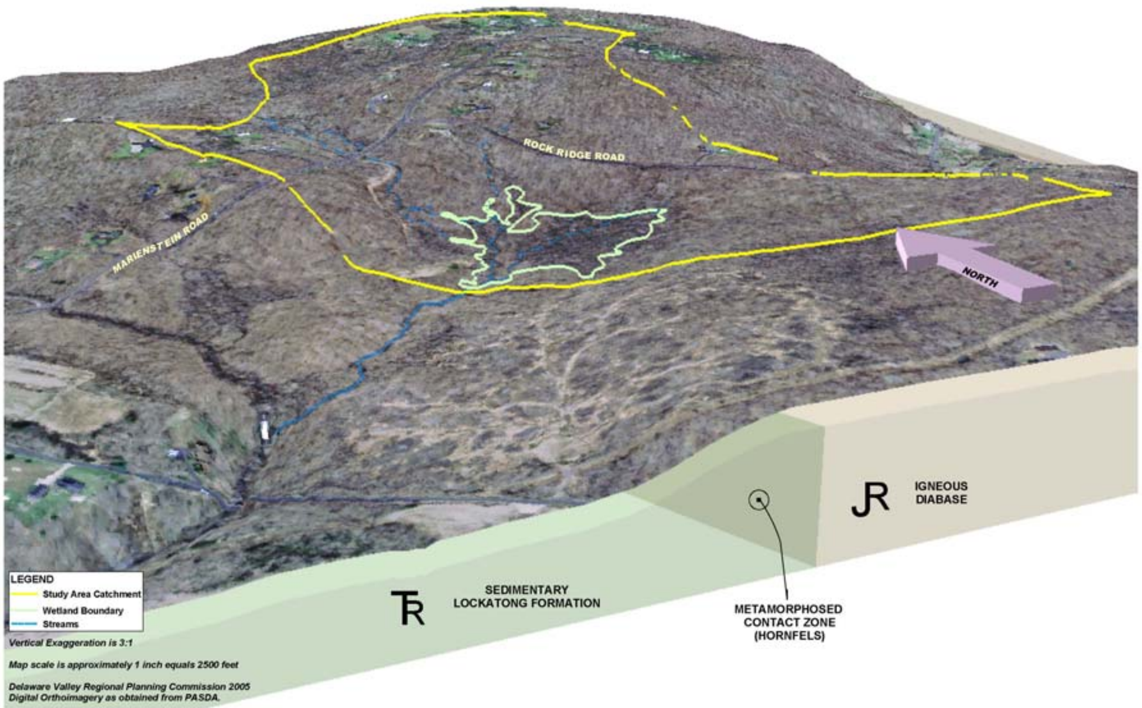
GROUNDWATER RECHARGE ASSESSMENT IN DIABASE TERRANE – IMPLICATIONS FOR POTABLE WATER SUPPLY AND NATURAL RESOURCE STEWARDSHIP IN BUCKS COUNTY, PENNSYLVANIA



PREPARED FOR:

Bridgeton – Nockamixon – Tinicum Joint Groundwater Committee

Tinicum Creek Watershed Wetlands Protection Development Program

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1 ABSTRACT

This report describes investigations in a Rapp Creek (northern Bucks County, Pennsylvania) headwaters catchment that occurred from 2005 through 2008 with the primary objective of characterizing interactions between surface and groundwater flow systems. This study included development of a water budget to account for the various hydrologic inputs, outputs, and storage components. Additional lines of evidence were derived using stream flow frequency and baseflow analysis methods to characterize water movement and water storage traits. Lastly, because amphibians respond primarily to water-based environmental cues, the local salamander community was surveyed repeatedly in the study setting in order to correlate its members' occurrence along a hydrologic gradient.

Findings of this study demonstrated that most rain and snow that enters headwaters catchments in Coffman Hill diabase terrane remains near the land surface. Following a rain (or melt) event, part of the water in the setting rapidly flows out through a network of small stream channels. Storage capacity in the headwaters catchment is limited due to the thin veneer of soil and the clay-dominated soil types that prevail. On a somewhat delayed basis, additional water also moves laterally and continuously through the thin (10 to 15 feet thick), shallow soil layer between the land surface and the top of bedrock. These local groundwater flowpaths discharge into headwaters wetlands, springs, and streams; their discharge rates adhere to seasonal patterns. Even during seasonal periods in which evapo-transpiration demands are low, the residence time for groundwater that infiltrates the soil is less than 45 days.

The outcome of this study is consistent with a potential for deep groundwater recharge of not more than one or two inches per year; equivalent to less than 5% of annual precipitation. Moreover, this study demonstrates that the functional hydrologic role of wetlands in diabase terrane is both to provide temporary, seasonal water storage and to serve as outlets from which shallow groundwater flowpaths drain the local landscape.

Stream-dependent salamander richness and abundance across all life stages is maximized at groundwater discharge settings and minimized where hydroperiod becomes interrupted in the catchment.

In diabase terrane, the local flowpath structure is vital to the integrity of aquatic resources (e.g., streams, wetlands, springs); however, local flowpaths exert little to no influence on the deep groundwater zones that serve as potable supply in the region. Because local groundwater flowpaths dominate the headwaters catchment settings, proper stewardship of the diabase region's *exceptional* natural resources warrants implementation of management strategies that ensure the integrity of the shallow groundwater zone. However, the shallow groundwater zone is functionally tied to the integrity of forest, spring, wetland, and stream in the diabase headwaters.

Although preliminary, this study also suggested that the potential exists to conduct targeted, "rapid" salamander surveys within forested headwaters catchments during early spring in order to readily identify and map the overall hydroperiod status of the catchment.

TABLE OF CONTENTS

ABBREVIATIONS/GLOSSARY

Baseflow – proportion of stream flow derived from discharging groundwater

bgs – below ground surface

BNT – Bridgeton Nockamixon Tinicum Township Joint Groundwater Management Committee

Catchment – portion of a watershed that encompasses surface drainage to a particular point

CH – Coffman Hill diabase, a massive, regional Jurassic-age igneous rock intrusion that underlies portions of Bridgeton, Nockamixon, and Tinicum Townships

ET – evaporation and transpiration

EV – Exceptional Value designation, highest protective measure afforded to a watershed

GIS – geographic information system

GPS – global position satellite

GSI – groundwater:surface water interface, used herein to refer to discharge of groundwater into streambed, wetland, or spring

HGM – hydrogeomorphic, wetland classification scheme based on landscape position, water source, and dynamics of water exchange

Hydrograph – time series chart that depicts water level, water elevation, or water discharge

Hydroperiod – timing of water available for discharge/flow in spring and stream or soil moisture regime consistent with wetland jurisdictional definition

ISSD – Individual subsurface disposal unit, septic system

msl – mean sea level

NRCS – Natural Resources Conservation Service

PET – potential evapo-transpiration

PZ – piezometer, a narrow tube device used to measure groundwater depth

Q – discharge

Recharge – water that enters a subsurface/groundwater zone

RG – rain gauge

SG – staff gauge

SGL56 – (Pennsylvania) State Game Lands no. 56

Terrain – reference to topographic features of landscape

Terrane – reference to landscape in the context of a geological control

USACE – United States Army Corps of Engineers

USGS – United States Geological Survey

2 INTRODUCTION

Concerns regarding groundwater infiltration and recharge are increasingly common components of regional water resource and watershed management plans. Effective management of potable water supplies as well as proper stewardship of natural resources requires an understanding of an area's hydrologic framework. It becomes especially important to distinguish the various flowpaths by which water moves in three dimensions across and through the landscape.

In northern Bucks County, Pennsylvania, the Joint Township (Bridgeton, Nockamixon, Tinicum Townships) Groundwater Management Committee (hereinafter, the BNT Committee) was created to allow participating municipal members to better understand their water resources. With partial funding provided by the United States Environmental Protection Agency (USEPA), the BNT Committee commissioned a hydrologic study in the Rapp Creek watershed.

Rapp Creek is part of the 17 square mile Tinicum Creek watershed. The Rapp Creek watershed was designated *exceptional value* (EV) status by the Commonwealth of Pennsylvania. In addition to its EV status, Rapp Creek is encompassed by the Lower Delaware Wild and Scenic River designation; both declarations provide a management framework for strict anti-degradation limits as well as one that furnishes protections for natural resources.

The current study was performed in part of the Rapp Creek watershed that is entirely underlain by a massive igneous bedrock formation, the Coffman Hill (CH) diabase sheet intrusion. Above the CH diabase, a thin layer (10 to 15 feet thick) of clay-rich soil type with limited groundwater storage capacity occurs. Additionally, the CH diabase is a solid, nearly impenetrable monolith that restricts groundwater infiltration and subsequent recharge to supply aquifer zones. This study concludes that deep groundwater recharge (i.e., to potable supply zones) on CH diabase accounts for a minor or negligible fraction of annual precipitation.

This report describes investigations in a Rapp Creek headwaters catchment that occurred from 2005 through 2008 with the primary objective of characterizing interactions between surface and groundwater flow systems. This study included development of a water budget to account for the various hydrologic inputs, outputs, and storage components. Additional lines of evidence were derived using stream flow frequency and baseflow analysis methods to characterize water movement and water storage traits. Lastly, because amphibians respond primarily to water-based environmental cues, the local salamander community was surveyed repeatedly in the study setting in order to correlate its members' occurrence along a hydrologic gradient.

Findings of this study demonstrated that most rain and snow that enters headwaters catchments in CH diabase terrane remains near the land surface. Following a rain (or melt) event, part of the water in the setting rapidly flows out through a network of small stream channels. On a somewhat delayed basis, additional water also moves laterally and continuously through the thin, shallow soil layer between the land surface and the top of bedrock. These local groundwater flowpaths discharge into headwaters wetlands and streams; their discharge rates adhere to seasonal patterns.

From November through early May, water enters the headwaters catchment at a faster rate than it departs, thereby resulting in a short-term build-up (i.e., storage) of groundwater. This short-term storage excess raises the water table, generates higher average stream discharge rates, and saturates and even inundates wetlands. Conversely, from May through November, evaporation and plant transpiration (collectively, evapo-transpiration) processes eclipse the rate at which water enters the headwaters catchment, thereby lowering the water table, reducing and even stopping stream and spring flows, and drying wetland soils.

The outcome of this study is consistent with a potential for deep recharge of not more than one or two inches per year; equivalent to less than 5% of annual precipitation. Moreover, this study demonstrates that the functional hydrologic role of wetlands in CH terrane is both to provide temporary water storage and to serve as outlets from which shallow groundwater flowpaths drain the local landscape.

The findings of the current study contradict earlier work performed by URS (2003); specifically, by revealing that wetlands in CH terrane primarily function as groundwater discharge rather than recharge settings. The current study also refines findings by others (i.e., Sloto and Schreffler 1994; Low et al 2002; Risser et al 2005) regarding groundwater recharge rates in Bucks County diabase terrane – principally, because of its finer spatial scale resolution, this study distinguished local, shallow groundwater flowpaths from those with likelihood for intermediate and deep aquifer recharge. In diabase terrane, the local flowpath structure is vital to the integrity of aquatic resources (e.g., streams and wetlands); however, local flowpaths exert little to no influence on the deep groundwater zones that serve as potable supply in the region. Implicit in the finding that local, shallow flowpaths dominate diabase terrane hydrology, is that recharge to deeper (i.e., intermediate and regional) flowpaths occurs elsewhere.

2.1 Site Setting

Bridgeton, Nockamixon, and Tinicum Townships are situated in the northern portion of Bucks County, Pennsylvania, in the Newark Basin Physiographic Province. Portions of each of the BNT municipalities are underlain by the early Jurassic-age CH diabase sheet, a near-monolithic igneous rock mass that was intruded as a sill into pre-Jurassic sedimentary host formations in the Newark Basin. The CH diabase sheet resists weathering and consequently forms a prominent, broadly oval-shaped, topographic landform in northern Bucks County. The CH diabase sheet dimensions are approximately 3.8 miles by 5 miles; thicknesses range from approximately 80 to 115 feet near the margins to 300 to 600 feet for interior portions (Sloto and Schreffler 1994). Due to its relative resistance to weathering processes, the CH diabase exhibits a generally convex landform that supports an array of headwaters drainage channels. Streams that originate on the CH diabase flow radially toward the diabase margins; all such streams drain to the Delaware River, a federally-designated Wild and Scenic River in this reach.

For this study, a low-order, headwaters tributary network to Rapp Creek was selected for study to better understand the mechanisms and timing for groundwater movement within areas underlain by CH diabase. Rapp Creek, designated EV status by the Commonwealth of Pennsylvania, is a tributary to Tinicum Creek. The approximately 150 acre study area was predominantly forested and typical of the region and included a mosaic of upland and wetland settings. The area is underlain entirely by CH diabase bedrock, although bedrock did not outcrop within the study area.

Figure 1 provides landscape context information regarding the site location.

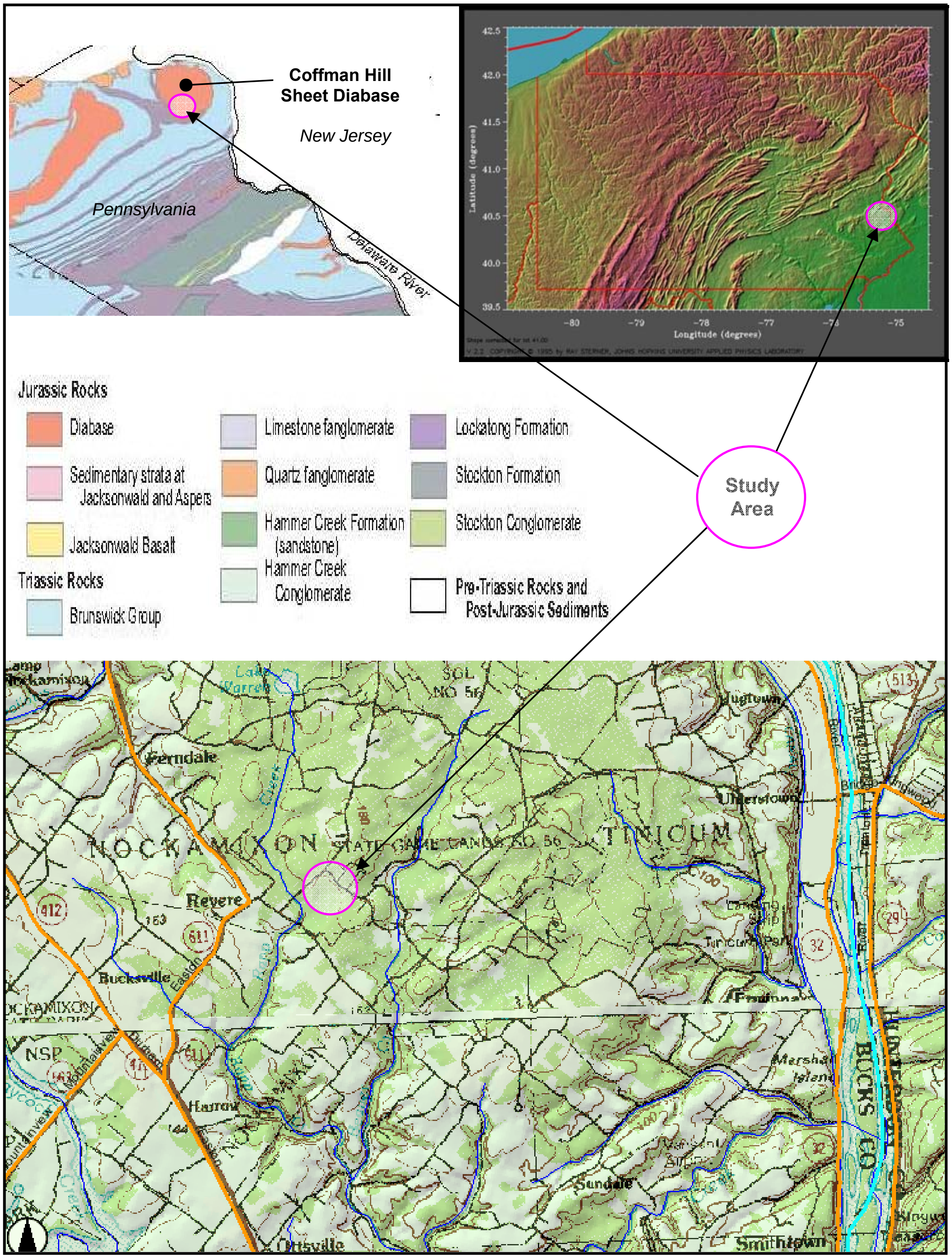


FIGURE 1. Site location depicted by circles on shaded relief (upper right), bedrock geology (lupper left), and topographic (bottom) base images.

Maximum elevation on the CH diabase is approximately 825 feet above mean sea level (msl). Maximum local relief occurs along the northern edge of the diabase where elevation descends along a steep escarpment from more than 600 feet to the elevation of the Delaware River flood plain – approximately 150 feet above msl.

CH diabase is characterized as dark gray to black, fine to coarse-grained crystalline, and composed mainly of calcic plagioclase and augite minerals. CH diabase becomes finer-grained with proximity to the sill's chilled margins. The intrusion occurred under a regime of high temperature and low pressure; a hornfels-dominated metamorphic halo characterizes the contact zone. Where exposed, the diabase weathers to large, spherical boulders that in turn, break down to buff-colored granular sand. The primary weathering end-product of the diabase is reddish-colored swelling clays that are dominated by montmorillonite.

The diabase bedrock lacks primary porosity; groundwater flow and storage occur via secondary porosity structures only. Because of its relatively young age (i.e., the intrusion followed most of the regional structural deformation episodes) and inherent weathering resistance, secondary porosity features in the diabase are restricted primarily to its uppermost depths. Working at a contaminated site situated approximately one mile northeast of the study area, Schreffler (1996) reported that potential water-bearing fractions in the CH were restricted to the uppermost 30 feet rind. Sloto and Schreffler (1994) reported that CH fracturing rarely exceeds 100 to 150 feet depths.

The clay-rich diabase soils contribute to relatively rapid rates of near-surface storm runoff. The prevalence of clay soil types coupled with limitations to groundwater flow and storage potential in the bedrock lead to development of local (i.e., shallow) flowpath system dominance. Again, working near the study area in CH diabase terrane, Schreffler (1996) reported that the overburden thickness ranged from 2 to 14 feet below ground surface (bgs); a weathered rock zone ranged from 2 to 15 feet bgs; and, the overburden soil lacked water.

Most streams in the diabase terrane exhibit gaining status and act to drain well-connected groundwater – surface water systems (Sloto and Schreffler 1994). Additionally, the clay-rich soil types are not well-suited to agriculture (most land "on the diabase" is forested).

Rapp Creek and Beaver Creek are adjacent watersheds that both originate in CH diabase. The confluence of Rapp and Beaver Creeks forms the main stem of Tinicum Creek. The Tinicum Creek watershed encompasses 17 square miles and as mentioned, the entire watershed was designated EV status by the Commonwealth of Pennsylvania. In addition to its EV status, the Tinicum Creek watershed is included in the Lower Delaware Wild and Scenic River designation and includes anti-degradation as well as protection of natural resources.

2.2 Conceptual Model

Interactions between surface and groundwater define the hydrologic framework in a headwaters catchment. *Recharge* refers to water that infiltrates the land surface and replenishes groundwater. Recognition that water moves within the subsurface according to different flowpaths is inherent to quantify recharge and characterize groundwater: surface water interactions (GSI). Moreover, physical flowpaths determine residence time for water movements in a three-dimensional space.

Figure 2 illustrates the physical pathways involving precipitation after it reaches the land surface. Inherently, local hydrologic flowpaths are expected to dominate in headwaters catchments. Except where conduit flow occurs, local groundwater flowpaths (e.g. no. 3

depicted in Figure 2) are shorter and briefer than intermediate (no. 4) and regional (no. 5) groundwater flowpaths. Note that in diabase terrane, flowpath nos. 4 and 5 are expected to be uncommon or altogether nonexistent.

The hydrological response to rainfall in forested headwater catchments results predominantly in generating subsurface lateral flow through shallow, *biotic zone* soil horizons (Shanley et al. 2002). The biotic zone[1] soil typically is characterized by high transmissivity due to networks of well-connected macropores (i.e., root traces, animal burrows, freeze-thaw openings, etc) as well as a soil structure that facilitates water infiltration and water holding capacity. Moreover, near-surface soil horizons often exhibit greater transmissivity than underlying layers.

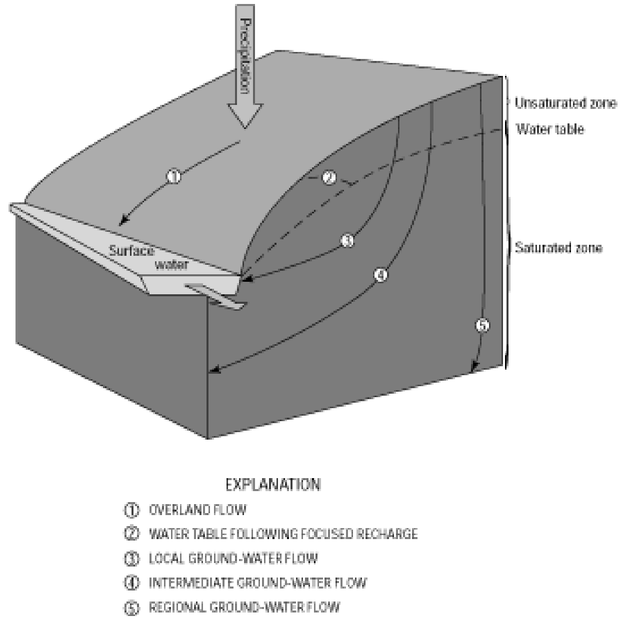


FIGURE 2. Variation among flowpath types.

The water table level in a given area results from the balance of long-term recharge and discharges to the surface due to springs, streams, plant transpiration, and evaporation. Seasonally, the water table is closer to the land surface during periods of high net rainfall[2] and deeper during periods of low net rainfall; consequently, recharge is expected to vary seasonally and to correlate to water table level.

2.3 Literature Review

Low et al. (2002) reported that topography-controlled, local flowpaths dominate groundwater movements in the Newark Basin and that the local flowpath system discharges to nearby springs, wetlands, and streams. Low et al. also concluded that precipitation was the main groundwater source and that most annual recharge occurs from late fall to early spring (due to low net ET).

Sloto and Schreffler (1994) inferred that stream reaches on the CH diabase effectively drained their catchments due to predominance by networks of short, shallow flowpaths. Slotto and Schreffler also reported that domestic wells installed on the CH diabase sheet connected to either of two water-bearing zones: (1) within the upper contact margin between bedrock and overlying unconsolidated material and (2) from within sedimentary bedrock formations that underlie the CH diabase sheet; implicit evidence that CH diabase lacks appreciable storage and/or transmissivity.

Based on an assumption that steady-state stream flow conditions represent the approximation of net groundwater recharge for discharging portions of a catchment, Sloto and Schreffler (1994) calculated regional baseflow that ranged from 6.7 to 10.5 inches/year.

[1] Biotic zone generally encompasses uppermost 2 to 3 feet bgs.
[2] Net rainfall refers to difference between precipitation and evapo-transpiration processes.

Using two different hydrograph separation techniques, Risser et al. (2005) reported annual groundwater recharge rates that ranged from 6.7 to 9.8 inches for two gauged stations located on Tohickon Creek (i.e., watershed adjacent to Tinicum Creek). Baseflow to Tohickon Creek is largely derived from regional flowpaths, while Tinicum Creek (particularly the Rapp and Beaver Creek headwaters reaches underlain by CH) baseflow is mostly generated by local flowpaths. Risser et al. did not specify the flowpath structure component for their annual recharge estimates, except implicitly by assuming that the baseflow fraction of stream flow effectively represented groundwater gain. Winter (2007) concluded that localized flowpaths that develop in small headwaters catchments with limited storage capacity likely generate insufficient contribution to maintain baseflow throughout the entire stream length. Rather, baseflow in higher-order reaches is derived, in part, from intermediate and regional flowpaths.

In a broad-based review of wetland functional roles pertaining to hydrology, Bullock and Acreman (2003) reported that the overwhelming majority of researchers (i.e., >80%; n = 439 studies) concluded wetlands exert a significant effect on some component of the water cycle. Bullock and Acreman also reported that *headwater wetlands*[3] generally increased the immediate response of streams to rainfall – a functional consequence that developed because headwater wetlands tend to be saturated (at least for part of an annual cycle) and located in close physical proximity to stream channels; therefore, headwater wetlands may rapidly convey stormflow downstream.

The hydrogeomorphic (HGM) wetland classification system (Brinson 1993) classifies wetlands by integrating the following series of functional traits: (i) landscape position; (ii) water source; and, (iii) hydrodynamics.

In its ***Wetlands Study Results for Tinicum Creek Watershed***, URS (2003) applied a GIS model[4] to calculate annual recharge potential values for three HGM wetland categories that occurred in the approximately 60 square mile BNT land area.

Table 1 summarizes HGM category types and annual recharge potential model results for the BNT land area (URS 2003).

TABLE 1. SUMMARY OF WETLAND RECHARGE ESTIMATES BY HGM TYPE – CALCULATED FOR BNT AREA (URS 2003)			
WETLAND TYPE	**DEPRESSION**	**RIVERINE**	**SLOPE**
Description	Occur in topographic depressions that allow accumulation of surface water; potential water sources include precipitation, overland flow, streams, and groundwater/interflow contributions from adjacent uplands; dominant water movement is toward the center of the depression	Occur in floodplains and riparian corridors adjacent to stream channels; dominant water sources are overbank flooding and subsurface hydraulic connection to stream channel; water movements characterized by variable exchanges with the adjacent stream channel	Occur where groundwater discharges to sloping land (slight to steep); dominant water sources are groundwater/interflow discharge; dominant water movement is unidirectional downslope
Percent of BNT Area	15.1 %	1.2 %	9.6 %

[3] Defined by authors as "wetlands not fed by significant stream sources".
[4] Modeled input parameters included precipitation, soil type and drainage traits, and local relief.

TABLE 1. SUMMARY OF WETLAND RECHARGE ESTIMATES BY HGM TYPE – CALCULATED FOR BNT AREA (URS 2003)			
WETLAND TYPE	**DEPRESSION**	**RIVERINE**	**SLOPE**
Annual Recharge (in)	7.8	10.1	11.7

Estimates for annual groundwater recharge in the BNT region as reported by Risser et al. (2005) and URS (2003), respectively ranged from approximately 12 to 25% of the long-term normal yearly precipitation amount. However, neither study attempted to separate groundwater recharge into a specifically deep flowpath structure (i.e., by distinguishing local, intermediate, or regional pathways).

2.4 Study Design

Headwaters catchments lend well to hydrology analyses because some terms can be simplified by assumption. Because of generally small dimensions, other terms can be measured readily or estimated with better consistency than for larger settings. A typical simplifying assumption is to consider that the change in storage term is negligible through an annual or other long-term cycle. Additionally, stream flow inputs were eliminated from the standard equation because, by definition, headwaters streams lack an upstream input component.

The findings of this investigation were based on four primary methods of inquiry as follows:

1. Climatic water balance – compartmental budgeting of water inputs, outputs, and storage fluxes for a defined space and time;
2. Frequency analysis – hydroperiod relationships derived from the magnitude and probability of particular flows;
3. Baseflow evaluation – separation of stream flow into two parts i.e., an immediate response to rainfall and long-term discharge from storage; and,
4. Biological metrics – biologically meaningful and consistently associated surrogate indicators of hydroperiod.

Streams in the 150-acre studied catchment generally flow in southeasterly direction; slope aspects face in southerly directions. The study area included sparse development by a few rural residences. Local dwellings are served by on-site potable wells and individual subsurface disposal (ISSD) systems. Neither surface and groundwater diversions nor returns were identified in the study catchment, except that each residence was assumed to draw water from a domestic well and manage waste via ISSD.

The catchment is forested by a mature (secondary growth) deciduous stand. The forest stand is dominated by red maple (*Acer rubrum*), hickory (*Carya* spp.), and oak (*Quercus* spp.); the forest comprises a mosaic of uplands and wetlands with little distinction among forest canopy and understory strata between upland and wetland.

3 METHODOLOGY

Parameters used in this study included terms that were modeled based on third-party data sets, variables that were calculated based on measurements performed in the study area, and items that were measured directly within/near the study area. The interconnectivity of precipitation, surface water (including stream and wetland resources), and groundwater underpins the basis of this study. Converging lines of evidence were developed and evaluated as part of this study.

3.1 APPROACHES

3.1.1 Frequency Analysis

Frequency analysis derives relationships between the magnitude and probability of hydrographic records to characterize the propensity for a setting to generate stream flows. In this study, surface water elevation data sets were transformed into probability curves in order to “map” a hydroperiod gradient in the study setting. Frequency analysis findings were interpreted in the context of the water balance and the overall conceptual model of hydrologic conditions.

3.1.2 Baseflow Evaluation

Stream flow is a composite of the direct hydrologic response to rainfall and longer-term discharge from storage. Hydrographs chart stream flow dynamics as a time series. Various methods exist to extract a catchment’s *baseflow signature* using time-series stream flow records. Analysis of baseflow components provides information about the storage parameters of a catchment. Stream flow includes a combination of storm flow and baseflow components. Various statistical measures of stream flow, particularly annual average and low and baseflow regimes, provide insight into the subcomponents of stream flow.

3.1.3 Biological Metrics

The life cycles of many organisms correspond in large part to the availability of water. Amphibians, especially many salamanders, exhibit complex life cycles for which water is a fundamental driving factor. Salamander distribution on the landscape occurs due to response by individual species to variability among an array of gradients. Because the community of salamanders includes species with differential evolution to hydroperiod, salamanders provide a potentially useful surrogate for hydrology conditions. Stream-dependent salamanders were surveyed repeatedly within the study setting and their by-species/by-life stage distributions were assessed in the context of hydroperiod information to develop correlations that might verify interpretations of hydrologic data.

3.2 DATA SETS

3.2.1 Wetland Delineation

Wetland visual assessment to and delineation according to United States Army Corps of Engineers (USACE) methodology was conducted in 2005. Wetland delineation methods were based on the USACE (1987) methodology that defines wetlands according to co-occurrence of wetland hydrology, hydric soils, and the preponderance of hydrophytic vegetation. Spatial coordinates of wetland boundary positions were determined using a

Trimble Pro global position satellite (GPS) device; GPS data were rendered into GIS format for use in the ArcView platform. An approximately 14-acre contiguous swath of wetland deciduous forest was delineated within the study area. Additional (smaller) wetland settings were suspected within and near the study catchment based on field observations as well as interpretation of aerial photographs, but additional wetlands were not delineated.

3.2.2 Climate Trend Context

For a headwaters catchment in a humid temperate region, rainfall is the dominant input variable in a water balance. Rainfall trends based on the 30-year span 1971 to 2000 and developed for the National Oceanic and Atmospheric Administration (NOAA) Northeast Regional Climate Center (NRCC) station located approximately two miles from the study area in Bucksville, Pennsylvania (Station ID 361080) were compared to measurements obtained during this study. Additionally, normal monthly temperatures for the NRCC's Bucksville station were used in PET calculations.

3.2.3 Hydrologic Data Collection

An array of hydrologic monitoring devices was established in the lower portion of the study area catchment, within part of State Game Lands No. 56 (SGL56) – refer to Figure 3. The instrumented portion of the study area was bounded (upgradient) by Marienstein and Rock Ridge Roads, respectively. The downgradient limit of the study area was defined by a stream staff gauge installed below the confluence of locally dominant drainage channels (i.e., Staff Gauge 3). Maximum relief in the 150-acre study area approximated 130 feet and elevations ranged from approximately 630 feet to 500 feet above msl.

In November 2005, two nested piezometer (PZ) clusters were installed into separate mechanical rotary-augered, 8-inch diameter boreholes in an upland area near the convergence point of two low-order stream channels. Each cluster contained three individual PZ that were screened to depths bgs of 5-feet, 10-feet, and 15-feet, respectively. A 5-feet screen length was established for each particular PZ. Individual PZ consisted of 1-inch diameter schedule 40 PVC with machine-slotted screen (0.020-inch openings) and a commensurate length of 1-inch diameter PVC riser was threaded to the screen - a slip tip was affixed to the bottom of each PZ apparatus. The annulus was completed sequentially with washed morie sand pack to approximately 2-3 inches above the top of the deepest PZ screen and a bentonite slurry was inserted to seal the annulus above the sand pack. The above steps were repeated within each successively higher/shallower PZ interval. The surface of each PZ cluster was completed inside a housing composed of an approximately 4-feet length of 6-inch diameter schedule 40 PVC casing inserted into the upper portion of the borehole; a PVC slip cover was placed over the collective PZ cluster opening.

In April 2006, two tipping bucket rain gauges (RG) were installed in the study area to monitor precipitation inputs. One RG was placed in an opening in the forest canopy created by the management of a game feed lot (i.e., plot that is plowed and seeded annually with grain crops); the second RG was located in a representative area beneath the mature deciduous forest canopy. A length of window screen was secured above the bucket openings to reduce fouling by particulates. RG were mounted approximately 7 to 8 feet above grade atop 6-inch by 6-inch wooden posts. Each RG was calibrated to "tip" based on input of 0.01 inch was water. Each RG was equipped with an event-counting electronic logger that recorded a date-time stamp for each bucket "tip" counted.

Also in April 2006, electronic pressure transducer (Global Water model WL16 and one model WL15) dataloggers were installed within individual PZ. The pressure transducers were lowered into each PZ by a 25-feet length of all-weather cable and the cable was secured to the wellhead leaving the transducer suspended approximately 1 to 2 feet above the PZ base. The datalogger electronic components are housed in a sealed metal canister; the dataloggers for each PZ cluster were placed inside a common wooden “hutch” to further shield against moisture and disturbance. Groundwater levels were recorded on 30-minute intervals.

One PZ (PZ3) also was installed into manually-augered boreholes situated in a forested wetland topographically upgradient of the PZ1/PZ2 clustered setting. PZ3 was comprised of a 5-feet length of 2-inch diameter schedule 40 PVC machine slotted (0.020-inch openings) along the majority of its length. A slip cap was affixed to the bottom of the PZ3 apparatus. The annulus was completed with washed morie sand pack to near-grade and a bentonite slurry was placed in the uppermost several inches to seal the annulus above the sand pack.

In March 2007, two low profile V-notch (or sharp-crested) weirs were constructed to span separate Rapp Creek low-order tributary segments that converge near the PZ1/PZ2 clustered setting. Each weir was constructed with a plywood “face” into which a galvanized sheet metal V-notch was fastened. Each weir was secured to a series of metal rods that had been driven into the stream bed. The weirs were supported further using boulders placed/wedged against the downstream side.

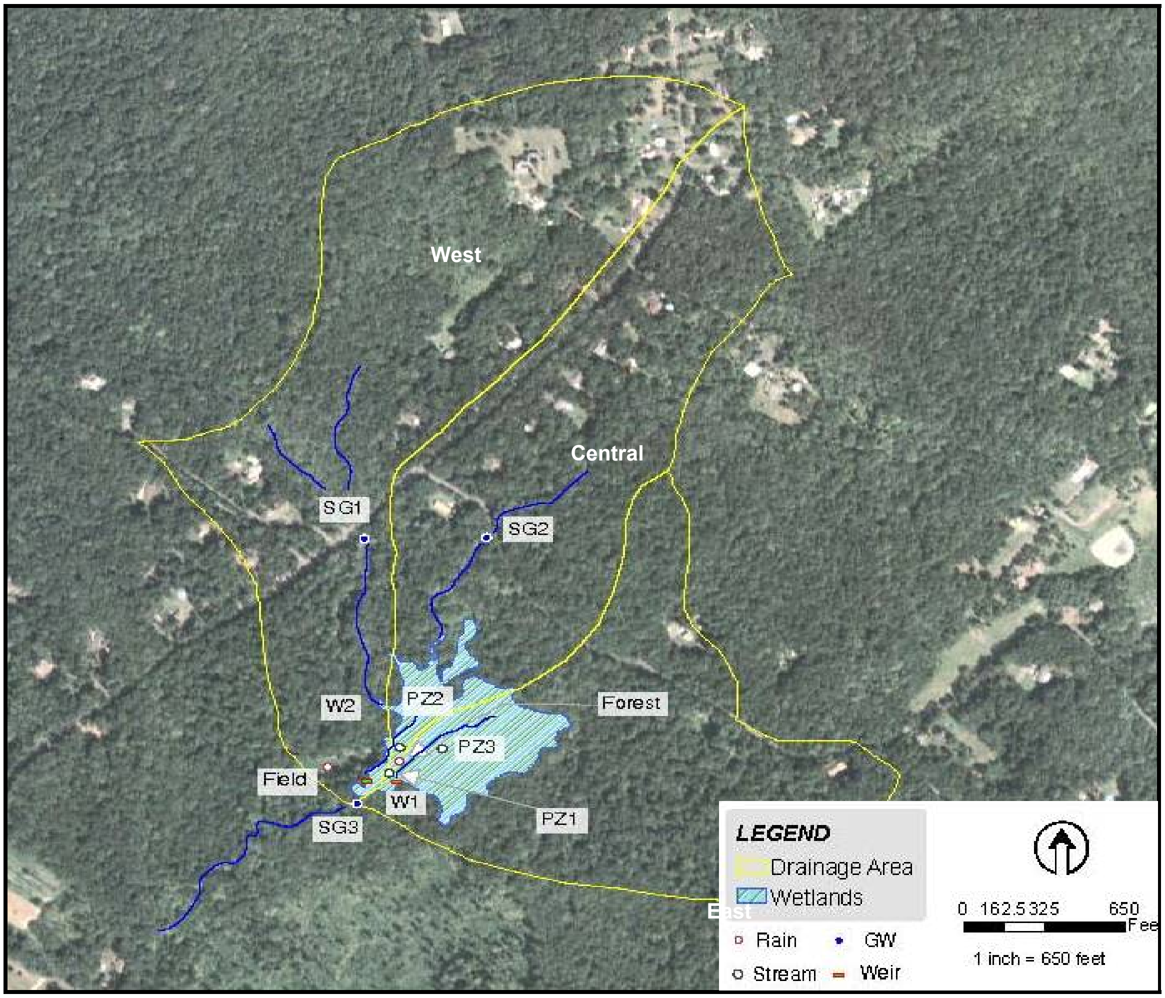


FIGURE 3. Study area location in ortho-rectified plan view showing sub-catchment topographic boundaries (yellow), hydrologic monitoring network (i.e., rain and staff gauges, weirs, and piezometers), prominent Rapp Creek tributary stream channels (dark blue) and wetlands (light blue). Base image is digital aerial photograph from 2008 acquired with 1-meter resolution (source: USDA).

To reduce potential leakage around the weir face, a polyvinyl plastic sheeting liner was draped over the leading face and fastened to the weir, layered across the weir pool “bed” a distance approximately 6 feet upstream of the V-notch, and extended up the pool flanks to above the V-notch elevation.

Also in March 2007, staff gauges (SG) were installed in each weir pool approximately 6 (horizontal) feet upstream of the V-notch, in the stream formed downstream of the convergence of the two weirs, and downstream of culverts that passed beneath Marienstein Road and Rock Ridge Road, respectively. SG were comprised of a variable length of enameled steel graduated in 0.01-feet increments and fastened to a metal rod that, in turn, was driven into the stream bed.

An electronic pressure transducer (Global Water model WL16) datalogger was placed within each weir pool. The pressure transducers were housed inside a length of 1-inch diameter machine-slotted PVC screen that was oriented horizontally on the pool bed and weighted with boulders. The canister-sealed datalogger electronic components were placed well above the top-of-stream bank inside a zipper-sealed plastic bag to reduce moisture exposure. Surface water levels in the weir pools were monitored continuously with the pressure transducer dataloggers; surface water levels were recorded on 6-minute increments.

Water levels in the catchment network were measured manually relative to the top of casing (PZ) using an electronic water level indicator (WLI) with sensor and cable graduated to 0.01-feet increments during routine field mobilization events. Similarly, during routine field mobilizations, manual readings of stream depth were recorded relative to SG. Mobilizations to the study area were conducted approximately once per month resulting in greater than 20 sets of SG measurements per device.

Stream bed and bank features, V-notch weir opening elevations, weir pool SG, and PZ casing and ground surface elevations were surveyed to a common, local datum. Spatial positions of water monitoring devices and certain other key features were acquired using a GPS instrument.

3.2.4 Salamander Surveys

In general, salamander species may be difficult to detect because most activity is nocturnal and, to facilitate oxygen uptake through membraneous skin or gills and/or prevent desiccation salamanders typically are located beneath cover items (i.e., rock, wood debris, leaf litter, vegetation) or in subterranean burrows/crevices. Stream-dependent salamanders, i.e., those with some life history requirement for an aquatic stage, as a class are more readily detected (at least seasonally or by life stage) because of their association in and near stream courses.

Table 2 summarizes basic life history traits and other details for the salamander species encountered in this study. Photographs of salamander species are presented in Appendix A.

TABLE 2. SUMMARY OF SALAMANDER SPECIES LIFE HISTORY TRAITS (after Petranka 1998; Lipps 2005)

Family	Genus species	Common	Description
Plethodontidae	*Plethodon cinereus*	Red-backed	Lungless; terrestrial all life stages; egg clusters laid in rotting wood/beneath cover early summer; hatchlings emerge late summer; prefer moist forest habitats.
Plethodontidae	*Desmognathus f. fuscus*	Northern dusky	Lungless; aquatic as larvae, terrestrial as adults; compact egg clusters secretly deposited near water in summer; adults may guard eggs/hatchlings; larval stage <1 year; metamorphic transformation may be hastened based on moisture regime; adults prefer deeply shaded, moist forests, springs, stream side habitats.
Plethodontidae	*Eurycea bislineata*	Northern two-lined	Lungless; aquatic as larvae, semi-terrestrial as adults; eggs laid late spring and attached singly in clusters to underside of submerged rocks; hatchlings emerge ~1 month later; larval stage >1 year; adults prefer moist forests, headwaters streams, springs.
Plethodontidae	*Pseudotriton r. rubber*	Northern red	Lungless; aquatic as larvae, terrestrial as adults; eggs laid singly in late fall or winter in cryptic locations; larval stage >>1 year; adults prefer springs and headwaters streams in forested settings.

In 2008, stream-dependent salamander survey stations that corresponded to three hydrologic regime categories (i.e., intermittent, groundwater discharge[5], perennial) were identified and marked in SGL56 within/near the hydrology study area. Each category was represented by four (4) replicate stations for total of 12 survey stations. Salamander survey station locations are depicted on Figure 4.

Each station consisted of approximately 25 linear feet of stream channel and 15 feet of adjacent upland measured from the top of each bank. Stations were separated by a minimum of 50 linear feet of stream corridor.

Water quality parameters (i.e., temperature, dissolved oxygen, pH, and conductivity) were measured at each site during each survey.

Between March and September 2008, eight (8) salamander surveys were performed by removing natural cover pieces both within the stream channel and adjacent corridor zones until a total of 50 cover pieces had been examined (40 within the stream corridor, 10 outside of stream corridor). Salamanders encountered were identified to species level and life stage (for biphasic species life stage was represented as “aquatic” or “terrestrial“) and enumerated. Small dipnets were used to capture individual salamanders as warranted to facilitate identification.

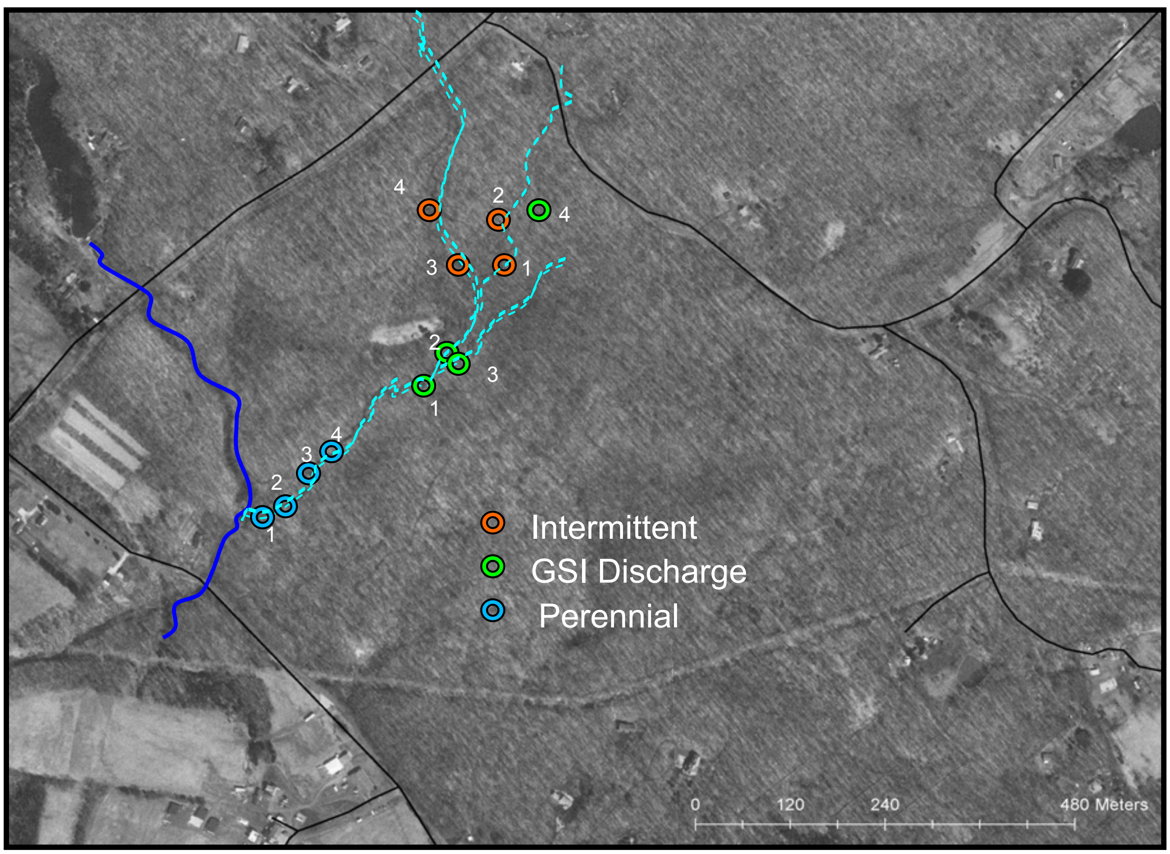


FIGURE 4. Salamander survey stations. Small closed circles represent hydrology data collection network. The main stem of Rapp Creek depicted by solid dark blue) line. Note GSI-4 location was spring unaligned with nearby intermittent channels.

[5] Groundwater discharge settings were characterized herein as groundwater:surface water interface (GSI) zones.

A one-time visual habitat assessment (Barbour et al. 1999) of the stream corridor was conducted to characterize the habitat and quality of each station. Copies of habitat assessment forms are provided in Appendix B.

3.3 Data Analysis

3.3.1 Climatic Water Balance

A climatic water balance approach (Thornthwaite 1944) expresses water inputs and outputs according to a simple mathematical equation as follows:

$$\Delta \text{Storage} = [P + S_{in} + GW_{in}] - [ET + S_{out} + GW_{out}] \pm \{\text{uncertainties}\} \quad (1)$$

Where ΔStorage is change in storage; P is precipitation; S_{in} is surface water inputs (channel and non-channel); GW_{in} is groundwater inputs; ET is evapotranspiration; S_{out} is surface water outputs (channel); GW_{out} is groundwater outputs; and, Uncertainties represent measurement and calculation errors/uncertainties.

The simple water balance expression can be presented more elaborately by separating certain components as follows:

ΔStorage = canopy interception +/- microtopography +/- soil moisture +/- groundwater; and,

S_{in} = stream flow + direct rainfall into channel + runoff + interflow + baseflow.

GW_{out} = interflow (quick flow) contribution to storm flow + local groundwater flow (headwater stream baseflow) + intermediate and regional groundwater flowpaths.

[Note that some surface water input and groundwater output terms overlap or are redundant.]

In a water balance equation, several factors are encompassed by the “surface water output” term including storm flow and baseflow components. Because surface water output represents an aggregate of sub-terms with possibility for redundancy, the individual sub-terms measured or otherwise estimated during this study were calculated iteratively in a series of water balance alternatives.

An annual water balance equation was developed for part of the SGL56 study area. The study area was defined as the approximately 150-acre headwaters catchment with surface water outlet positioned at SG3. The water balance was evaluated for the 12-month period April 2007 through April 2008. The groundwater component was estimated as the mathematical residual of all other terms in the water balance equation.

Individual terms of the water balance equation were measured, calculated, or estimated based on a combination of landscape-scale models and site-specific data sets.

Potential Evapo-Transpiration (PET)

In combination, the ET term in a water balance equation typically is the dominant output variable. ET processes are regarded generally as among the most substantial output variables in a catchment water balance equation. For example Slotto and Schreffler (1994) estimated that ET processes accounted for 55 to 75% of annual output in water budget assessments of four stream basins in northern Bucks County, Pennsylvania – their study reported Tinicum Creek’s annual water budget included an average ET output during 1991 and 1992 equivalent to 67% of annual rainfall. The average annual rainfall for 1991 and 1992 amounted to 41.5 inches.

Actual ET data are generally considered difficult and costly to determine and consequently various (P)ET models exist to estimate this term or it is estimated as the residual value in a water balance equation. Although many variables such as humidity, wind speed, antecedent moisture, and vegetation type exert influence, temperature and day-length are considered as the primary explanatory factors for ET.

The Hargreaves – Samani (1982) equation is a simple model to estimate PET using average temperature, temperature range, and latitude on a daily time-step.

$$ET_0 = 0.0135(KT)(R_a)(TD)^{0.5}(TC+17.8) \quad (2)$$

Where ET_0 is reference crop evapotranspiration in millimeters (mm); KT is an empirical coefficient (unitless) that relates global solar radiation to daily temperature range, R_a is extraterrestrial solar radiation (mm/day); TD is the difference between daily maximum and minimum temperatures (°C); and TC is the average daily temperature (°C).

Runoff

Rainfall runoff is an important component of stream flow. Runoff is the rapid response to rainfall that occurs during and immediately following a storm (or melt) event. Runoff may include a combination of overland flow and shallow subsurface storm flow components.

Stormwater contribution to stream flow was calculated based on application of the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) Technical Release-55 (TR-55) methodology. Stormwater contributions to stream flow represent the by-product of landscape interactions with rainfall. As cited by Weiler and McDonnell (2007), Engler (1919) reported that overland flow was minor or nonexistent even during high intensity rainfall periods in forested catchments. Rather, Engler (1919) observed that water infiltrated the near-surface soil layer and moved laterally within the main root zone or at the soil – bedrock interface; observations in the study area during and following rain events were consistent with Engler's description.

TR-55 computes runoff according to peak rate, volume, and event hydrographs based primarily on a curve number (CN) value that incorporates soil permeability, surface cover, hydrologic condition, and antecedent moisture. Catchment-weighted CN values were developed using USDA soil mapping information provided as GIS data sets.

The runoff equation is:

$$Q = (P-I_a)^2/(P-I_a)+S \quad (3)$$

Where Q is runoff in inches; P is rainfall (in); S is potential maximum retention after on-set of rainfall (in); and, I_a is initial abstraction (in) determined empirically as 0.2S.

S is related to CN by:

$S = (1000/CN) – 10$

Where, CN ranges from 0 to 100 and values are selected from standard tables (NRCS 1988).

Stream Flow: Regionalized Statistics

The United States Geological Survey (USGS) GIS application *StreamStats* was used to estimate stream flow statistics for the study area. *StreamStats* integrates ArcIMS, ArcSDE, ArcGIS, and ArcHydro Tools in a map-based, on-line user interface that facilitates site selection. *StreamStats* employs state-specific databases that contain information from stream gauging stations; a GIS program to delineate drainage basins and measure basin characteristics; and a GIS database that contains land elevation models, historic weather data, and other items required to delineate and measure catchment characteristics.

Equations used to estimate stream flow statistics for ungauged sites were developed through a process know as “regionalization” whereby regression analyses were used to relate stream flow statistics computed for a group of selected gauged streams to their measured basin characteristics and apply models to ungauged streams that exhibit similar basin traits.

Stream Flow

Stage – discharge relationships were estimated for five (5) points within the hydrology monitoring network based on application of either instantaneous stream velocity measurements at staff gauges or flow through V-notch weirs. Based on the geometry of V-notch weirs, the devices were limited to estimating discharge across a narrow stage range of low flows. Additionally, given the modest stream channel dimensions, rating curve equations calculated for staff gauges were expected to be unreliable at high stage as flows depart the stream banks.

Stream Velocity

Stage – discharge relationships were developed at three specific locations (SG1, SG2, SG3) in the study area through repeated stream discharge measurements obtained five separate times according to USGS-advocated methods described by Buchanan and Somers, (1969). Discharge measurements consisted of three distinct components: (i) flow velocity; (ii) water depth; and, (iii) distance along a cross-sectional transect line. In the diagram below, x_i represents distance to measurement points along the transect relative to one stream bank and y_i represents stream depth. The number of velocity measurements was selected to limit separation between adjacent points to less than 10% of total discharge along the transect as practical.

FIGURE 5. Typical stream cross-sectional profile and velocity measurement approach used to calculate discharge.

Flow velocity measurements were made utilizing a vertical-axis anemometer flow meter; a type recommended by USGS. The flow meter was used in conjunction with a top-setting wading rod that was used to measure stream depth and to set the anemometer height at the 0.6-depth (Leopold et al. 1964); the level empirically established to approximate the average stream velocity in flowing waters less than 2.5 feet deep.

Instantaneous stream velocity measurements were converted to stream discharge estimates in a two-step process as follows:

Incremental discharge (q_i) was calculated for each “step” along the width profile:

$$q_i = (y_i)(\text{velocity})(x_{i-1} - x_i) \qquad (4)$$

Instantaneous discharge at each cross-section was calculated by integrating the sum of incremental discharges as follows:

$$Q = \Sigma[q_i] \qquad (5)$$

Instantaneous discharge values were used to develop stage-discharge ratings curves for each station according to procedure of Kennedy (1984). Both stage height and instantaneous discharge were transformed to natural logarithms to account for the non-linear relationship between water depth and discharge. A linear equation then was derived based on the transformed stage – discharge relationship. The observed stage – discharge relationship was compared to that derived from the transformed data set via a least-squares regression analysis. Automated and manual staff gauge data sets were processed according to the stage – discharge rating curve equations to generate estimates of stream discharge at each monitoring station throughout the study period.

V-Notch Weir

Estimates of baseflow discharge through V-notch weir openings were based on the relationship between width, depth, and the V-notch angle as depicted below.

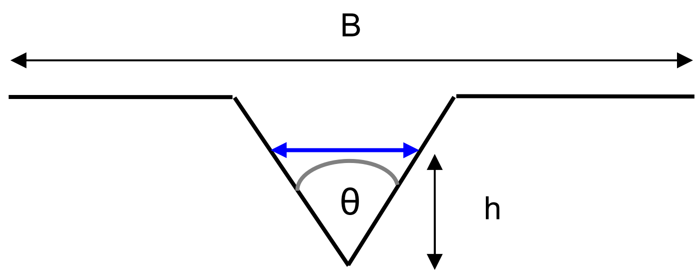


FIGURE 6. Diagram of V-notch (sharp-crested) weir configuration and terms used in Equation 7.

$$Q = 4.28\ C \tan(\theta/2)\ (h + k)^{5/2} \qquad (6)$$

Where Q = discharge (ft^3/s); Θ = notch angle (degrees) - weir should be between 0.03 and 0.08 inches thick in the V; B = width of the weir at the flowing rate (feet) – should exceed 3 feet; h = head (feet) – measured at least 4h upstream of notch; C = discharge coefficient – varies from 0.576 to 0.6; K = head correction factor (feet) – varies from 0.003 to 0.008 (USBR 1997).

Table 3 is a summary of the data sets utilized/generated in this study.

TABLE 3. SUMMARY OF DATA SETS USED IN THIS STUDY

Parameter	Derivation	Record Period
Rainfall	Monthly normal trends based on Bucksville, PA climate monitoring station records	1971 – 2000
	Monthly and yearly rainfall based on Bucksville, PA climate monitoring station	2006 – 2008
	Event-based measurements for rain gauge in open setting at Tinicum Municipal Building	2006 – 2008
Interception	Event-based measurements in study area for rain gauges in open field and beneath forested settings	30 days in 2006

TABLE 3. SUMMARY OF DATA SETS USED IN THIS STUDY		
Parameter	**Derivation**	**Record Period**
ET	Daily PET values calculated according to Hargreaves – Samani (1982) method and temp recorded at Bucksville, PA	2007 – 2008
Surface Water	Non-channel storm flow calculated according to TR-55 methodology	NA
	Stream flow statistics (mean annual and baseflow values) generated using on-line USGS interface i.e., StreamStats (ArcGIS with ArcHydro)	NA
	Stream level measured continuously at 2 locations using pressure transducer dataloggers; converted to stream elevation by survey to local datum	2007 – 2008
	Stream level measured intermittently at 5 locations based on staff gauge readings	2007 – 2008
	Discharge estimated at 3 locations based on stage – discharge ratings curves developed through instantaneous stream velocity measurements	5x in 2007-'08
	Discharge derived at 2 locations based on flow through V-notch weirs	2007
Groundwater	Groundwater level monitored continuously at 2 locations using pressure transducer dataloggers; converted to elevation by survey to local datum	2006 – 2008
	Groundwater level monitored intermittently at 1 location using manual measurements within a piezometer	2007
Biological	Salamander occurrence was surveyed 8 times at 12 locations within/near study area	2008

3.3.2 Baseflow Recession

Various techniques are used to extract watershed characteristics from analysis of baseflow hydrographs.

The baseflow recession constant term, k_b (lower-case), is commonly used to describe aquifer traits by relating basin hydraulic conductivity and soil porosity (Vogel and Kroll 1992). The baseflow recession constant describes the rate of stream flow decrease during baseflow interludes – it is a measure of discharge from the various storage compartments in the catchment. Relatively higher (i.e., >0.9) values of k_b indicate dominance of baseflow in overall stream flow; relatively lower (i.e., 0.2 to 0.8) values indicate dominance by runoff and/or interflow processes (Brodie et al. 2007a).

The recession constant may be estimated through various techniques; in a comparison of approaches, Vogel and Kroll (1996) determined that taking the natural logarithm of terms in a steady-state exponential function performed well statistically and was simple to implement as follows.

$$\ln(Q_t) - \ln(Q_0) + \ln(k_b)t + \epsilon_t \qquad (7)$$

Where, Q_t is baseflow discharge after t days; Q_0 is initial baseflow discharge; k_b is baseflow recession constant; and ϵ_t is residual error.

A baseflow recession index, K (upper-case), is the time required for baseflow to recede by one log-cycle and is obtained using a semi-log plot of discharge versus time. Longer K values indicate relatively stable inflows.

Stormflow recharge is the contribution to overall stream flow that results from groundwater gained after some peak flow (Brodie et al. 2007b) according to the following:

$$R = [2(Q_2 - Q_1)K]/2.3026 \times 86{,}400 \text{ seconds/day} \quad (8)$$

Where, R is stormflow recharge (ft^3); Q_1 is groundwater discharge at a critical time (t_c; refer to equation no. 9 below) extrapolated from the pre-storm recession segment (cfs); Q_2 is groundwater discharge at a critical time (t_c) extrapolated from the post-storm recession segment (cfs); and K is the baseflow recession index described above (days).

In order to solve Equation no. 8, the critical time, t_c, must be established. The following equation derives critical time from the baseflow recession index (K) value obtained by graphical analysis:

$$t_c = 0.2144K \quad (9)$$

Where, t_c is the critical time in days.

4 INVESTIGATION RESULTS

4.1 *WATER BALANCE*

<u>Input Terms</u>

4.1.1 Rainfall Trend Assessment

Rainfall recorded at the Tinicum Township municipal services complex RG during the 12-month used in water balance equation April 2007 through April 2008 was applied to the water balance equation. Overall, the measured rainfall during the year-long study period applied to water balance calculations (April 2007 – March 2008) was above normal (56.6 inches measured versus 50 inches normal). During the same time span, the Bucksville station recorded 57.5 inches of precipitation. Additionally, for the 12 month period April 2006 through March 2007, the Bucksville station reported 56.9 inches of precipitation.

Based on comparison to monthly normal precipitation patterns for the Bucksville climate monitoring station, the investigation period applied to water balance calculations included three months of rainfall comparable to drought, two months less than normal, one month equal to normal, and six months of above-normal rainfall input.

In general, rainfall measured during the study period approximated the 30-year period normal trends; however, certain months deviated from long-term normal pattern considerably. In April 2007, approximately 12 inches of rainfall was recorded; equivalent to 25% of annual rainfall total and more than double the 30-year normal amount for April. In September 2007, approximately 60% of the 30-year drought rainfall amount was recorded.

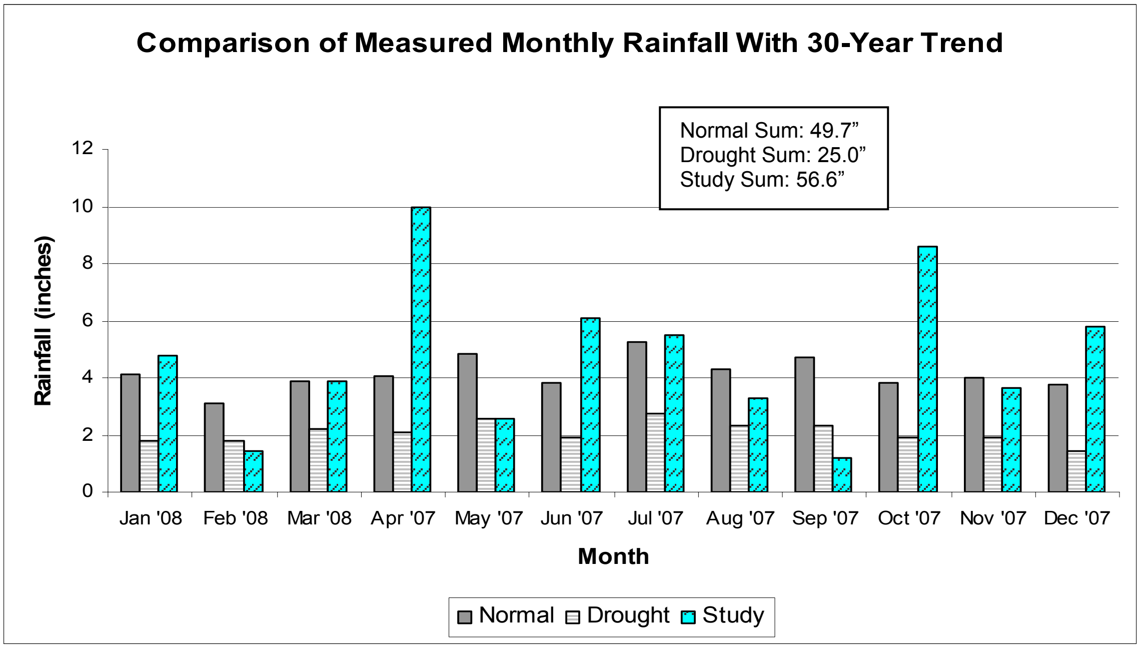


FIGURE 7. Chart comparison of rainfall measured during 12-month study period used for water balance calculations with 30-year long-term trend for Bucksville, Pennsylvania.

<u>**Output Terms**</u>

4.1.2 Potential Evapotranspiration Estimate

The following chart is a comparison of PET by the Hargreaves – Samani (1982) equation and rainfall measured during the 12-month span April 2007 through April 2008.

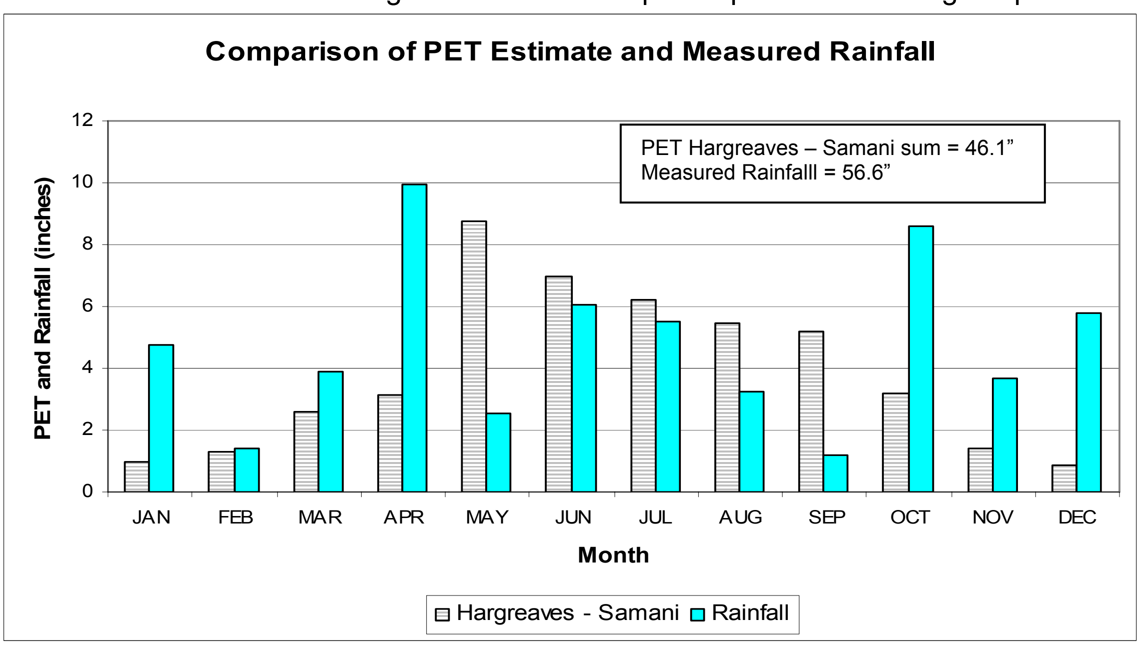


FIGURE 8. Chart comparison of rainfall measured during 12-month study period and PET calculations according to Thornthwaite and Hargreaves – Samani methods.

As indicated by review of the chart on Figure 8 above, measured rainfall exceeded Hargreaves – Samani estimates of PET values from October through April. The

Hargreaves – Samani annual PET value amounted to 81% of measured rainfall. As mentioned previously, Slotto and Schreffler (1994) estimated the ET component of the Tinicum Creek watershed balance for 1991 and 1992 (annual rainfall both years was below-normal) at average of 67% of annual rainfall. For comparison to the Hargreaves – Samani estimates of PET, 67% of the average annual rainfall recorded at the Bucksville station during the two year span April 2006 – March 2008 amounts to 38.3 inches/year.

4.1.3 Runoff

The TR-55 modeled runoff output was separated according to three subcatchments (i.e., West, Central, and East) that comprised the hydrology study area – refer to Figure 2.

The following table summarizes parameters used in the TR-55 model and includes the estimated non-channel flow contributed by each subcatchment based on rainfall measurements recorded during this study for the period 31 March 2007 through 31 March 2008.

TABLE 4. TR-55 Parameters Applied by Subcatchment and Estimated Runoff April 2007 to March 2008

Subcatchment	Area (ac)	Weighted CN	I_a (in)	T_c (hr)	Runoff Sum (in)
West	61.4	66.5	0.25	0.9	3.9
Central	44.2	60.3	0.33	0.7	3.4
East	42.9	67.4	0.24	0.5	4.0
Total	148.5	64.9	--	--	11.3

The TR-55 output indicated that the East subcatchment (i.e., portion that includes the majority of the delineated 14-acre forested wetland) generated more unit area-adjusted runoff than either the West (30% higher) or Central (20% higher) subcatchments. As indicated, total runoff estimated for the study area was 11.3 inches.

4.1.4 Stream Flow: Regionalized Statistics

The USGS *StreamStats* model was used to estimate various stream flow statistics for the study area based on a GIS algorithm mapping of the catchment with outlet positioned at SG3. Note that *StreamStats* reported that some parameters were beyond the suggested range of the model and that unknown errors will enter extrapolations.

The following stream flow statistics were reported based on *StreamStats*:

- Mean annual flow (QA) – estimated combination of baseflow and storm flow derived for normal rainfall trend;
- Harmonic mean annual flow (QAH) – measure of central tendency calculated approximately as the reciprocal of mean flow. QAH has been used to estimate lower limits to effective hydraulic conductivity of an aquifer system (Limbrunner et al. 2000);
- 7-Day mean low flow every 2 years ($Q_{7,2}$) – consecutive 7-day low flow based on 2-year recurrence interval probability distribution – Q_7 statistics traditionally used to define ecologically-based limits on flow;

- 7-Day mean low flow every 10 years ($Q_{7,10}$) – consecutive 7-day low flow based on 10-year recurrence interval probability distribution – 7-day 10-year low flow often used to define extreme low flow conditions;
- 10-Year baseflow (BF10Y) – annual baseflow with 10% probability (i.e., occurs 1 year in 10).

The following table summarizes select stream flow statistics for the study area and portrays the results in terms of instantaneous discharge (cfs) and annualized sum.

TABLE 5. Summary of Select Stream Flow Statistics Estimated Using *StreamStats*

Statistic	QA	QAH	$Q_{7,2}$	$Q_{7,10}$	BF10Y
cfs	0.21	0.04	0.01	0.005	0.11
In/year	12.16	2.32	0.58	0.29	6.37

Ideally, the mean annual stream flow value (~12.2 inches) would represent the comprehensive surface water output variable for this study area based on long-term normal precipitation inputs. Because rainfall measured during the study period exceeded long-term normal precipitation, mean annual stream flow calculated based on application of regionalized statistics was expected to under-estimate the surface water outflow term.

4.1.5 Stage – Discharge Relationships Derived from Instantaneous Velocity and V-Notch Weir

The following table depicts the ratings curve equations obtained for five surface water monitoring points in the study area. The study area downstream limit was defined by SG3.

TABLE 6. Summary of Stage-Discharge Ratings Curve Equations

Station Name	Location	Stage-Discharge Ratings Curve, cfs	R^2
SG1	Marienstein Road Culvert	Discharge = 1.12E-52*Staff Gage Height$^{58.9}$	0.98
SG2	Rock Ridge Road Culvert	Discharge = 3.30E-250*Staff Gage Height$^{259.6}$	0.98
W1	Weir No. 1 Pool	Discharge = 9.57E-36*Staff Gage Height$^{42.208}$	0.91
W2	Weir No. 2 Pool	Discharge = 2.54E-18*Staff Gage Height$^{21.733}$	0.91
SG3	Downstream of Weirs	Discharge = 4.79E-24*Staff Gage Height$^{31.3}$	0.89

Continuous stage gauging was not conducted at SG3 during this study; rather a synthetic hydrograph was developed for SG3 based on regression analysis that correlated manual stage measurements to continuous stage data sets obtained at W1 and W2. The SG3 synthetic hydrograph was factored by the ratings curve equation in Table 6 in order to estimate total discharge for the study period. During the 12-month study period for which the water balance was calculated (April 2007 through April 2008), cumulative discharge at SG3 was estimated at 8 inches.

Storage Terms

4.1.6 Canopy Interception

Canopy interception of rainfall was considered to represent a storage term for the water balance calculation in this study. Rainfall interception loss by temperate forests typically ranges between approximately 10 and 50% of gross incident precipitation (Hormann et al 1996). To estimate canopy interception effects in the study area, rainfall events were measured synchronously by RG positioned in a field and below forest canopy and separated by just several hundred feet.

The chart depicted on Figure 9 demonstrates the effect of forest canopy structure on the through-fall fraction of rainfall during a 30-day span in 2006 that coincided approximately with forest leaf-out. During the 30-day period, the open field RG recorded approximately 8 inches of cumulative rainfall; the RG located beneath the forest canopy recorded 6.7 inches or approximately 20% less.

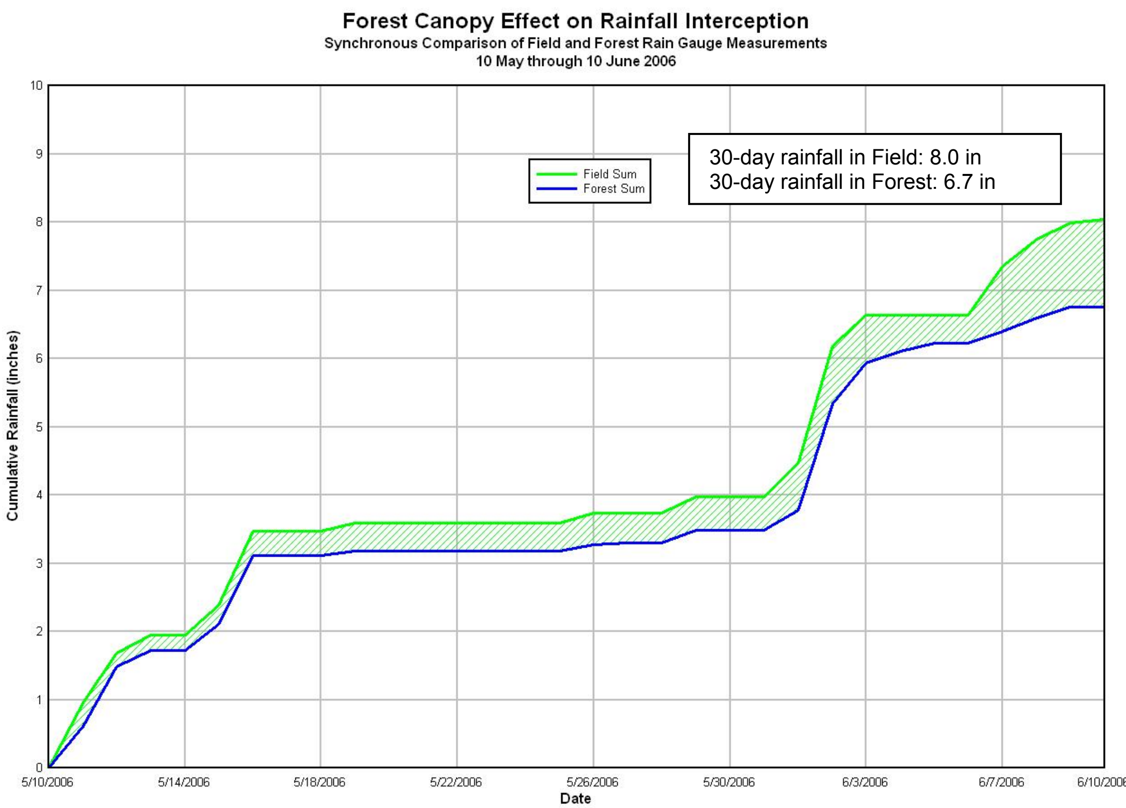


FIGURE 9. Synchronous comparison of Rain Gauge (RG) measurements in SGL56 field and forest during 30-day period that spanned canopy leaf-out (May – June 2006).

In 2007 and 2008, forest leaf-out in SGL56 was observed to be largely complete by approximately the third week of May; the on-set of killing frost events and subsequent deciduous leaf drop was observed to be largely complete by mid-November. Based on the (Bucksville) normal trends, approximately 62% of annual rainfall occurs during the months from May through November inclusive. Although the physical structure of forest is likely to account for some preferential interception regardless of season, for water balance equation purposes herein, annual rainfall interception was normalized to half the monthly difference between forest and field RG as presented above; i.e., 10% of annual rainfall.

4.1.7 Groundwater Storage – Local Flowpath Structure

Following reduction from water height to elevation, groundwater level data obtained for both nested PZ clusters (i.e., PZ1 and PZ2) from 2006 through early 2007 indicated the existence of a common water table elevation despite differences in screened interval height. The shallow water table elevation data were inferred to exhibit phreatic (i.e., unconfined) conditions. The groundwater level data were inadequate to ascertain whether the three discretely-screened depth zones (e.g., bottom depths -5, -10, -15 feet bgs) were hydraulically common or whether the data resulted as an artifact of PZ construction methods (i.e., vertical leakage within the common borehole).

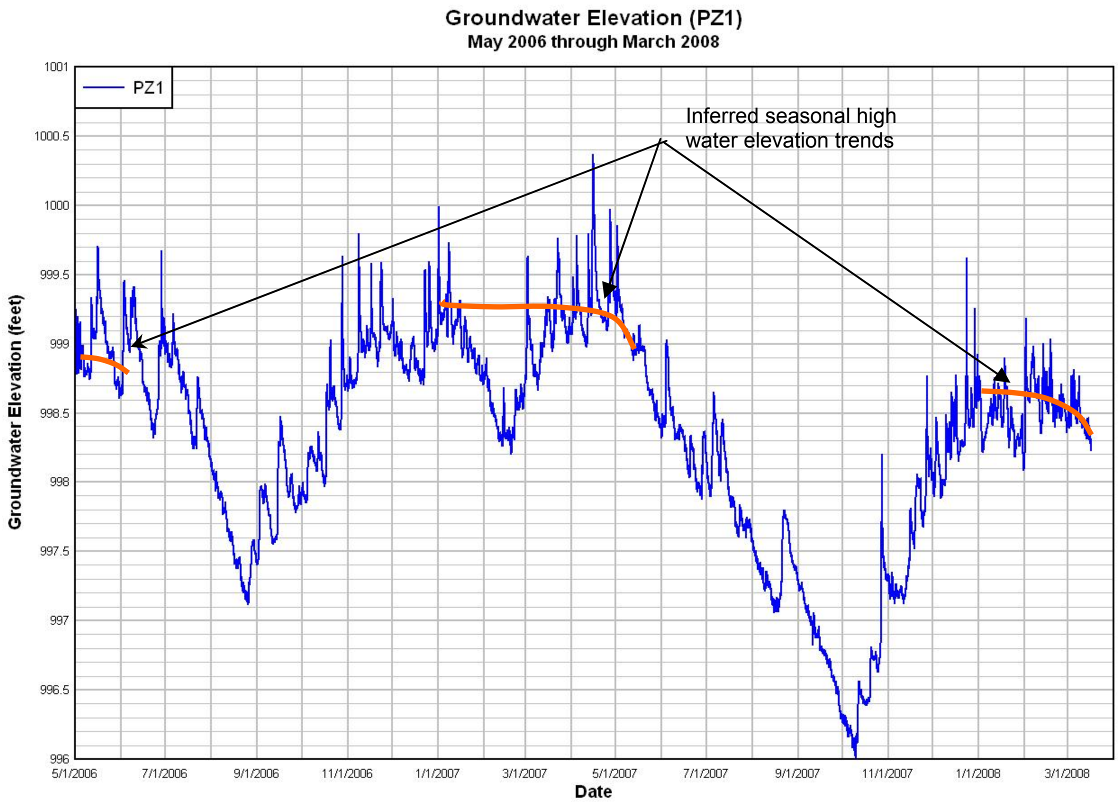


FIGURE 10. Representative groundwater elevation hydrograph for PZ1 for period May 2006 through March 2008. Water table elevation relative to local, arbitrary datum.

Groundwater level data were acquired continuously from spring 2006 through spring 2008 within two PZ clusters. Groundwater level patterns were correlated for both PZ clusters. Figure 10 depicts the PZ1 groundwater hydrograph. As indicated by review, the seasonal high water table elevation recorded for PZ1 in 2007 was inferred to be more than 0.5 feet higher than the (partial) seasonal water table elevation as of March 2008. A difference between the seasonal groundwater elevation for successive years indicates a change for the groundwater storage term in a water balance equation. Note that total precipitation recorded at Bucksville was 56.9 inches for the 12 months ended March 2007 and 57.5 inches for the 12 months ended March 2008.

4.1.8 Water Balance Output

Due to uncertainty inherent in various components, the basic water balance equation (1) was solved using various values for certain parameters. Six alternate water balances for the study catchment were calculated for the one-year period 1 April 2007 through 31

March 2008. Figure 11 illustrates the typical water balance components, some of which were deemed non-applicable to the current study based on landscape position in a headwaters catchment, for example stream inflow and intermediate and regional groundwater inflows each was assumed zero.

Groundwater inflow was not measured or calculated, except to assume that stream baseflow was equivalent to groundwater inflow gains realized along local flowpaths. Groundwater inflow also was assumed to derive entirely from within the study area (i.e., subsurface 'catchment' boundary assumed equal to topographic catchment area); therefore, groundwater inflow was assumed to be accounted for by the precipitation term. Groundwater outflow was aggregated among shallow flowpaths that intersect the land surface downgradient of the study area (local flowpaths), deeper flowpaths that contribute to lateral groundwater movements above the bedrock surface (intermediate), and very deep flowpaths that recharge potable aquifer zones (regional).

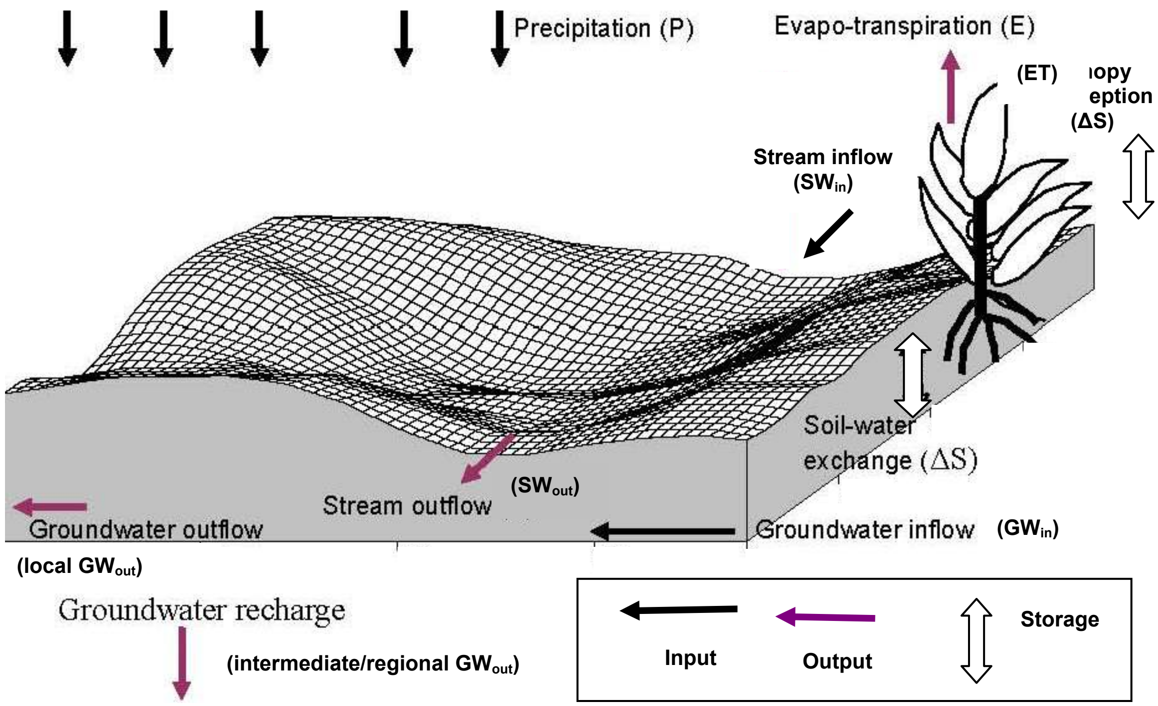


FIGURE 11. Generalized water balance model that depicts inputs, outputs, and storage components (modified after Mohamoud 2004).

Table 7 summarizes the water balance calculations according to six scenarios. Rainfall measured at Tinicum Township Municipal complex represented input (56.6 inches) for four of six scenarios; for two scenarios the 30-year normal rainfall level was applied. Output terms differed based on two alternative ET approaches: (i) PET calculated according to Hargreaves – Samani Equation (46.1 inches) and based on daily temperature data recorded at the Bucksville climate monitoring station during the study period and (ii) 67% of annual rainfall (38.0 inches) i.e., the average fraction of precipitation apportioned to ET processes by Sloto and Schreffler (1994) for the years 1991 and 1992. Surface water output also differed based on three alternatives: (i) cumulative discharge estimated at SG3 (8.0 inches) and derived from ratings curve calculations and a synthetic hydrograph generated through regression analysis of the continuously gauged, upstream stations W1 and W2, (ii) annual mean discharge based on regionalized regression analysis (12.2 inches) using the USGS *StreamStats* application, and (iii) sum of runoff based on TR-55 (11.3 inches) estimates derived from

GIS soil data sets and rainfall measurements during the study period plus the 10-year baseflow based on regionalized regression analysis (6.4 inches) obtained using *StreamStats*.

TABLE 7. SUMMARY OF WATER BALANCE SCENARIOS						
Alternative	Inputs	Outputs			GW_{Out}	Comment
	P	ET	SW_{Out}	GW_{In}		
1	56.6	46.1	8	--	2.5	SW_{Out} was the cumulative discharge at SG3 - known to underestimate total annual discharge.
2	56.6	46.1	12.2	--	-1.7	SW_{Out} derived from USGS regionalized annual mean stream flow – uncertainty regarding error direction (over/under) is unknown.
3	56.6	46.1	11.3	6.4	-7.2	SW_{Out} from TR-55 runoff estimate; GW_{In} regionalized BF10Y.
4	50	33.5	12.2	--	4.3	SW_{Out} regionalized annual mean stream flow.
5	50	33.5	11.3	6.4	-1.2	SW_{Out} from TR-55 runoff estimate; GW_{In} regionalized BF10Y.
6	56.6	38	8	--	10.6	SW_{Out} was the cumulative discharge at SG3 - known to underestimate total annual discharge.

Notes: All water balance terms in inches; SW refers to surface water; BF10Y is the statistical baseflow for a 10-year recurrence interval.

The residual term in the alternative water balance equations represented groundwater recharge (all possible flowpaths), plus change in storage, plus aggregate uncertainties.

The term with the lowest uncertainty in the water balance equation was rainfall. Rainfall was recorded on an event basis at the Tinicum Municipal services complex and at the Bucksville climate monitoring station continuously throughout the study period with close agreement for both data sets (56.6 and 57.5 inches, respectively).

The highest uncertainty may be attributed to the ET term. The Hargreaves – Samani approach to ET calculation was based on daily temperature data acquired during the study period, including the daily temperature range (a means to buffer effects of relative humidity). The alternative approach to ET used herein was to accept the average of two annual ET values derived as the residual term in water balance analyses of Tinicum Creek watershed that were developed by Sloto and Schreffler (1994). The Hargreaves – Samani method was inferred to be the more robust approach to estimate ET.

Stream output was estimated at SG3 based on a stage – discharge relationship developed empirically from five sets of stream flow measurements and applied to a synthetic hydrograph that was generated through regression analysis to continuously gauged stations elsewhere in the study setting. Discharge estimated at SG3 was expected to under-estimate cumulative stream output at the station because the empirical data set used to develop stage – discharge curves was biased toward baseflow intervals. Additionally, the synthetic hydrograph was constructed based on mean daily flows. Because stage – discharge relationships are non-linear, adjustment to a daily mean value underestimates stream flow, particularly during periods when stage is rising and/or falling in response to input events.

Relative uncertainty regarding stream output and groundwater input (i.e., local baseflow contribution) terms based on regionalized statistical approaches and TR-55 methodology are unknowable in the context of this study and were presented herein for comparison purposes.

4.2 Flow Duration Analysis

The hydroperiod of wetlands and stream segments was correlated to catchment elevation. Figure 12 is a composite hydrograph that depicts surface and groundwater elevation data in the context of cumulative rainfall for the period spring 2007 through spring 2008.

As indicated by review of the composite hydrograph, the water table exhibited a seasonal pattern of decline that corresponded to the active growing season (approximately mid-April through late October). The hydroperiod duration for surface flows was correlated to relative elevation within the catchment; that is, hydroperiod length increased with decreasing catchment elevation.

Characterization of stream flow status based on the proportion of time that flow/stage at a location equals or exceeds some threshold of interest is a useful means to assess catchment characteristics. Figure 13 summarizes probabilities for stream stage at W1, W2, and SG3. Intermittent flow status was indicated for W1 (31%) and W2 (11%) during parts of the study period. At SG3, perennial (i.e., continuous) discharge occurred. Convex inflections in the duration analysis curves corresponded approximately to forest leaf-out.

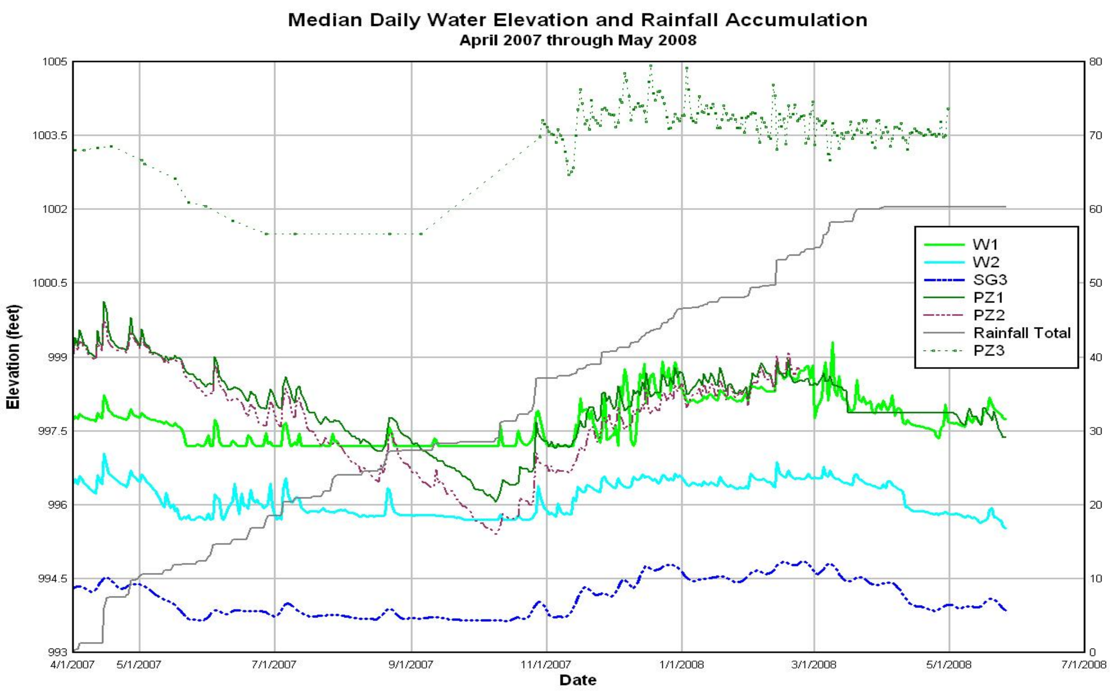
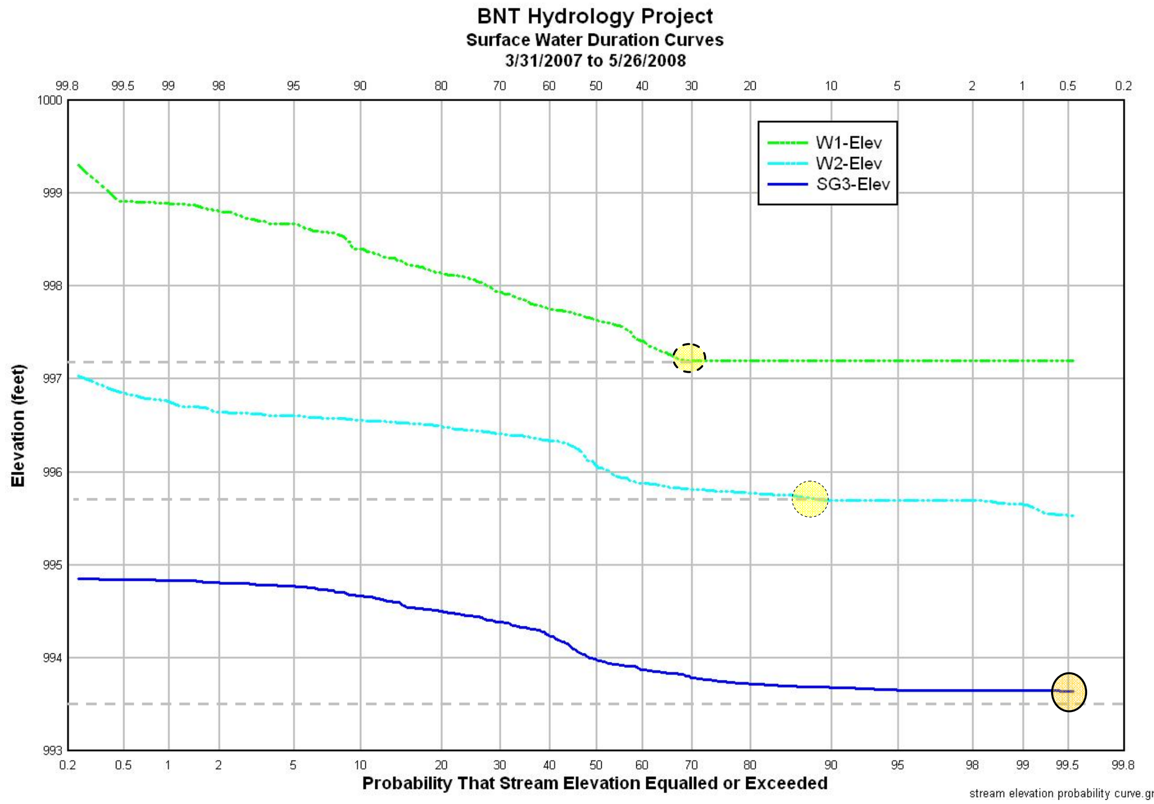


FIGURE 12. Composite surface and groundwater hydrograph with cumulative rainfall for period April 2007 through May 2008. Note that an arbitrary elevation datum applies to this chart.

At relatively higher elevation, stream hydroperiod was shorter – W1 exhibited discharge for 69% of the period April 2007 through May 2008, whereas SG3 exhibited continuous discharge during the same period. Vertical separation between W1 and SG3 was approximately 3.5 feet.



Dashed horizontal lines indicate stream bed elevation for each station.

FIGURE 13. Probability distribution curve comparison of surface water elevations at stream channels W1, W2, and SG3. Note that an arbitrary elevation datum applies to this chart.

4.3 Baseflow Analysis

Rainfall measurements were evaluated to identify interludes for which stream flows were expected to be dominated by baseflow contributions. Figure 14 provides baseflow hydrographs for W2 that coincide with spring (pre-leaf emergence) and early summer (post-leaf emergence) periods. Each hydrograph represents an eight-day span bracketed by rainfall events.

Comparison of the April and June hydrographs demonstrates the seasonal disparity of discharge – higher flows in early spring versus early summer. The June 2007 hydrograph also reveals diel patterns indicative of ET processes whereby daily discharge peaked during overnight hours in which plant transpiration and evaporation rates exhibit lowest magnitude. Note that daylight discharge effectively declined to zero by the second day following rainfall verification of intermittent status.

Figure 15 illustrates hydrographs for W1 and W2 during the recession segment period that occurred between 4 April and 12 April 2007. Variation in the baseflow recession constant for the two stream channels indicates differences regarding the outflow response of each subcatchment.

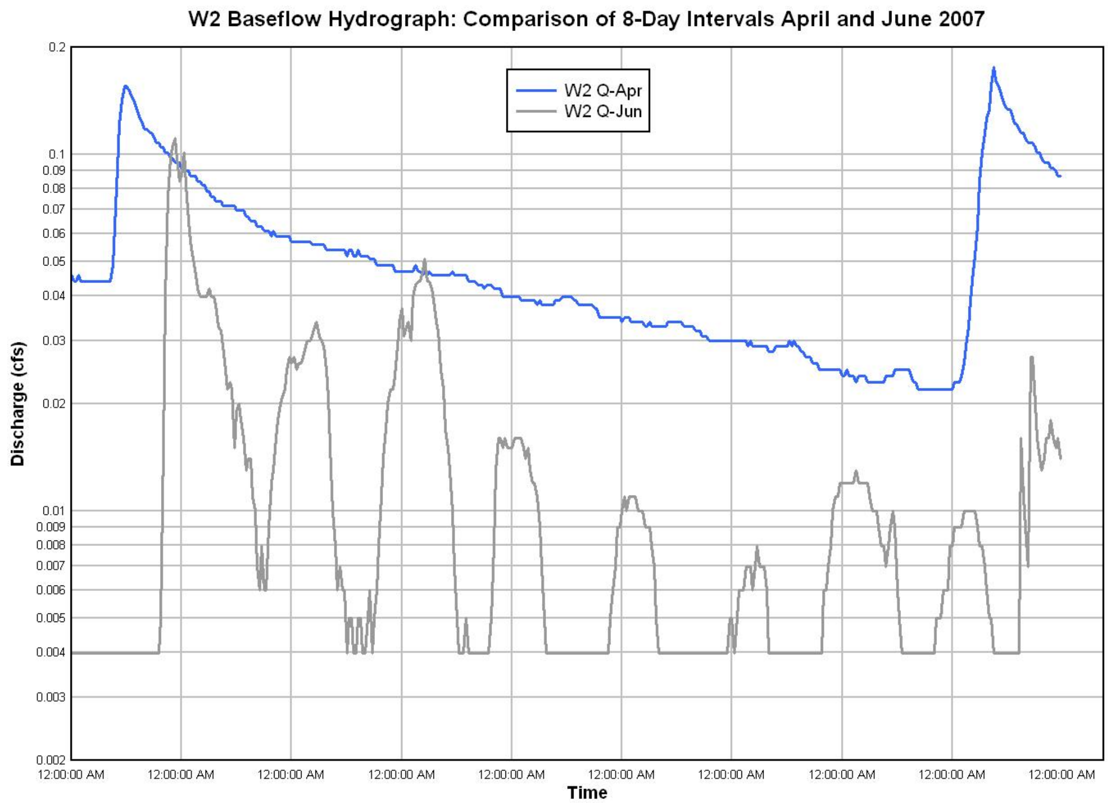


FIGURE 14. Baseflow hydrograph for W2 – pre and post-leaf emergence periods.

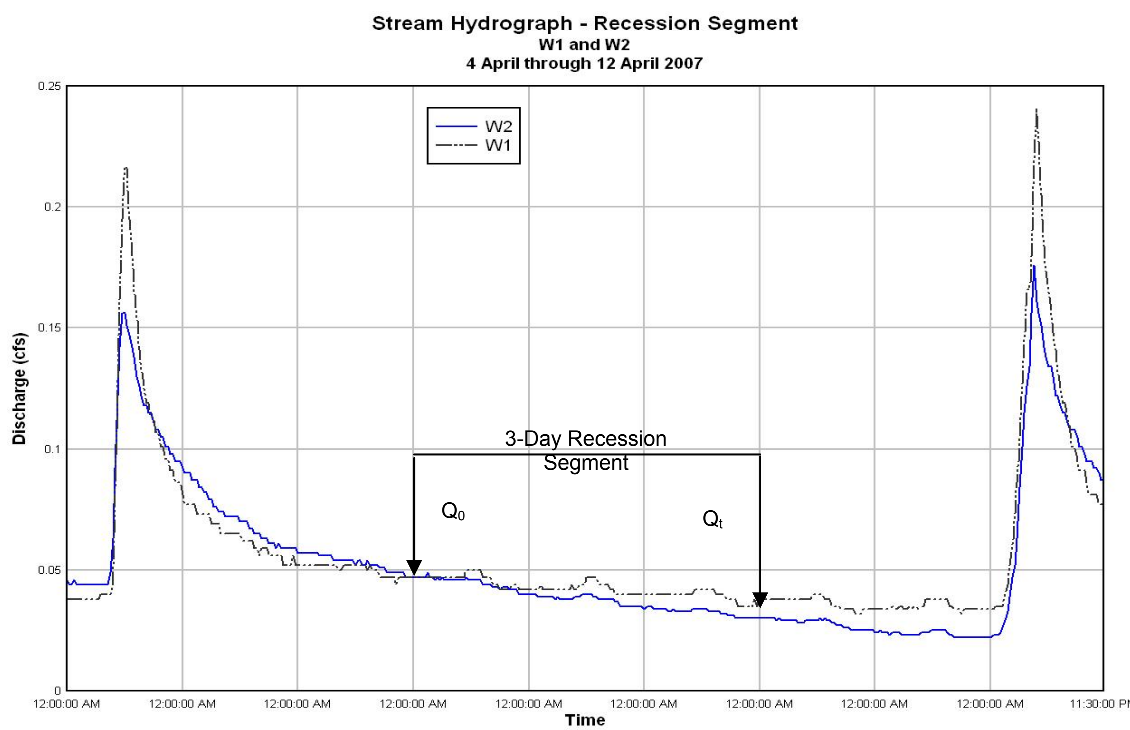


FIGURE 15. Recession constant trends for W1 and W2 based on rain-free hydrograph segment that occurred 6 April through 11 April 2007. Recession constant, k = Q_t/Q_0. k values were calculated for W1 and W2 for 3-day span indicated.

Figure 15 is a graphical examination of the same 8-day recession segment plotted for W1 and W2 that occurred early April 2007. The recession constant (i.e., k_b from Equation 7) calculated for W1 was 0.93; for W2 the recession constant was 0.86. The higher recession constant value for W1 versus W2 indicated that contributions to discharge by baseflow processes were more dominant for the East subcatchment; i.e., area that includes a prominent wetland (Brodie et al. 2007b).

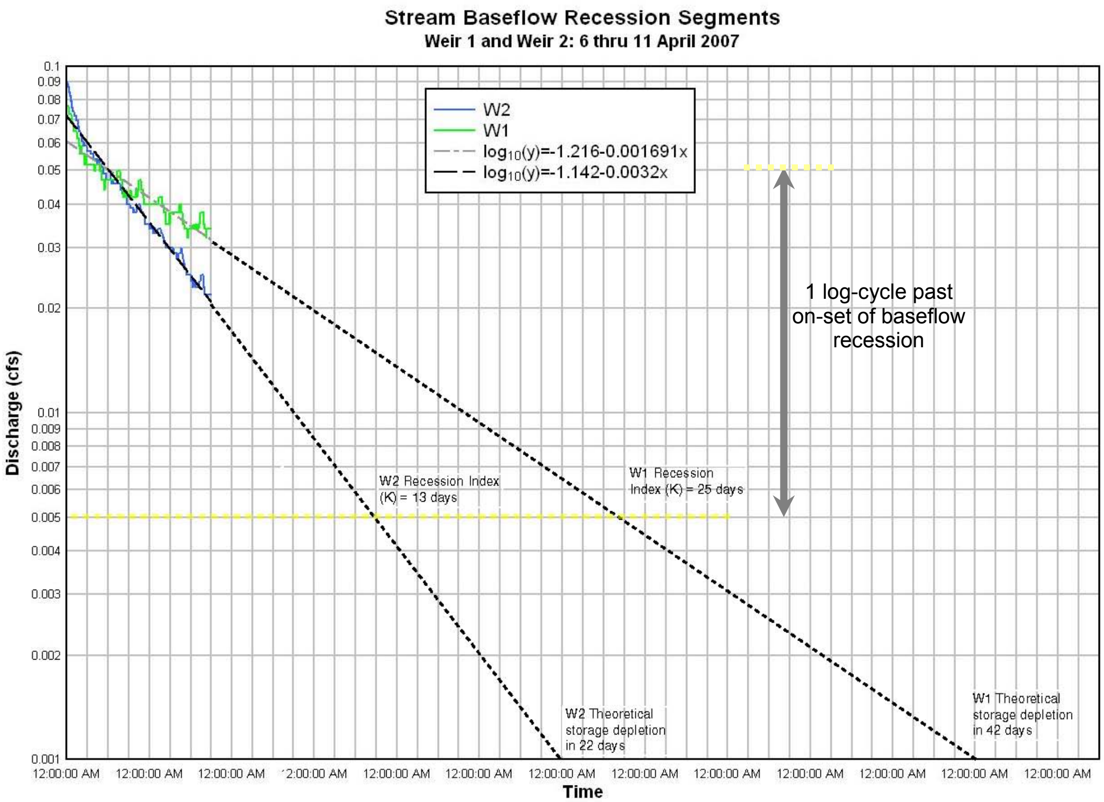


FIGURE 16. Semi-log plot of the recession segments for W1 and W2 from early April 2007. Linear best-fit models were extrapolated by 1 log-cycle to calculate baseflow recession index (K) for each tributary. K_{W1} = 25 days; K_{W2} = 13 days. Extrapolation was extended to Q = 0.001 cfs to estimate a theoretical residence time to fully deplete baseflow storage for each tributary as: 42 days for W1 and 22 days for W2.

Similar to the recession constants calculated according to Equation 7, the baseflow recession index (K) values obtained by graphical solution depicted on Figure 16 indicated higher stability of discharge from W1 (K = 25 days) versus W2 (K = 13 days).

In addition to providing the graphical solution for baseflow recession index (K), Figure 16 also illustrates extrapolation to a theoretical zero discharge (herein, assumed = 0.001 cfs) to estimate a full depletion cycle (Vitvar et al. 2002). Storage depletion is described as the time in which the (un-replenished) baseflow storage compartments completely drain. As indicated on Figure 16, storage depletion would occur in 42 days for W1 and 22 days for W2.

Approximately 0.8 inches of rainfall was measured on 4 April 2007. Using Equation nos. 8 and 9, the baseflow component was separated from overall of stream flow in the aftermath of the 4 April event for W1 and W2. Figure 17 depicts graphically solution of the recession curve displacement approach for the 4 April 2007 storm in order to calculate the volume of groundwater recharge derived from the 4 April 2007 storm event. Based on the graphical solution for K shown in Figure 16, critical times (t_c) were calculated for both W1 and W2 according to Equation no. 9, then Equation no. 8 was solved for the event-derived groundwater recharge volume component (R) unique for the W1 and W2 subcatchments.

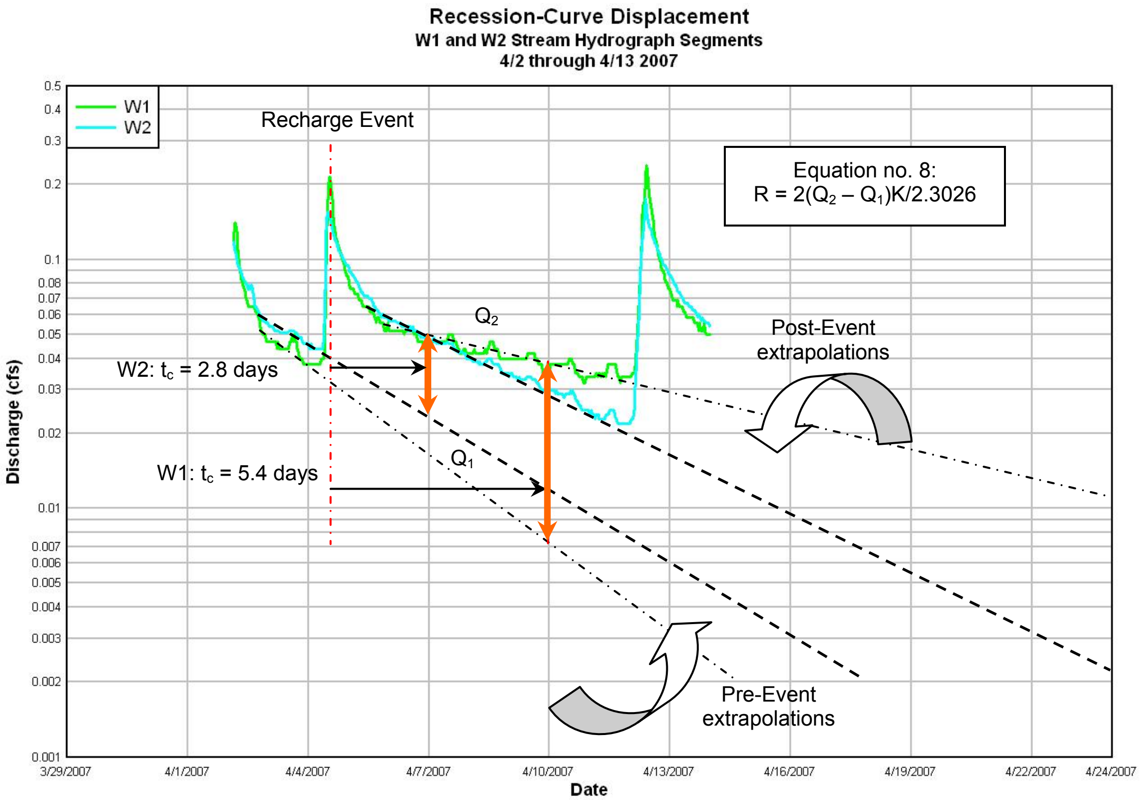


FIGURE 17. Comparison of subcatchment area-adjusted discharge from W1 (i.e., includes East subcatchment and approximately 30% of area comprised of forested wetland) and W2 (i.e., combination West and Central subcatchments and <5% comprised of wetland) to demonstrate the event-based groundwater recharge component (R).

As indicated based on review of Figure 17, the two subcatchments in the study area responded differently to the 4 April rain event. On an area-adjusted basis, estimated the groundwater recharge for W1 was 0.35 inches, whereas for W2 the groundwater recharge amounted to 0.06 inches.

Figure 18 illustrates the comparison of discharge in stream channels at W1 and W2 following adjustment to subcatcment area for period April through June 2007. In contrast to the much larger catchment area of W2 (approximately 105 acres), area-adjusted discharge from W1 was 20% greater than W2 – *until* the on-set of intermittent flow status occurred in W1, after which time discharge from W2 exceeded discharge from W1 in response to every rainfall episode except for the first week of June. This observation adhered to the dominant pattern reported by Bullock and Acreman (2003) for headwaters wetlands – i.e., that wetlands efficiently convey water to headwaters streams, presumably because of pre-existence of wetted soil conditions and landscape positioning at the interface of preferential local flowpaths.

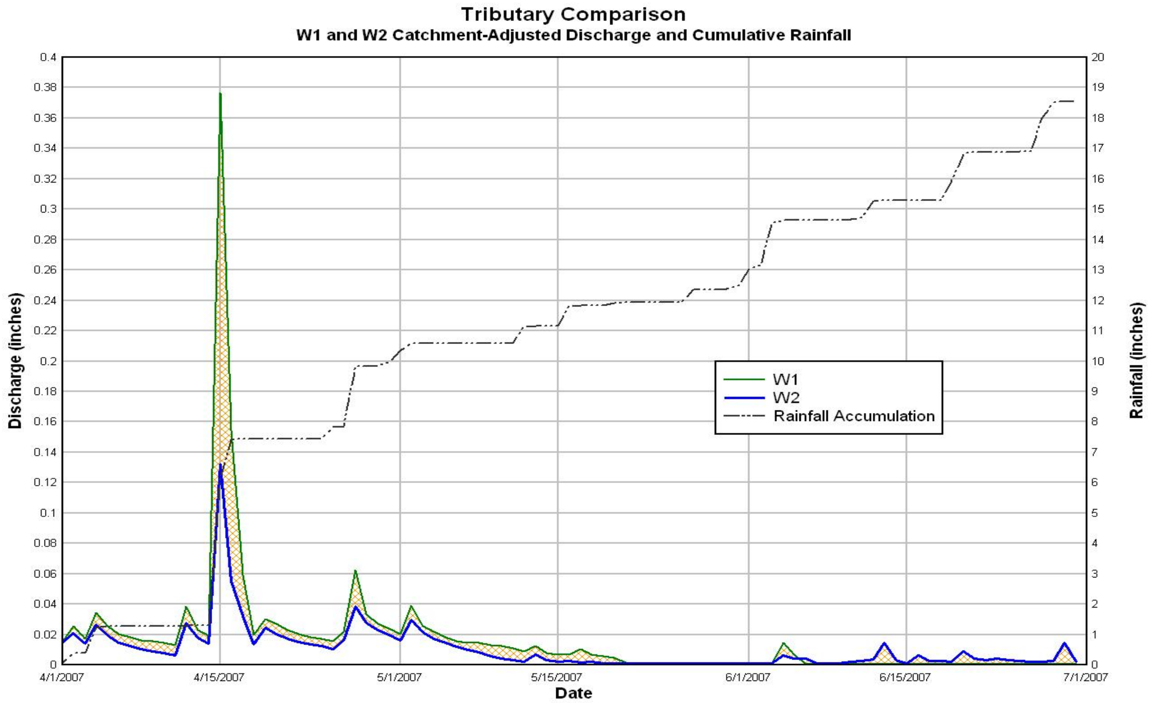


FIGURE 18. Comparison of subcatchment area-adjusted discharge from W1 (i.e., includes East subcatchment and approximately 30% of area comprised of forested wetland) and W2 (i.e., combination West and Central subcatchments and <5% comprised of wetland).

As indicated by review of Figure 18, the area-adjusted baseflow output response was greater for the wetland-dominated subcatchment.

In combination, Figures 15 – 18 and the various parameters derived from each, support the inference that the functional hydrologic role of wetlands in the study area is as settings of preferential storage and release for local flowpaths.

4.4 Biological Metrics

During the course of eight salamander survey events, greater than 950 salamanders were enumerated. Four different salamander species were encountered in the study area including redbacked (*Plethodon cinereus)*, northern two-lined (*Eurycea bislineata)*, northern red (*Pseudotriton r. ruber)*, and northern dusky (*Desmognathus f. fuscus*). Redbacked salamanders remain terrestrial throughout their life cycle and thus were omitted from evaluation regarding hydric status; the remaining three species exhibit biphasic life histories in which they are aquatic as larvae and terrestrial as adults. Northern red salamanders exhibit a multi-year aquatic phase prior to transformation into terrestrial adults; northern dusky salamanders are able to hasten transformation from aquatic to terrestrial forms in response to hydroperiod. Northern two-lined salamanders also exhibit a multi-year aquatic phase, but because aquatic and terrestrial forms were not as readily discriminated in the field, separate life stages were lumped for evaluation.

Table 8 summarizes salamander occurrence data according to three hydric regimes, four salamander species, and eight survey events conducted from March through September 2008.

TABLE 8. SUMMARY OF SALAMANDER SURVEY DATA.

STATION / EVENT DATE	SUM of INTERMITTENT STATIONS								
	3/14/2008	4/11/2008	4/30/2008	5/23/2008	6/13/2008	7/15/2008	8/14/2008	9/19/2008	SUM
Plethodon cinereus redback phase									
Adult	2	9	7	2	8	1	1	2	32
Sub-Adult	0	0	0	3	0	0	0	0	3
Larvae	0	0	2	0	0	0	0	0	2
Subtotal	2	9	9	5	8	1	1	2	37
Plethodon cinereus leadback phase									
Adult	4	2	3	1	2	1	3	2	18
Sub-Adult	0	0	0	0	0	1	0	0	1
Larvae	0	0	1	0	0	0	0	0	1
Subtotal	4	2	4	1	2	2	3	2	20
Subtotal Combined *P. cinereus*	6	11	13	6	10	3	4	4	57
Eurycea bislineata northern two-lined									
Adult	0	1	0	0	2	0	2	1	6
Sub-Adult	0	0	0	0	0	0	0	0	0
Larvae	0	1	0	0	0	0	0	0	1
Subtotal	0	2	0	0	2	0	2	1	7
Desmognathus f. fuscus northern dusky									
Adult	0	1	2	9	10	9	24	10	65
Sub-Adult	0	0	0	0	1	0	0	5	6
Larvae	0	0	1	1	0	0	0	0	2
Subtotal	0	1	3	10	11	9	24	15	73
Pseudotriton r. ruber northern red									
Adult	0	0	0	0	0	0	0	0	0
Sub-Adult	0	0	0	0	0	0	0	0	0
Larvae	0	0	0	0	0	0	0	0	0
Subtotal	0	0	0	0	0	0	0	0	0
Total Observed Individuals:	6	14	2	16	23	12	30	20	123
Total Unique Taxa:	1	3	2	2	3	2	3	3	3
Plethodon cinereus	x	x	x	x	x	x	x	x	x
Eurycea bislineata		x			x		x	x	x
Desmognathus f. fuscus		x	x	x	x	x	x	x	x
Pseudotriton r. ruber									

STATION / EVENT DATE	SUM of PERENNIAL STATIONS								
	3/14/2008	4/11/2008	4/30/2008	5/23/2008	6/13/2008	7/15/2008	8/14/2008	9/19/2008	SUM
Plethodon cinereus redback phase									
Adult	0	2	0	4	0	0	0	0	6
Sub-Adult	0	0	0	0	0	0	0	0	0
Larvae	0	0	0	0	0	0	0	0	0
Subtotal	0	2	0	4	0	0	0	0	6
Plethodon cinereus leadback phase									
Adult	2	0	0	0	1	0	0	0	3
Sub-Adult	0	0	0	0	1	0	0	0	1
Larvae	0	0	0	0	0	0	0	0	0
Subtotal	2	0	0	0	2	0	0	0	4
Subtotal Combined *P. cinereus*	2	2	0	4	2	0	0	0	10
Eurycea bislineata northern two-lined									
Adult	1	6	1	0	3	3	3	3	20
Sub-Adult	0	0	0	0	0	0	0	0	0
Larvae	0	0	0	0	0	5	1	0	6
Subtotal	1	6	1	0	3	8	4	3	26
Desmognathus f. fuscus northern dusky									
Adult	0	0	0	0	1	2	2	0	24
Sub-Adult	0	0	0	0	1	0	0	0	1
Larvae	24	40	38	26	29	38	29	25	230
Subtotal	24	40	38	26	31	40	31	25	255
Pseudotriton r. ruber northern red									
Adult	0	0	0	0	0	0	0	0	0
Sub-Adult	0	0	0	0	0	0	0	0	0
Larvae	1	3	0	0	0	0	0	1	5
Subtotal	1	3	0	0	0	0	0	1	5
Total Observed Individuals:	28	53	39	34	36	48	35	29	302
Total Unique Taxa:	4	4	2	2	3	2	2	3	4
Plethodon cinereus	x	x		x	x				x
Eurycea bislineata	x	x	x		x	x	x	x	x
Desmognathus f. fuscus	x	x	x	x	x	x	x	x	x
Pseudotriton r. ruber	x	x						x	x

STATION / EVENT DATE	SUM of GSI STATIONS								
	3/14/2008	4/11/2008	4/30/2008	5/23/2008	6/13/2008	7/15/2008	8/14/2008	9/19/2008	SUM
Plethodon cinereus redback phase									
Adult	1	5	2	3	2	1	2	2	18
Sub-Adult	0	0	0	0	0	0	0	0	0
Larvae	0	0	1	0	0	0	0	0	1
Subtotal	1	5	3	3	2	1	2	2	19
Plethodon cinereus leadback phase									
Adult	3	9	7	1	1	1	3	0	25
Sub-Adult	0	0	0	0	0	0	0	0	0
Larvae	0	0	0	0	0	0	0	0	0
Subtotal	3	9	7	1	1	1	3	0	25
Subtotal Combined *P. cinereus*	4	14	10	4	3	2	5	2	44
Eurycea bislineata northern two-lined									
Adult	10	17	4	1	6	7	9	4	58
Sub-Adult	0	0	0	0	0	6	0	0	6
Larvae	0	0	2	0	0	1	0	0	3
Subtotal	10	17	6	1	6	14	9	4	67
Desmognathus f. fuscus northern dusky									
Adult	1	10	3	3	18	27	30	17	109
Sub-Adult	0	0	1	1	25	0	0	11	38
Larvae	17	29	37	24	28	48	40	21	244
Subtotal	18	39	41	28	71	75	70	49	391
Pseudotriton r. ruber northern red									
Adult	0	0	1	0	1	0	0	6	8
Sub-Adult	0	0	0	0	0	2	1	0	3
Larvae	0	3	3	2	2	0	0	3	13
Subtotal	0	3	4	2	3	2	1	9	24
Total Observed Individuals:	32	73	61	35	83	93	85	64	526
Total Unique Taxa:	3	4	4	4	4	4	4	4	4
Plethodon cinereus	x	x	x	x	x	x	x	x	x
Eurycea bislineata	x	x	x	x	x	x	x	x	x
Desmognathus f. fuscus	x	x	x	x	x	x	x	x	x
Pseudotriton r. ruber		x	x	x	x	x	x	x	x

Total No. Salamanders Identified for All Stations and All Events: 951

In sum, 951 salamanders were encountered during the survey period. As indicated above, all salamanders and all life stages were encountered in groundwater discharge (referred herein as GSI) settings. Northern red salamanders were not encountered in intermittent stream reaches; aquatic-phase northern dusky salamanders were rarely encountered in intermittent stream reaches. Moreover, subadult and adult northern red salamanders only were encountered in GSI settings; larval northern red salamanders were encountered in perennial and GSI settings.

5 INTERPRETATIONS

Converging lines of evidence were developed and evaluated as part of this study in order to characterize interactions between surface and groundwater flow systems for a headwaters catchment in CH diabase terrane.

The results of water balance calculations suggest limited propensity for groundwater recharge of intermediate and/or regional flowpaths. The thin, clay-rich soils that developed through chemical weathering of diabase minerals limit both water infiltration and storage capacity in CH terrane. Local flowpaths with brief residence times predominate in headwaters catchments. Stream channels and wetland settings serve to efficiently drain the landscape and the hydroperiod for stream reaches, wetlands, and springs was correlated to landscape position and elevation. Furthermore, because the CH diabase lacks primary porosity and has limited secondary porosity, the opportunity for development of deep (i.e., regional) groundwater flowpaths is nearly non-existent.

Based on a water balance approach applied to the 12-month period April 2007 through April 2008, the amount of water that entered the headwaters catchment and was potentially available for intermediate and deep groundwater recharge was estimated *conservatively* at less than 2 inches. Others (URS 2003; Sloto and Schreffler 1994; Low et al. 2002; Risser et al. 2005) estimated higher annual groundwater recharge rates in the region that ranged from approximately 6 to 10+ inches; however, such estimates generally were not specific with respect to, nor intended to quantify differences between, local and intermediate/regional flowpaths.

Commonly, ET is the least well-developed term in water balance equations (derived as the residual value) and typically, ET is the single largest annual output process in a headwaters catchment. In the current study, ET was estimated based on the Hargreaves – Samani (1982) approach that incorporates day-length and daily temperature data; collectively, considered as the two most important variables that underlie and drive ET processes.

Of six alternative scenarios used to solve the water balance equation, two outcomes were considered superior to the others based on greater reliance of site-specific, empirically-derived data. As portrayed on Table 7, alternative no. 1 resulted in groundwater output estimated at 2.5 inches and alternative no. 2 resulted in -1.7 inches for the year ended April 2008. Both alternatives utilized local rainfall measurements and the Hargreaves – Samani method for ET estimation (also using local temperature measurements).

Alternative no. 1 based stream outflows on the empirically-derived cumulative discharge value modeled for SG3 (i.e., the study catchment outlet). Cumulative discharge at SG3 was known to be an underestimate of actual discharge; therefore, the residual value in the water balance equation was assumed (within limits of uncertainty) to exceed the calculated value. Alternative no. 2 based stream outflows on USGS-derived regionalized statistics applied to normal precipitation trends. Other regionalized low and baseflow statistics appeared to reflect actual site conditions well (i.e., harmonic mean annual discharge was comparable to measured summer baseflow at SG3). Moreover, the annual water balance deficit (i.e., -1.7 inches) that was calculated by alternative no. 2 was plausible given the observed reduced seasonal high water table elevation in the study area catchment documented from 2007 to 2008.

Distinguishing flowpath structure is fundamentally essential to the development of effective water resource management strategies. In CH diabase terrane, headwaters catchments are dominated by local flowpaths. Groundwater moves in shallow settings; lateral flows dominate; and, residence times are brief. Based on this study, residence time in the shallow groundwater zone was estimated to be less than 45 days, even during seasonal periods in which ET processes are diminished.

During seasonal periods when ET demand is low, water input rates exceed outputs and a temporary storage build-up results. Temporary storage is manifested as a rise in the shallow water table. The thin soil cover above the CH diabase limits groundwater storage capacity; therefore, water preferentially drains from the catchment via GSI discharge settings that coincide with stream channels, springs, and wetlands. During seasonal periods when ET demand is high, water output process rates exceed inputs and a draw-down of storage compartments results.

According to traditional models of shallow (i.e., local) groundwater flowpath, water in the near-surface saturated zone is expected to adhere to a subdued pattern that corresponds approximately to surface topography (Low et al. 2002). In the study area and common in the CH diabase terrane in general, forested wetlands develop below breaks in slope. Results of this study indicated that such wetlands likely developed due to inherent moisture-retaining traits of the clay-rich soils that develop above diabase. Additionally, the abrupt change in slope causes shallow groundwater flowpaths to emerge at the land surface. The gentler topographic gradient, coupled with microtopographic features facilitates water storage.

Differences in hydroperiod across the headwaters catchment study area were attributed primarily to landscape position and the response of a seasonal dynamic equilibrium.

The following sequence of images illustrates portions of the study area that were expected to support GSI discharge (into wetlands, springs, and/or stream channels) on seasonal basis.

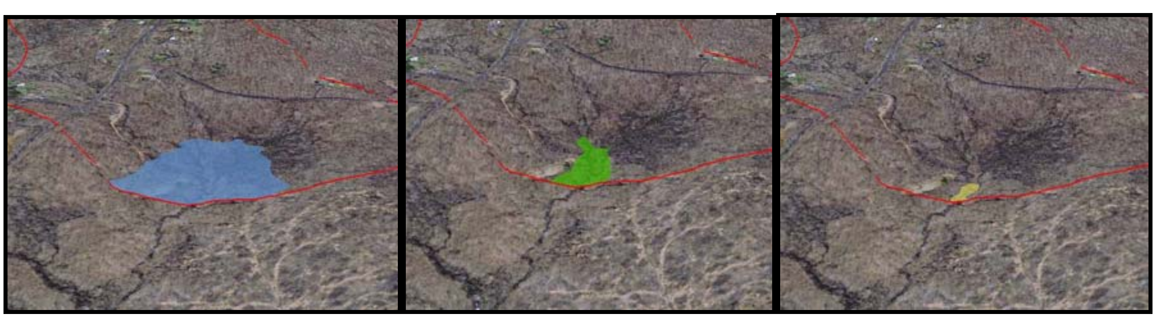


FIGURE 19. Sequence shaded to depict seasonal variation in groundwater outflow zone in the study area (Left over-winter, Center late spring, Right summer to fall).

Headwaters catchments on CH diabase occupy positions of regional maximum relief and are not subject to intermediate or regional groundwater input flowpaths due to landscape position alone. Soils that develop in diabase terrane generally are thin and clay-rich and limit water storage capacity. Additionally, CH diabase lacks primary porosity and secondary porosity features are limited. Residence time for water that enters the headwaters catchment as rainfall was anticipated to be brief (i.e., << 1 year) because storm flow, local groundwater flowpaths, and high seasonal ET rates predominate.

Water level data during the study period were consistent with the generalized seasonal pattern reported by various researchers of storage recharge during winter and draw-down (storage release) across the period from the on-set of growing season conditions and forest leaf-out to first killing frost. Potential groundwater recharge was restricted to an approximately 6 month window in which rainfall exceeds PET demand. Even during an above-normal rainfall year (April 2007 – April 2008), water balance calculations herein suggested that water may be unavailable for intermediate or regional (deep) groundwater recharge altogether.

The hydrologic role of headwaters wetlands that occur in CH terrane is comparable to the low-order stream networks in such catchments – that is, the settings serve as drains for the local landscape. Baseflow recession constants, baseflow recession indices, and unit area-adjusted discharge comparisons of output through channels that arise principally from wetland (W1) versus upland (W2) demonstrated the functional hydrology role of wetlands in the catchment as follows: wetlands efficiently drain their surroundings during the period when ET demand is less than rainfall (i.e., temporary water storage is maximized) and during the season when water table elevation is high.

The event-based groundwater recharge component of the April 2007 stream hydrograph segment suggested that preferential groundwater recharge occurred in the W1 subcatchment compared to the W2 subcatchment (i.e., 83% higher apparent groundwater recharge for W1). An alternate and more plausible interpretation of this information; however, is to consider that the prominent wetland in the W1 subcatchment was more efficiently connected to the shallow groundwater zone than was the W2 stream channel network. With a broader water table/land surface interface, the W1 subcatchment would more efficiently capture and transmit groundwater to the surface; thereby creating an artifact of the appearance of relatively higher area-adjusted recharge.

The inference of better connection between groundwater and wetlands in the study area also is supported by Bullock and Acreman's (2003) conclusion that headwaters wetlands are well-connected to shallow subsurface flowpaths in manners that readily transmit groundwater to streams. This study demonstrated that broader conclusion at least during the seasonal for which water table position was high. Furthermore, the local landform and clay-rich soils combine to efficiently store a fraction of the seasonal excess water and release that storage component on some delayed basis as part of the local flowpath framework. During seasons when ET demand exceeds rainfall, moisture is removed efficiently from the catchment by ET. Throughout the year, lateral draining through local preferential groundwater flowpaths at GSI discharge settings persists provided the water table elevation intersects the land surface – the persistence of one such flowpath was demonstrated in the stream channel at and slightly upstream of SG3 where surface flow was observed for 100% of the manual measurement visits – this point of origin for the stream remained stable throughout the study period.

The application of biological surveys verified findings regarding the hydroperiod dynamics in the study area. Stream-dependent salamander abundance, species richness, and life stage variation were correlated to flow regime as follows:

- Salamander abundance, species richness, and life stage variation were lowest in intermittent reaches; and,
- Salamander abundance, species richness, and life stage variation were highest in GSI discharge reaches.

Moreover, the GSI discharge setting that was positioned “high” in the study area catchment (GSI-4) was an outlier with respect to salamander occurrence in the local network of intermittent stream channels and with respect to other GSI settings. The hydroperiod for GSI-4 was shorter than for the GSI discharge reaches positioned at lower catchment elevations. In comparison to the other GSI salamander survey stations, GSI-4 exhibited a distinct and unique trend; for GSI-1 through GSI-3 (inclusive), three stream-dependent salamander species were detected and for two such species, juvenile and adult members were confirmed. At GSI-4, the only stream-dependent salamander species detected was northern dusky; however, juvenile and adult both were well-represented. In the intermittent stream reaches located nearest GSI-4, overall salamander abundance was markedly lower and occurrence by northern dusky juveniles was especially sparse – as expected by life history requirements, larval dusky salamanders were not detected in intermittent reaches after the seasonal on-set of intermittent flow status. Presumably, adult northern dusky salamanders use the intermittent reaches for refuge (i.e., higher relative moisture) during summer/dry periods.

This study demonstrated the importance of GSI discharge settings in the headwaters forest to the stream-dependent salamander community overall. The GSI discharge settings in the study area were vital for salamander breeding and larval development. Moreover, when weighted by surface area (or some linear channel metric), the ecological “value” of GSI in the context of salamander community is emphasized. GSI settings in the study area, although not quantified, accounted for a small fraction of either the length (or surface area) of both intermittent and perennial reach stream channels.

Not only were GSI discharge settings shown to be crucially significant for the overall salamander community, particularly in parts of the catchment that supported year-round drainage, but the relative importance of GSI discharges that exhibit shorter hydroperiods also was demonstrated as these settings represented “hot spots” for congregation and breeding by northern dusky salamanders in portions of the catchment that exhibit relatively shorter hydroperiod (i.e., due to higher elevation).

This study also suggested that the potential exists to conduct targeted, “rapid” salamander surveys within forested headwaters catchments during early spring in order to readily identify and map the overall hydroperiod status of the catchment. Stream-dependent salamander richness and abundance across all life stages is maximized at GSI discharge settings and minimized in intermittent reaches. Moreover, given the short, shallow, localized flowpaths in such settings, management strategies (i.e., local ordinances; state regulations) that preserve/protect the structure and integrity of those flowpath networks are essential toward the proclaimed regulatory objective of meeting EV status.

The following chart displays the salamander occurrence data in format that emphasizes the hydric status categories.

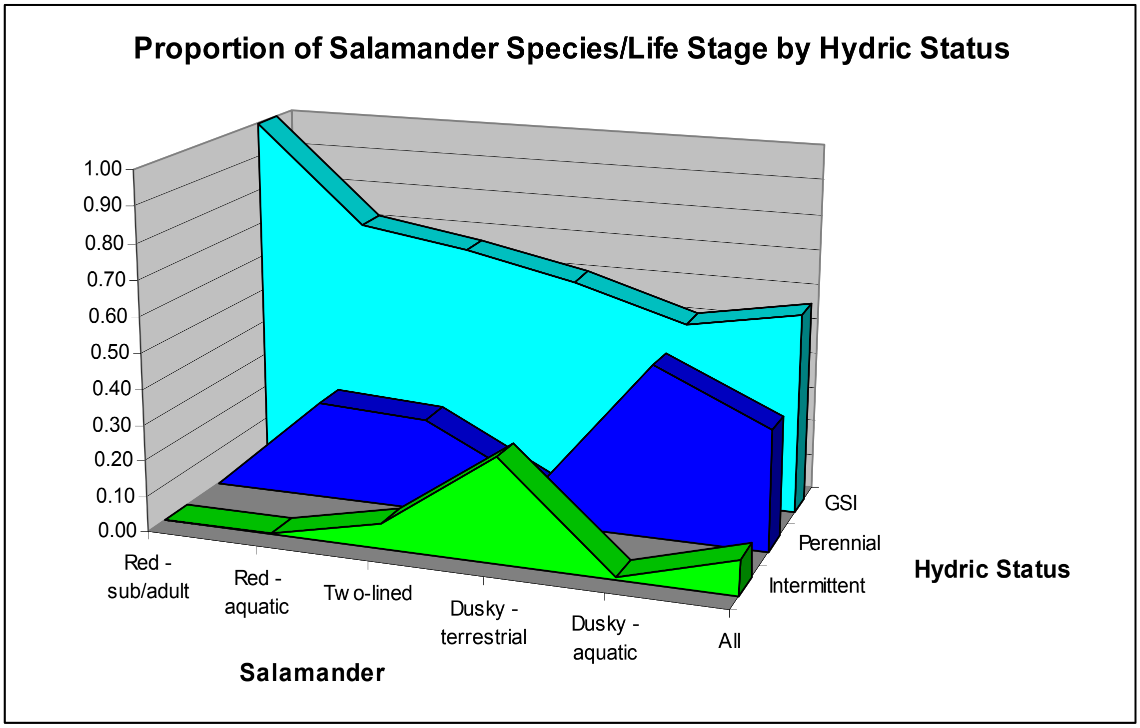


FIGURE 20. Chart comparison of salamander survey data with emphasis on hydric status.

Based on review of Figure 20, the comparative importance of GSI discharge settings to the salamander species encountered in this study across all life stages is evident.

Although not "measured" by this study, the CH diabase headwaters catchment conceptual model can be extended to expect that intermediate groundwater flowpaths likely result in preferential lateral movement at the upper CH diabase interface. Also, at the intersection of the diabase intrusion with its metamorphic rind, hydraulic head and porosity differentials (higher porosity due to secondary features is anticipated for metamorphic rind) should create preferential flowpaths with an expectation that discharge settings (i.e., springs/seepage faces) would develop along escarpment face and base or potentially promote regional groundwater pathway structure.

Figure 21 illustrates the SGL56 study area in context of the contact between CH diabase and Lockatong Formation country rock. Intermediate groundwater flowpaths can be expected to develop at the upper interface of the diabase with preferential lateral flow toward the downgradient edge of the intrusion. The metamorphic rind may be expected to exhibit higher secondary porosity relative to the CH diabase. Moreover, the escarpment is expected to generate a head differential sufficient to facilitate recharge into the metamorphic rind and country rock and/or lead to development of groundwater discharge features along the escarpment.

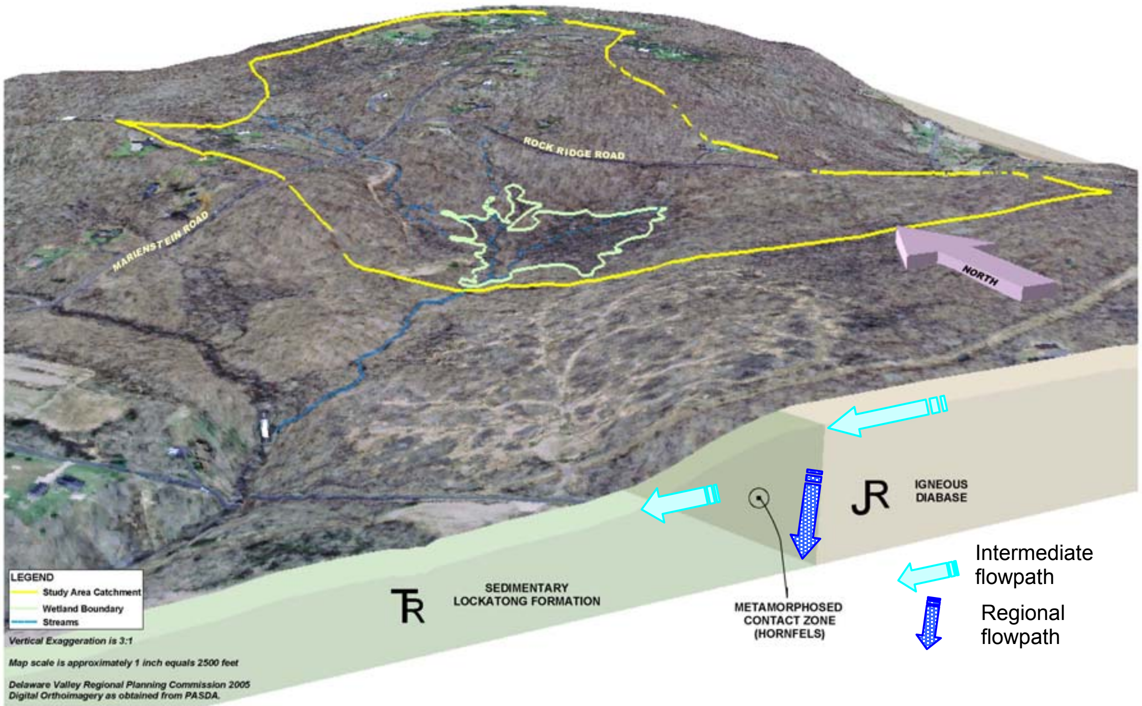


FIGURE 21. Three-dimensional perspective depicting the study area and hydrologic monitoring array. Base image is digital aerial photograph from 2005. Vertical exaggeration is 3:1. Separation between land surface and bedrock surface is arbitrary.

Intermediate and regional groundwater flowpaths are not likely to occur or develop on CH diabase; however, due to its comparatively higher landscape position and differences in primary and/or secondary porosity, the contact between CH diabase, its metamorphic rind, and Lockatong Formation country rock may facilitate development of intermediate and/or regional groundwater flowpaths.

6 CONCLUSIONS

This report summarizes geologic and hydrogeologic setting information reported by others as means to develop a conceptual model of the hydrological framework in the study area. A hydrology monitoring network comprised of both automated and manual-read devices including rainfall gauges, stream staff gauges, weirs, and piezometers was established in a low-order, forested tributary of Rapp Creek that is underlain by CH diabase. Stream-dependent salamander abundance also was surveyed repeatedly at a series of discrete stations throughout the study area. Hydrology data sets were compiled and evaluated to characterize variables for application in water balance calculations, statistical evaluations, and baseflow analyses. Salamander data were evaluated to assess potential biological responses related to hydroperiod.

The overall findings of the study were interpreted in the context of stewardship of EV/Wild and Scenic watershed resources as well as potable supply management implications.

The CH diabase sheet represents a regional topographic high point such that groundwater recharge to/through diabase from external terrane is precluded by the greater hydraulic head afforded by its landscape position alone. Additionally, in general, residual soil types (i.e., clay-rich) that derive from diabase weathering are not expected to readily facilitate groundwater infiltration. Also, the thin soil layer that developed atop the CH diabase from chemical weathering processes limits groundwater storage capacity. Moreover, especially given the intrinsic lack of primary porosity and scarcity of secondary porosity features in the CH diabase sheet bedrock “monolith”, regional (deep) groundwater flowpaths that originate in the area are expected to be uncommon.

Overall, local groundwater flow paths dominate diabase headwaters catchments and the potential for groundwater recharge of deep or longer-term flowpath structures is minimal. This study estimated intermediate and deep groundwater recharge potential conservatively at less than 2 inches per year (equivalent to less than 5% of annual precipitation). Others have developed estimates of annual groundwater recharge for the region that ranged from approximately 6 to 10+ inches; however, such studies either included or exclusively emphasized local, shallow groundwater flowpaths.

This study also demonstrated that wetland settings that commonly occur within the diabase terrane in the region function as net drains to the local landscape – comparable to gaining stream reaches and springs. In practical terms, headwaters forests, springs, wetlands, and streams are functionally inseparable due to interconnection of the shallow groundwater flowpath system. Such functional inseparability complicates the regulatory framework and land management approaches in diabase terrane headwaters because of the inherent difficulty in distinguishing one part of the system from another.

Results of this study also indicated the possibility of using stream-dependent salamanders as a surrogate to rapidly assess and gain insight into the hydrologic regime of forested, headwaters catchments. The community of stream-dependent salamanders responded to hydric-based environmental cues that were predictable based on life history requirements. In principle, salamander community surveys could be performed and results interpreted as a means to “map” the relative hydroperiod/hydric regime of springs, wetlands, and stream reaches.

This study demonstrated the importance of shallow flowpath networks for headwaters catchments in diabase terrane with implications for water supply management and environmental resource stewardship.

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APPENDIX A: PHOTOGRAPH LOG

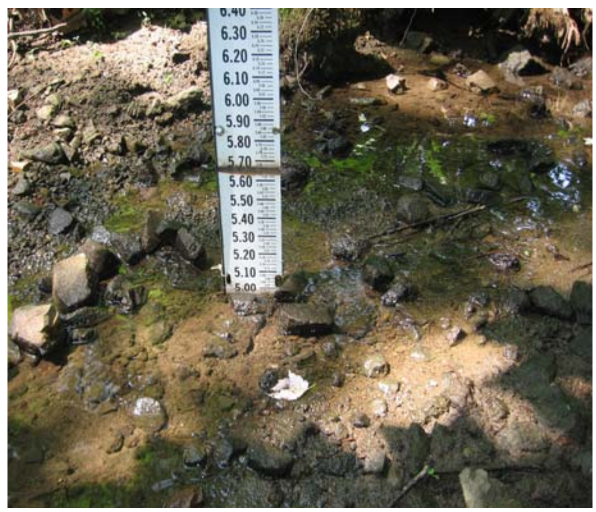
<table>
<tr><td></td><td></td></tr>
<tr><td>Photograph 1. Rain Gauge in field – tipping bucket type rain gauge located in game feed lot in SGL56. Rain gauges in field and forest were compared to assess effect of forest canopy upon interception (May 2007).</td><td>Photograph 2. Rain Gauge in forest – tipping bucket type gauge located within deciduous forest between PZ1 and PZ2. Bucket calibrated to tip in response to each 0.01-inch rain event; datalogger records date and time of every bucket tip event (April 2007).</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Photograph 3. Weir No. 1 (W1) view of water passage through V-notch. The low-profile weir design was intended to withstand high flow episodes by over-topping, but facilitated baseflow discharge estimates only. Weir face and pool lined with plastic sheeting to reduce by-pass flows (March 2007).</td><td>Photograph 4. W1 view of polyvinyl sheet lining pool; staff gauge evident in pool at right; PVC screen housing for pressure transducer visible in background (March 2007).</td></tr>
</table>

APPENDIX A: PHOTOGRAPH LOG

Photograph 5. Weir No. 2 (W2) view of water passage through V-notch from bank – note housing and data cable for datalogger visible at left (March 2007).

Photograph 6. W1 view of downstream face of weir (March 2007).

Photograph 7. Piezometer No. 3 (PZ3) view of set-up for datalogger download. Note that PZ3 was situated within delineated wetland forest; image depicts period for which groundwater elevation was near annual minimum (October 2007).



Photograph 8. Staff Gauge No. 3 (SG3) viewed during baseflow status. Note that from March 2007 through October 2008, stream level at SG3 was not observed/measured lower than level depicted herein – the SG3 reach effectively represented onset of perennial flow status for this stream (late May 2007).

APPENDIX A: PHOTOGRAPH LOG

Photograph 9. Staff Gauge No. 1 (SG1) downstream side of Marienstein Road viewed during intermittent flow status. Note this drainage channel connects to W2 via the western sub-catchment (late May 2007).

Photograph 10. Staff Gauge No. 2 (SG2) downstream side of Rock Ridge Road viewed during intermittent flow status. Note this drainage channel connects to W2 via the central sub-catchment (late May 2007)

Photograph 11. W1 view of downstream face of weir depicting period of no-flow/intermittent status (late May 2007).

Photograph 12. W2 view of downstream face of weir depicting low-flow (late May 2007).

APPENDIX A: PHOTOGRAPH LOG

Photograph 13. Adult northern dusky salamander guarding eggs (August 2008).

Photograph 14. Northern two-lined salamander (September 2008).

Photograph 15. Aquatic life stage northern red salamander (June 2008).

Photograph 16. Subadult northern red salamander (August 2008).