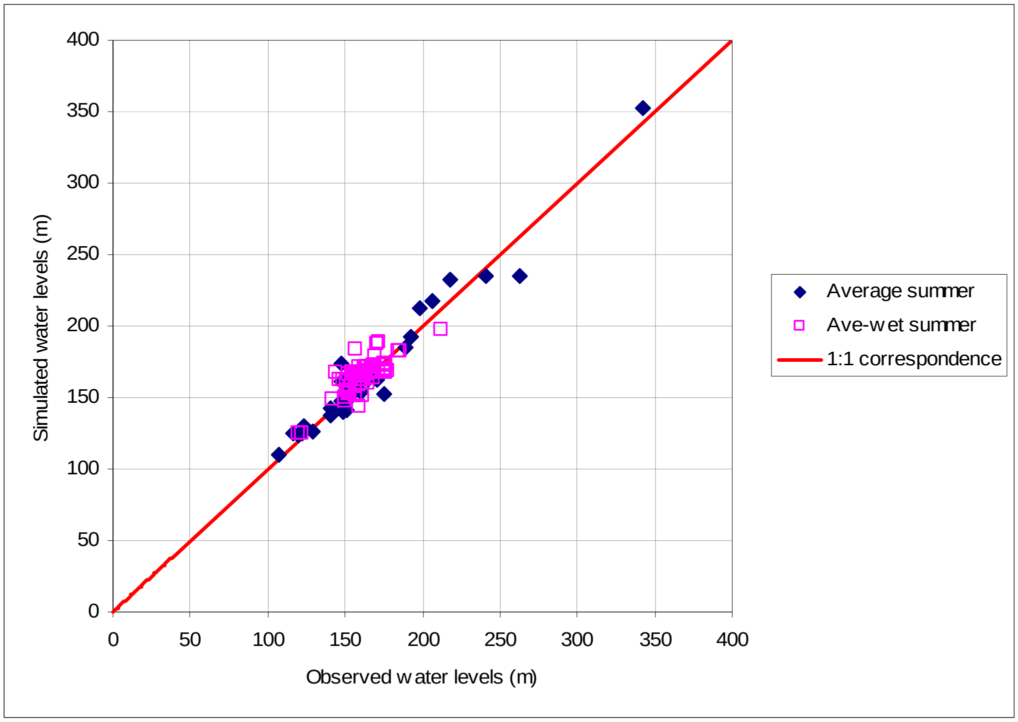

Figure 10. Simulated vs. observed aquifer levels for average vs. average-wet summers

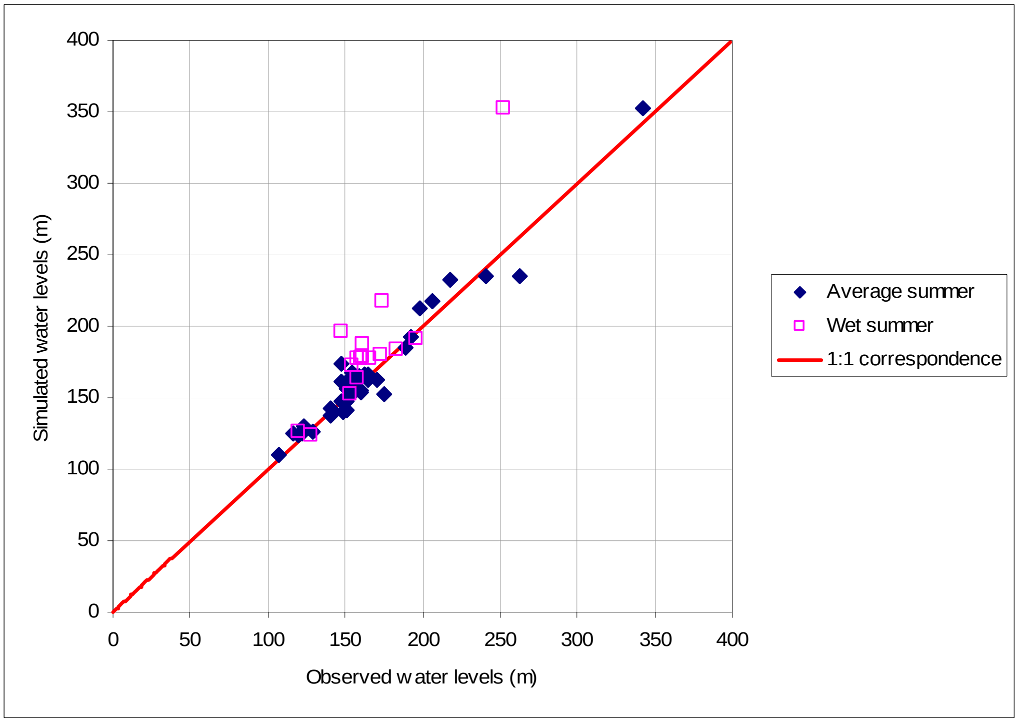

Figure 11. Simulated vs. observed aquifers levels for average and wet summers

Simulation of dry and losing stream reaches

The upper Monocacy ground water/stream flow model output includes predictions of flow into and out of each simulated stream reach. This allows identification for each model run of predicted dry stream reaches and "losing" stream reaches, that is, stretches of streams where the underlying aquifer has dropped to a level below the bottom of the stream bed, causing the stream to lose water due to leakage to the aquifer below. These results are shown in Figures 12, 13, and 14 and summarized in Table 9 for three of the summertime hydrologic conditions of the calibration and verification runs, "wet", "average", and "dry" summers.

Three additional model runs were done to predict potential increases in dry and losing stream reaches during "dry" summers due to future increases in ground water withdrawals throughout the basin. These runs simulate increased ground water withdrawals by reducing net recharge rates uniformly throughout the model domain, to values given in Table 8. Though this spatial representation of new ground water withdrawals is not realistic, because well withdrawals occur at specific locations, it is consistent with the overall design of the model, which assumes that existing withdrawals are reflected by the mean stream base flows values used to simulate net recharge and uses data for model calibration and verification from 43 different years. However, this representation of ground water withdrawals limits the model's ability to accurately simulate aquifer levels at a local scale.

The three additional model runs, labeled scenarios 1, 2, and 3, simulate increases in ground water withdrawals throughout the study area, and corresponding to reductions in net recharge of 0.5 mgd, 1.0 mgd, and 1.5 mgd, respectively, in the combined Marsh/Rock/Alloway Creek watershed – see Table 8. These hypothetical ground water withdrawal increases lead to decreases in mean summertime stream base flow in the Monocacy River at Bridgeport during typical "dry" summers from its historical value of 5.14 cfs to approximately 4.33 cfs for scenario 1, 3.55 cfs for scenario 2, and 2.78 cfs for scenario 3.

Increases in dry and losing stream reaches in the future scenario runs are shown in Figures 15, 16, and 17, and summarized in Table 9. Because the spatial scale of the model is regional, predictions for individual streams, depicted in Figures 12 through 17, are not likely to be reliable, and little information is available to verify the predictions of dry or losing stream reaches. However, the predicted increases in total miles of dry and losing reaches in the upper Monocacy basin, given in Table 9 and shown in Figure 18 indicates that future increases in ground water withdrawals of the magnitude considered in the scenario runs, including on the order of ½ to 1 ½ mgd in the Marsh/Rock/Alloway Creek watersheds, will have a significant impact on basin streams.

Table 8. Recharge inputs for potential future scenario runs, by model recharge zone

	10 - Upper Monocacy River			11 - Toms Creek			12 - Piney Creek		
	mgd	cfs	m/day	mgd	cfs	m/day	mgd	cfs	m/day
Dry	3.30	5.10	2.79E-05	3.00	4.63	1.06E-04	0.298	0.460	1.39E-05
S1	2.80	4.33	2.37E-05	2.54	3.93	9.00E-05	0.253	0.390	1.18E-05
S2	2.30	3.55	1.94E-05	2.09	3.23	7.40E-05	0.207	0.321	9.7E-06
S3	1.80	2.78	1.52E-05	1.63	2.53	5.79E-05	0.162	0.251	7.59E-06

Table 9. Model predictions of miles of dry or losing stream reaches, by summertime hydrologic condition

	Predicted stream miles		Simulated flow at Bridgeport (Station 01639000)			
	Dry	Dry or losing	cfs	mgd	m3/day	m/day
Wet summer - model verification run	2%	5%	42.39	27.42	103,702	2.32E-04
Average-wet summer - model verification run	7%	12%	21.21	13.72	51,885	1.16E-04
Average summer - model calibration run	11%	17%	15.13	9.79	37,021	8.28E-05
Average-dry summer - model verification run	18%	25%	9.42	6.10	23,058	5.16E-05
Dry summer - model verification run	29%	38%	5.14	3.32	12,563	2.81E-05
Dry summer - scenario 1	34%	44%	4.33	2.80	10,587	2.37E-05
Dry summer - scenario 2	37%	47%	3.55	2.30	8,696	1.94E-05
Dry summer - scenario 3	42%	52%	2.78	1.80	6,805	1.52E-05

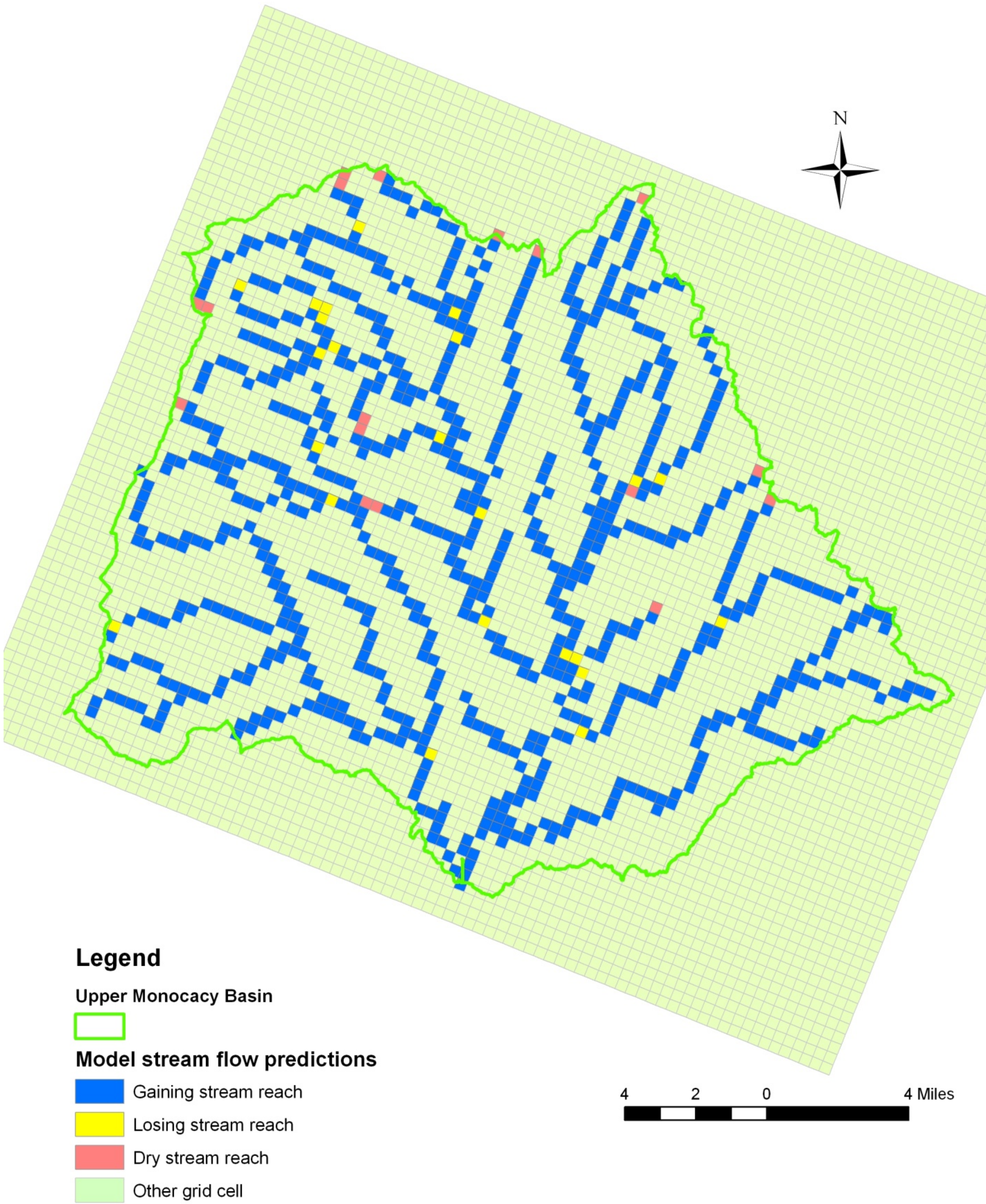

Figure 12. Model predictions of dry and losing stream reaches for wet summers

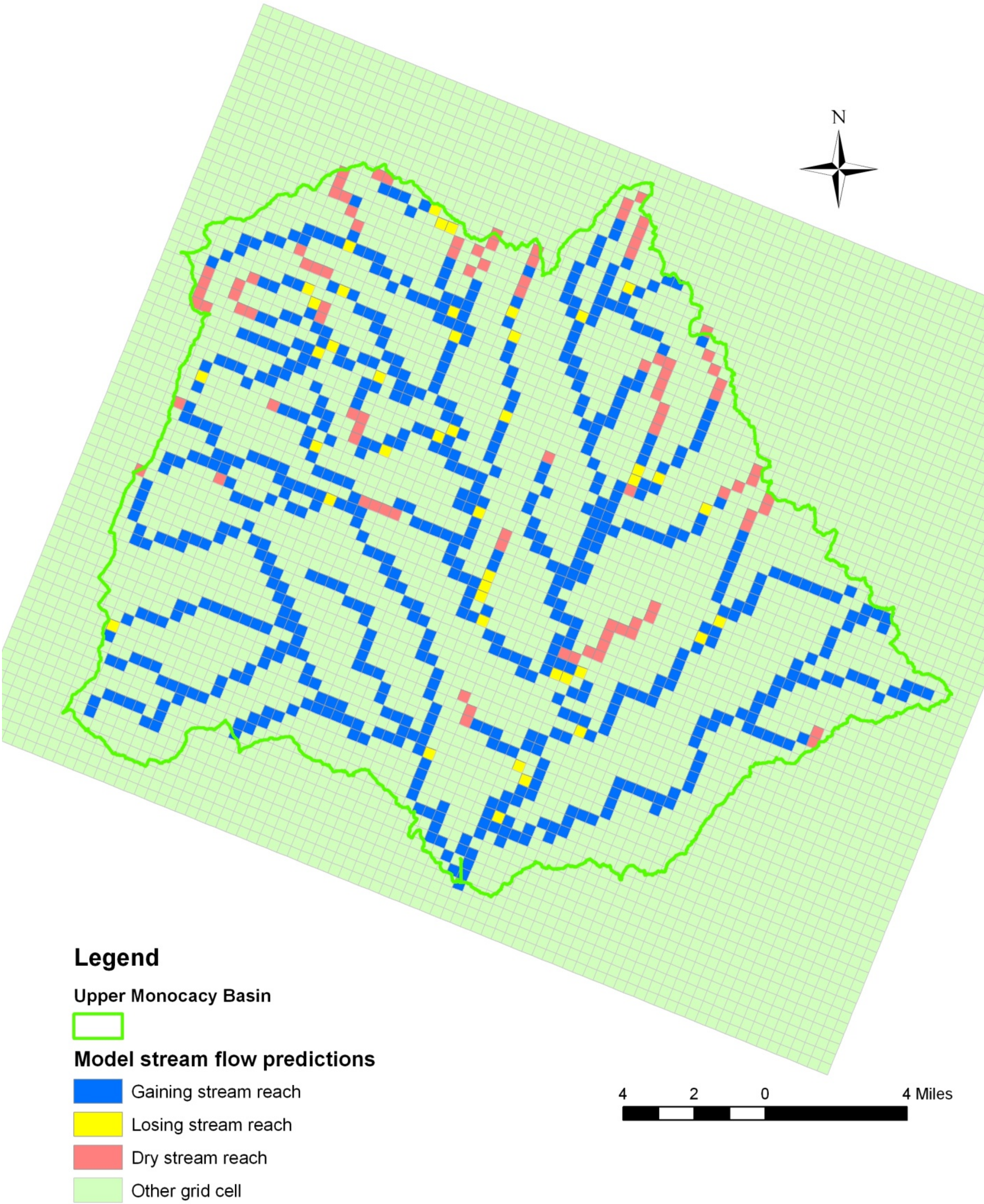

Figure 13. Model predictions of dry and losing stream reaches for average summers

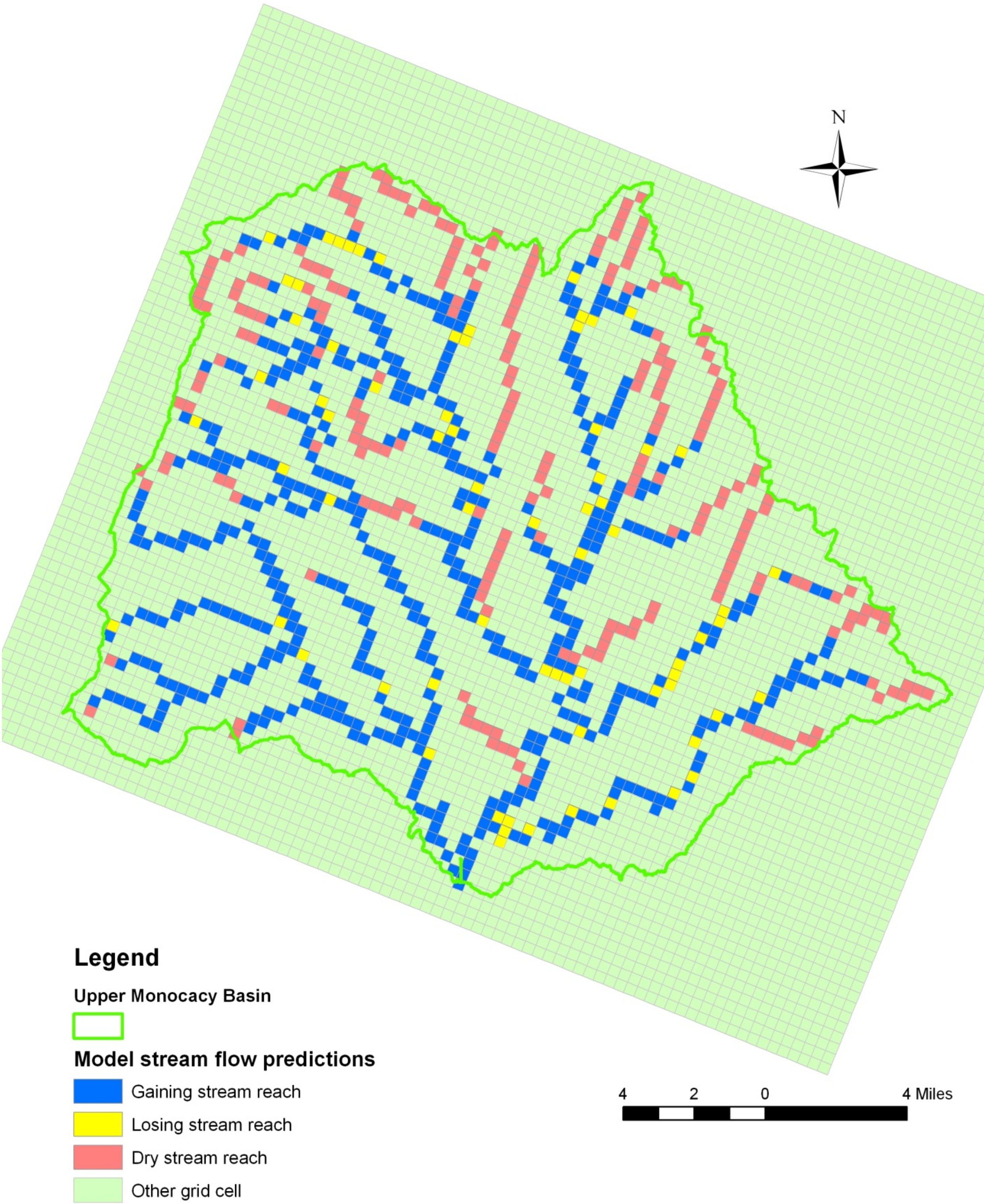

Figure 14. Model predictions of dry and losing stream reaches for dry summers

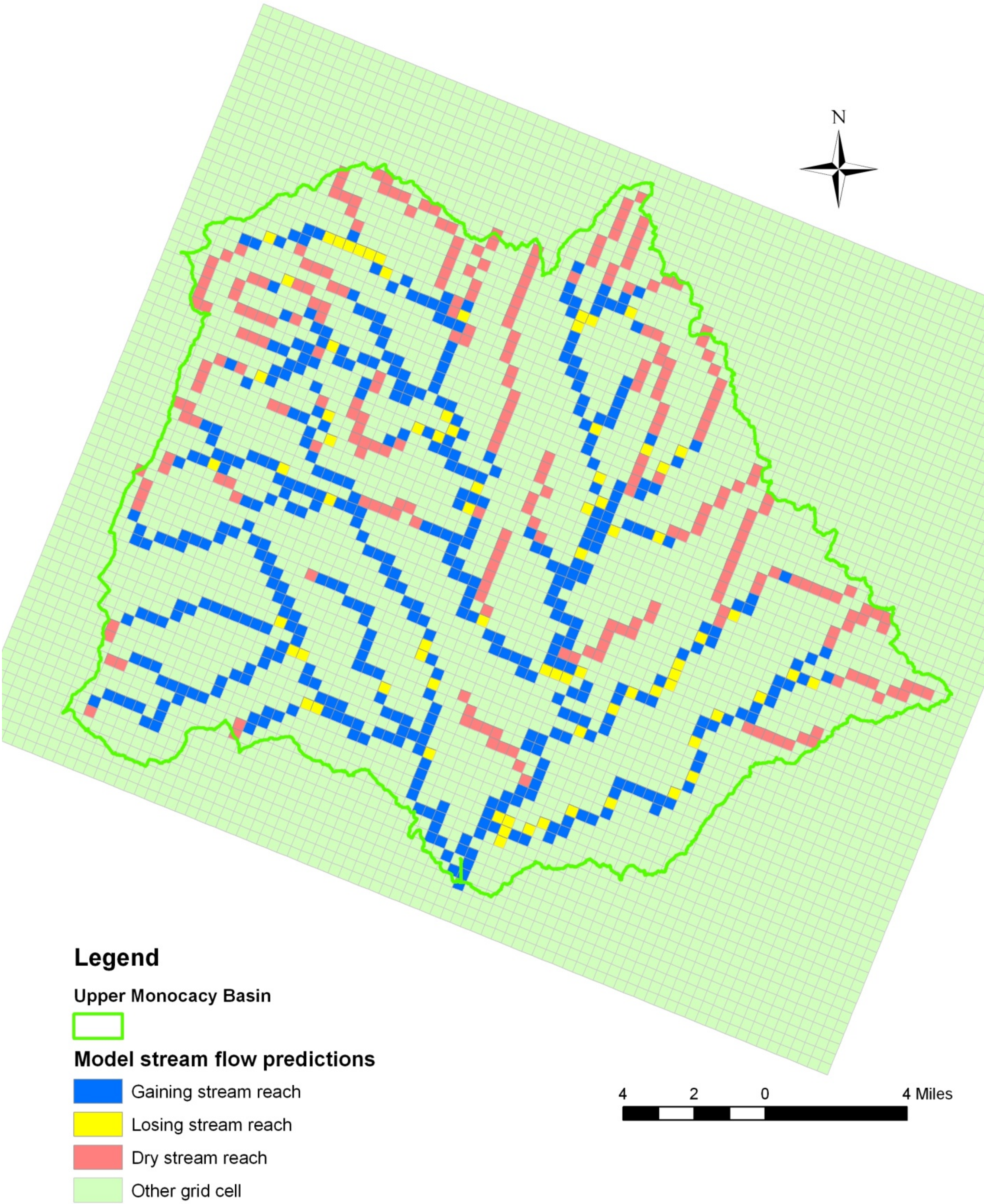

Figure 15. Model predictions of dry and losing stream reaches for dry summers under future scenario 1

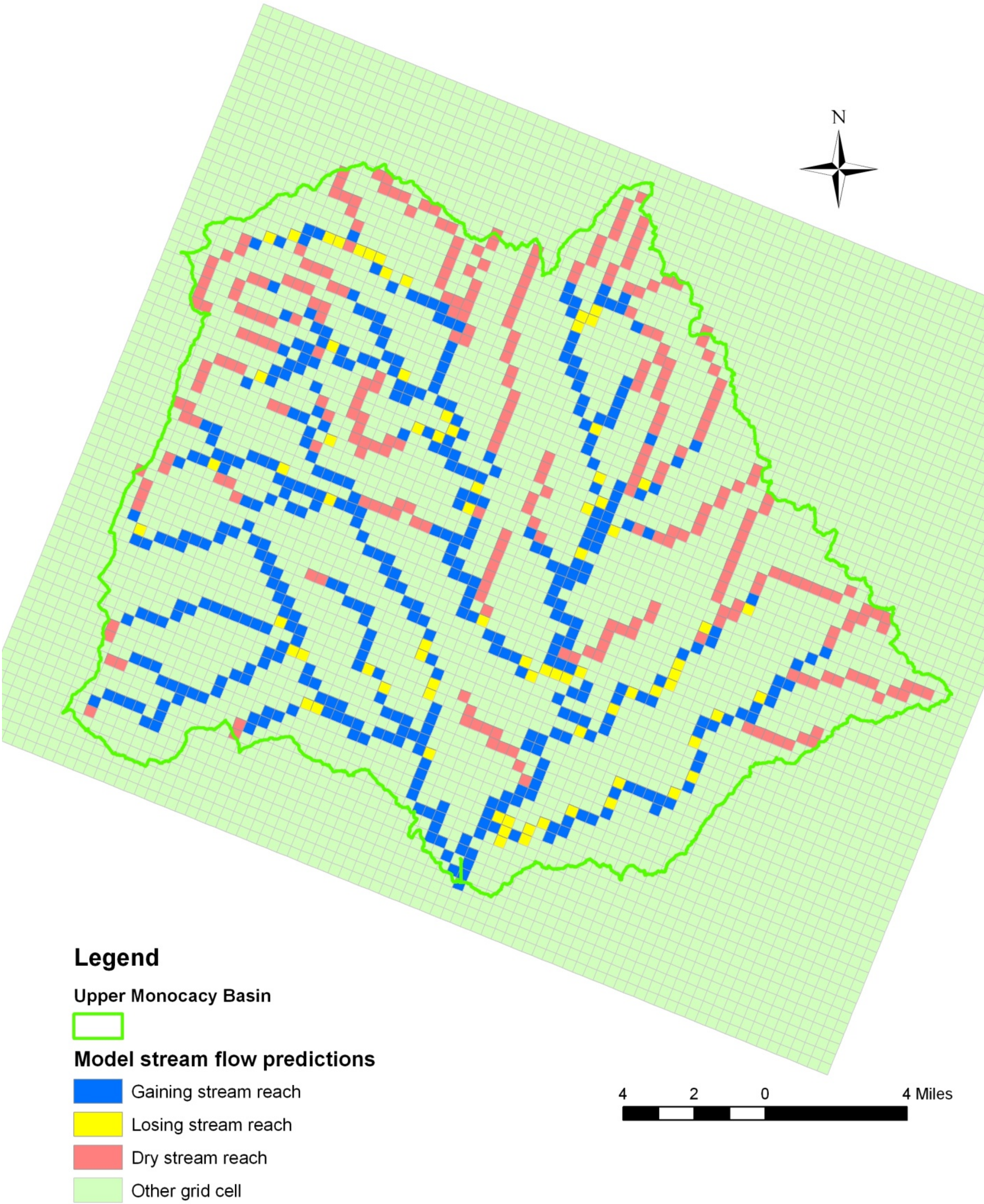

Figure 16. Model predictions of dry and losing stream reaches for dry summers under future scenario 2

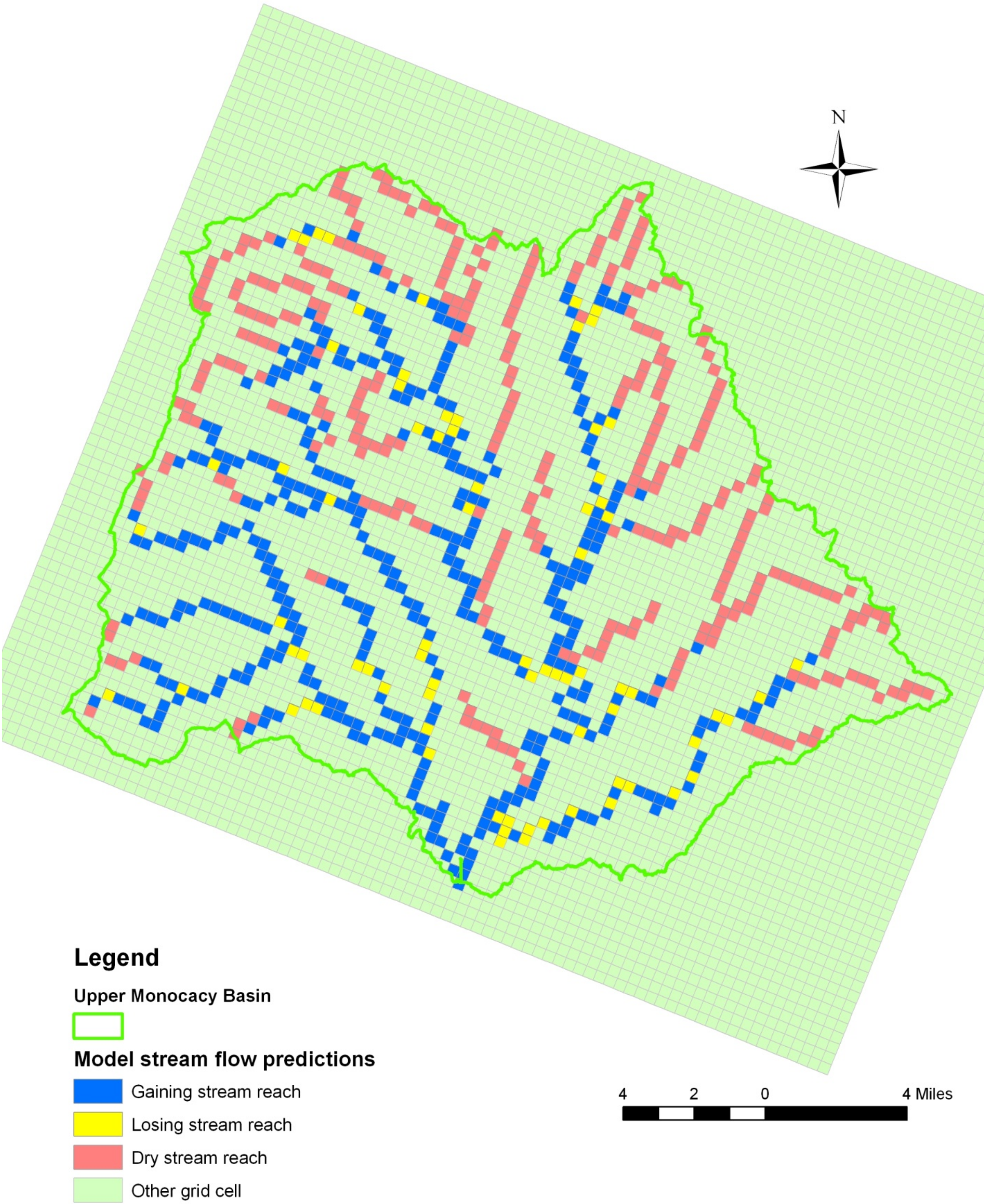

Figure 17. Model predictions of dry and losing stream reaches for dry summers under future scenario 3

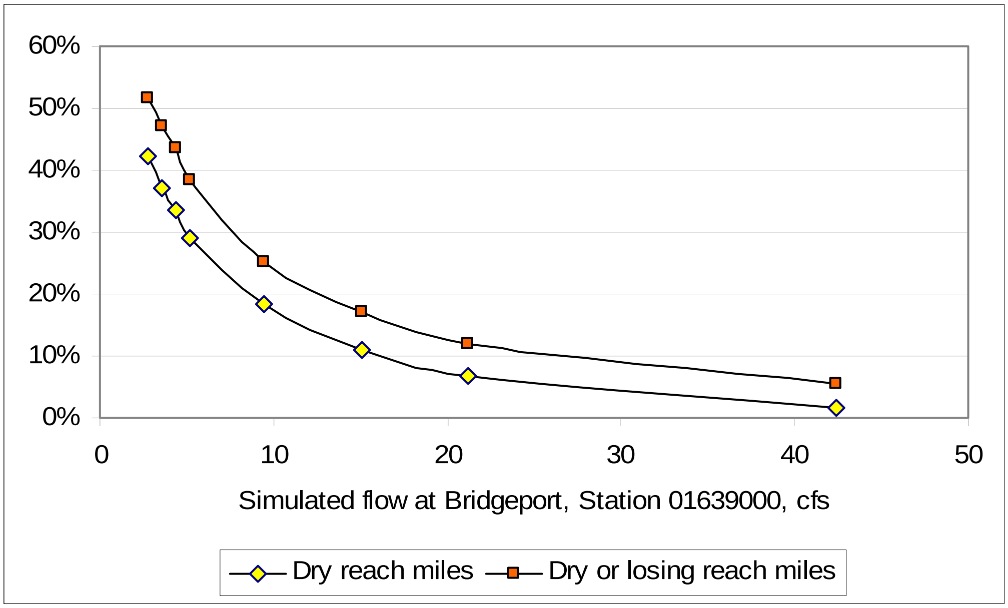

Figure 18. Model predictions of basin-wide percentage of summertime dry/losing stream reach miles for model calibration/verification/scenarios runs

Conclusions

A regional scale steady-state ground water/stream flow model of the upper Monocacy River basin was constructed to investigate the impact of potential basin-wide increases in ground water withdrawals on summertime stream flows. The model is based on available summertime well and stream flow data from a 43-year study period, 1960 through 2002. Results from the study by Schultz et al. (2005) indicate that a steady-state model may provide a reasonable approximation to average summertime conditions in the upper Monocacy basin, because ground water storage at the beginning of the summer is small due to rapid base flow recession rates (where storage is measured from the level associated with zero stream flow). Thus, summertime aquifer levels in this basin are largely determined by summertime recharge.

Because of limitations in available data, well observations and stream flow measurements from eight different years were combined to represent typical conditions during an “average” summer, and this data set was used for model calibration. The mean residual for the calibration run, that is, the mean difference between simulated and observed aquifer levels, was –1.7 m, the standard deviation of residuals was 9.8 m, and the correlation was 0.948. Though the match between simulated and observed aquifer levels in the calibration run was quite good, the scale and the inherent variability of the multi-year calibration data set is expected to limit the accuracy and predictive capabilities of the model.

To further test the model’s ability to simulate summertime aquifer levels, four verification runs were done. In these runs, the model input parameters representing net aquifer recharge were changed to reflect estimated recharge corresponding to dry, average-dry, average-wet, and wet summers, and simulated aquifer levels were compared with water level observations from sets of years in the study period which represented hydrologic conditions corresponding to the recharge inputs. Results of the verification runs for dry, average-dry, and average-wet summers were good, though aquifer levels were over-estimated for wet summers. Model calibration and verification runs indicate that for dry to average-wet hydrologic conditions, the model can predict mean aquifers levels in the upper Monocacy basin to within 2 or 3 meters. However, at any given location in the basin, predicted aquifer levels are only likely to be within 20 to 30 meters of observed levels.

Model stream flow predictions were also compared with observed values at the available stream flow gaging stations on the Monocacy River, Toms Creek, and Piney Creek. Because model recharge inputs were derived from observed base flow for these three streams, the comparison of observed and predicted stream flow is not a true test of the predictive capabilities of the model but rather a test of the assumption, which is only expected to be approximately true, that recharge to each of these three watersheds eventually discharges solely to that watershed’s stream. Results show that for all simulated summertime conditions, stream flow is accurately predicted for the Monocacy River at Bridgeport and for Toms Creek, but is over-simulated for Piney Creek.

The calibrated model was used to predict dry stream reaches and "losing" stream reaches, that is, stretches of streams where the underlying aquifer has dropped to a level below the bottom of the stream bed, causing the stream to lose water due to leakage to the aquifer below. Model runs were done to predict the number of miles dry and losing stream reaches for the five categories of summertime hydrologic conditions defined in this study, and to predict changes due to potential future increases in ground water withdrawals throughout the basin, simulated by reducing net recharge uniformly throughout the model domain. Three future scenarios were simulated, corresponding to increases in ground water withdrawals of approximately 0.5 mgd, 1.0 mgd, and 1.5 mgd in the combined Marsh/Rock/Alloway Creek watershed. For stream reaches represented in the model, the basin-wide percentage of dry or losing stream miles during dry summers is predicted to increase from approximately 40% to approximately 50% for the third scenario, as shown in Figure 18.

The accuracy of the upper Monocacy ground water/stream flow model is expected to be limited, especially in its predictions of local conditions. These limitations in accuracy stem from the regional scale of the model and the lack of detailed data on geologic structure. In addition, there is a lack of water level observation data and little information or data to verify the stream flow predictions of the model calibration and verification runs. However, the predicted increases in total miles of dry and losing reaches in the upper Monocacy basin shown in Figure 18 and Table 9 may be indicative of the impact that future increases in ground water withdrawals will have on basin streams.

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Appendix A

Instantaneous flow measurements were taken for this project by USGS staff from the Pennsylvania Water Science Center in New Cumberland, Pa. Measurements were made on both Marsh Creek and on Rock Creek on six separate days in 2007 and 2008. The Marsh Creek measurements were taken at a site just south of the Mason Dixon Road bridge at: Latitude 39 deg. 43 min. 41 sec. N, Longitude 77 deg. 15 min. 24 sec. W. The Rock Creek measurements were taken at a site just south of the Mason Dixon Road bridge at: Latitude 39 deg. 43 min. 47 sec. N, Longitude 77 deg. 13 min. 48 sec. W. The locations of these flow measurement sites are depicted in Figure 2 of this report. The data are summarized in Table A-1, below.

The Marsh and Rock Creek flow measurements were taken at times believed to represent base flow conditions. These tributary flows were compared with instantaneous flows measured downstream at USGS Station 01639000 at Bridgeport, Maryland. The drainage areas above the Marsh Creek and Rock Creek measurement sites are 77.8 and 60.0 mi^2, respectively, representing 45% and 35%, respectively of the 173.0 mi^2 drainage area associated with flow measurements at the Bridgeport gage. Each of the six Marsh and Rock flow measurements were compared with simultaneous instantaneous flow measurements at the Bridgeport gage by computing percentages. The mean percentages for each location are given in Table A-2, along with 95% confidence intervals. The flow measurements on Marsh Creek represented 39% of the flow measured at the Bridgeport gage, on average, which is slightly less than would be expected based on the relative size of the corresponding drainage areas. The flow measurements on Rock Creek represented 41% of the flow measured at the Bridgeport gage, on average, which is slightly more than would be expected. Statistical hypothesis tests were also done, and it was found that the measured flows on Marsh and Rock Creeks, as a percentage of the flow at the Bridgeport gage, did not differ significantly from the values expected from area adjustments, 45% and 35%, respectively. This lack of statistical significance is likely due to the small sample size.

Table A-1. Flow data from Marsh and Rock Creek, Adams County, Pennsylvania[4]

DateTime	Measured flow, cfs	Bridgeport instan-taneous flow, cfs	Bridgeport daily flow, cfs	Comments
Marsh Creek at Mason Dixon Road:				
8/27/07 11:58	8.8	35	34	Bridgeport instantaneous flow from USGS Instantaneous Data Archive.
10/10/07 9:45	0.33	2.1	2.2	Bridgeport instantaneous flow from USGS provisional data.
11/2/07 9:25	4.0	9.6	9.7	Bridgeport instantaneous flow from USGS provisional data.
12/12/07 9:05	42.7	92	106	Bridgeport instantaneous flow from USGS provisional data.
1/28/08 9:50	18.2	37	35	Bridgeport instantaneous flow from USGS provisional data.
3/17/08 10:36	89.9	152	154	Bridgeport instantaneous flow from USGS provisional data.
Rock Creek at Mason Dixon Road:				
8/27/2007 10:49	17.1	36	34	Bridgeport instantaneous flow from USGS Instantaneous Data Archive.
10/10/2007 8:45	0.71	2.1	2.2	Bridgeport instantaneous flow from USGS provisional data.
11/2/2007 8:25	5.2	10	9.7	Bridgeport instantaneous flow from USGS provisional data.
12/12/2007 8:05	43.5	93	106	Bridgeport instantaneous flow from USGS provisional data.
1/28/2008 8:48	13.7	37	35	Bridgeport instantaneous flow from USGS provisional data.
3/17/2008 9:29	43.1	155	154	Bridgeport instantaneous flow from USGS provisional data.

[4] Data transmitted by Robert Hainly, USGS, Pennsylvania Water Science Center, New Cumberland, Pa.

Table A-2. Means of Marsh and Rock Creek measured flows as percentage of flow at USGS Station 01639000, at Bridgeport, Md.

			Means and 95% confidence intervals for flows as a percentage of flow at Bridgeport station		
	Drainage Area, mi2	Drainage Area, % of Bridgeport station	Mean	Lower limit of confidence interval	Upper limit of confidence interval
Marsh Creek site:	77.8	45%	39%	26%	52%
Rock Creek site:	60	35%	41%	33%	48%
Marsh + Rock:	137.8	80%			
Monocacy River at Bridgeport (USGS Station 01639000):	173	100%			