Kirkwood-Cohansey Project

The Effect of Streamflow Reductions on Aquatic Habitat Availability and Fish and Macroinvertebrate Assemblages in Coastal Plain Streams

State of New Jersey · Pinelands Commission

Cover: Muskingum Brook below Tuckerton Road. Photograph taken by Nicholas A. Procopio.

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Abstract

The purpose of this study was to estimate changes to aquatic habitat availability and fish and aquatic-macroinvertebrate assemblages in coastal plain streams that may occur from groundwater withdrawals. Simulated streamflow reductions of 5, 10, 20 and 30 percent of average annual streamflow and the seven-day low-flow were calculated for fourteen study sites. Using study-site streamflow and channel morphology data, relationships were developed to estimate five physical habitat metrics including average stream width, stream depth, stream cross-sectional area, stream-reach volume, and stream velocity. A second set of relationships was then developed to estimate the percentage reduction to each habitat metric under the simulated streamflow-reduction scenarios. The average percentage decrease and variability of each habitat metric increased with successive streamflow reductions. Average percentage decreases in stream width, stream depth, stream cross-sectional area, and stream-reach volume were more pronounced for the simulated reductions of average flow, whereas the average percentage decreases in stream velocity were more pronounced for the simulated reductions of low flow. Models derived from a separate fish and macroinvertebrate study were used to estimate assemblage structure responses based on simulated reductions in average annual streamflow. The results of this study can be used to estimate the potential impact of groundwater withdrawals and subsequent streamflow reductions on available aquatic habitat and changes to fish and macroinvertebrate assemblages.

Introduction

Groundwater withdrawals and diversions necessary to meet the demands associated with increased development, agriculture, and other uses have the potential to alter baseline hydrologic patterns (Modica 1996), including changes to the characteristic magnitude, frequency, duration, and variability of stream discharge at any given point in a watershed (Poff et al. 1997, Brown et al. 2005). Changes in the natural flow regime may lead to alterations to the stream channel form (Wolman and Miller 1960) and structure (Leopold and Wolman 1957). Changes to either element may ultimately alter aquatic ecosystems (Poff et al. 1997, Postel 2000, Arthington et al. 2006, McKay and King 2006).

Simon (1989) described stream channels as being in a state of dynamic equilibrium through which channel width and bank-slope adjustments are driven by periods of aggradation and degradation resulting from variations in discharge over time. Channel adjustments resulting from modified hydrologic conditions have been described by numerous authors and include changes to channel width, depth, and velocity (Leopold and Maddock 1953, Merigliano 1997, Pizzuto 1986, Xu 2004), stream area (Leopold et al. 1964, Pizzuto 1994), sediment supply (Ferguson 1986, Rhodes 1987, Pizzuto et al. 2000, Emmett and Wolman 2001), stream power (Simon et al. 2007), and longitudinal connectivity (Bunn and Arthington 2002, Whiting 2002, Lexartza-Artza and Waineright 2009).

In-stream habitat availability is strongly guided by hydrogeomorphic variables, including discharge, channel width and depth, stream velocity, substrate size, bedload sediment, and flooding frequency (Resh et al. 1988). Environmental factors, including water temperature, dissolved oxygen, and water chemistry, also contribute to the maintenance of suitable habitat (Richter et al. 1996). Changes in discharge, channel dimensions, and sediment supply can lead to changes in aquatic habitat diversity and availability (Beschta and Platts 1986, Poff et al. 1997, Bunn and Arthington 2002, Crowder and Diplas 2002, Kennen and Ayers 2002) and may result in shifts in community dynamics (Vannote et al. 1980, Junk et al. 1989).

The purpose of this study was to estimate changes to aquatic habitat availability and fish and aquatic macroinvertebrate assemblages in streams of the New Jersey Pinelands when impacted by varying levels of simulated water withdrawals. Simulated streamflow-reduction scenarios of 5, 10, 20 and 30 percent of average annual streamflow and the seven-day low-flow statistic were derived for fourteen study sites and used to estimate changes to five habitat metrics, including average stream width, stream depth, stream cross-sectional area, stream-reach volume, and stream velocity. Models derived from a separate fish and macroinvertebrate study (Kennen and Riskin 2010) were used to estimate assemblage structure responses based on simulated reductions in average annual streamflow. This study, which uses data collected as part of the fish and macroinvertebrate study, was part of a larger research project designed to evaluate the potential effects of groundwater withdrawals on aquatic and wetland communities associated with the Kirkwood-Cohansey aquifer (Pinelands Commission 2003), the primary water-table aquifer in the Pinelands (Rhodehamel 1979a, 1979b).

Methods

Regional Setting

This study was conducted in the New Jersey Pinelands, which sits atop the Atlantic Coastal Plain physiographic province. The Cohansey sands and Kirkwood formation are the primary surficial components, which together function as one cohesive surficial aquifer. Thin veneers of discontinuous surficial deposits are located across the region (Zapecza 1989).

Groundwater discharge to forested Pinelands streams contributes 89% (50.8 cm) of annual runoff (Rhodehamel 1979b). Surface runoff, which is limited primarily to flooded swamps, is a small percentage of the overall stream discharge in part because precipitation can infiltrate the loose sandy soils at rates of 5.1 to 16 cm hr^{-1} (Rhodehamel 1970). Since overland flow is a minimal portion of the total discharge, streamflow tends to be uniform resulting in infrequent flash flooding (Rhodehamel 1979b). Groundwater withdrawals from the Kirkwood-Cohansey aquifer system were estimated at a total of 84 million gallons per day for 1994 (Nawyn 1997).

Study Area

This study was based on data collected during a fish and macroinvertebrate study (Kennen and Riskin 2010), where fourteen study sites were selected in the Mullica River Watershed (Figure 1, Table 1). Sites were limited to stream reaches in the Batsto River, Albertson Brook, Morses Mill Stream, and West Branch Bass River subbasins. Subbasin sizes ranged from 4.1 to 66.3 km^2. Although the number of reaches sampled as part of Kennen and Riskin (2010) ranged from two to four, two reaches of 100 meters in length were chosen at each site for consistency. At each reach, five transects were established twenty-five meters apart and perpendicular to the stream channel for a total of ten transects at each site.

Hydrologic Assessment

As part of Kennen and Riskin (2010), each study site was equipped with a staff gage which was read bi-weekly (twice per month) between November 2004 and September 2006 by either New Jersey Pinelands Commission or United States Geological Survey (USGS) staff. A total of 46 stage measurements were collected at each site. Instantaneous discharge measurements and staff gage readings were made approximately every 6 weeks under a variety of flow conditions at each study site from spring 2004 through fall 2006 by USGS staff. Measured discharge values and staff-gage readings were used to create stage-discharge relationships and rating tables for each study site. The rating tables were used to estimate stream discharge for individual staff-gage measurements. An average streamflow value for each site was calculated by averaging the discharge values determined from the staff gage measurements made on the 46 sample dates.

As part of Kennen and Riskin (2010), synthetic-daily-streamflow values were estimated for 12 of the fourteen study sites using the Maintenance of Variance Extension Type 1 (MOVE1) method of analysis (Hirsch 1982). This methodology regresses streamflow values collected at each study site with daily-mean-streamflow values from a nearby continuous-record gaging station in order to estimate daily streamflows for the partial-record study sites. Daily streamflow values at the other two study sites were acquired from continuous discharge measurements collected at those sites. These two continuous-gaging stations were installed as part of the larger Kirkwood-Cohansey Project (Pinelands Commission 2003). For each site, a seven-day low-flow value was calculated from the daily streamflow values as the lowest seven-consecutive-day average streamflow during the November 2004 – September 2006 study period.

Pinelands-wide Streamflow and Basin Area Relationships

Average daily discharge values were acquired for an independent set of twelve regional USGS continuously gaged discharge-recording index stations (Figure 1) to evaluate the use of the 46 study-date discharge average as a reliable measure of the overall study period average. Averages were computed for the twelve USGS gaging stations using the 46 sample dates and the entire study period. Simple linear regression was used to evaluate the level of similarity between the averages determined

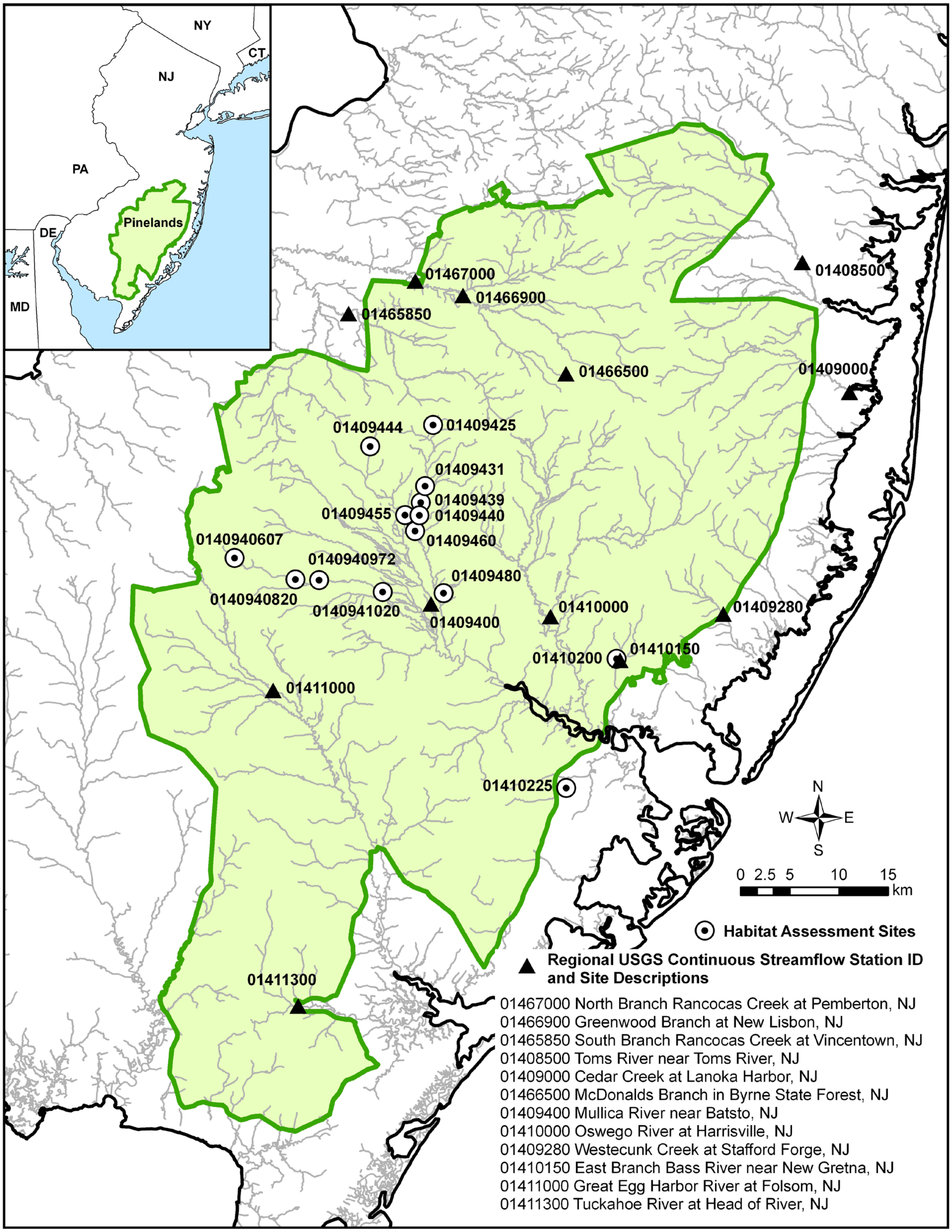

Figure 1. Location of 14 habitat assessment study sites and 12 regional USGS continuously gaged index stations. Site numbers refer to each unique USGS station. Refer to Table 1 for the habitat assessment study-site descriptions.

Table 1. Study sites and aquatic-habitat metrics for average streamflow and the seven-day low flow.

			Average Streamflow						Seven-Day Low Flow					
Site Name	USGS Station ID	Basin Area (km^2)	Flow (m^3s^{-1})	Stream-reach Volume (m^3)	Cross-sectional Area (m^2)	Stream Width (m)	Stream Depth (m)	Stream Velocity ($m\ s^{-1}$)	Flow (m^3s^{-1})	Stream-reach Volume (m^3)	Cross-sectional Area (m^2)	Stream Width (m)	Stream Depth (m)	Stream Velocity ($m\ s^{-1}$)
Albertson Brook above Great Swamp Branch near Hammonton, NJ	0140941020	52.3	0.918	282.3	2.9	6.22	0.46	0.33	0.287	148.7	1.5	4.79	0.32	0.20
Albertson Brook below RR bridge near Elm, NJ	0140940972	45.3	0.637	338.8	3.4	7.77	0.44	0.19	0.237	196.0	1.9	5.95	0.32	0.13
Batsto River near Hampton Furnace, NJ	01409440	66.3	1.026	354.6	3.5	6.11	0.56	0.35	0.241	179.2	1.8	4.39	0.37	0.22
Batsto River near High Crossing , NJ	01409431	35.0	0.538	181.7	1.8	3.75	0.47	0.32	0.092	90.7	0.9	2.81	0.30	0.12
Batsto River near Tabernacle, NJ	01409425	4.1	0.058	53.3	0.6	2.59	0.21	0.12	0.001	12.4	0.2	1.62	0.09	0.01
Morses Mill Stream at Port Republic, NJ	01410225	21.4	0.246	139.5	1.4	4.31	0.30	0.26	0.049	84.8	0.9	3.34	0.22	0.12
Muskingum Brook at Oriental, NJ	01409444	7.7	0.103	99.8	0.9	3.23	0.27	0.16	0.024	72.4	0.7	2.72	0.22	0.07
Penn Swamp Branch near Batsto, NJ	01409480	12.4	0.067	89.7	0.8	2.70	0.28	0.12	0.007	54.9	0.5	2.01	0.20	0.03
Pump Branch at Cedar Brook, NJ	0140940607	8.8	0.012	30.4	0.3	2.76	0.11	0.05	0.002	22.9	0.2	2.44	0.09	0.01
Pump Branch above Blue Anchor near Elm, NJ	0140940820	28.6	0.351	442.4	4.5	9.80	0.46	0.08	0.085	334.3	3.4	8.80	0.39	0.03
Skit Branch at Hampton Furnace, NJ	01409439	28.0	0.433	138.8	1.4	4.58	0.31	0.32	0.118	66.3	0.7	3.67	0.19	0.20
Springers Brook near Atsion, NJ	01409460	54.9	0.684	399.7	3.8	5.74	0.65	0.20	0.030	124.1	1.1	3.08	0.31	0.06
Springers Brook near Hampton Furnace, NJ	01409455	47.4	0.652	204.4	2.0	4.00	0.52	0.32	0.008	24.1	0.2	1.47	0.15	0.06
West Branch Bass River near New Gretna, NJ	01410200	16.9	0.303	124.0	1.3	3.44	0.36	0.26	0.104	54.7	0.6	2.51	0.22	0.22

from the two periods of record. Absolute differences between these two measures were related to basin area using Pearson correlation analysis. As with the study sites, low-flow values were calculated for each USGS station from daily streamflow values as the lowest seven-consecutive-day average streamflow during the November 2004 – September 2006 study period. Basin area of the twelve USGS stations ranged from 6.1 to 319 km^2.

Streamflow data is not always available for watersheds where water withdrawals are proposed, but basin area has been used as a reliable surrogate for streamflow estimation (Riggs 1973, Dunne and Leopold 1978). Separate regression analyses were used to evaluate the relationships between basin area and the average and low-flow streamflow metrics for the twelve USGS stations and the fourteen study sites. In order to develop a region-wide predictive relationship, the twelve USGS stations and the fourteen study sites were used collectively to relate basin area to average streamflow and low flow using simple linear regression.

Geomorphic Assessment

Each of the hydrogeomorphic variables evaluated in this study (stream width, stream depth, stream cross-sectional area, stream-reach volume, and stream velocity) were selected to represent structural and functional components of aquatic habitat. As part of Kennen and Riskin (2010), bankfull-channel width and depth measurements were made at each transect and used in this study to develop a model to simulate the effects of streamflow reductions on the selected habitat metrics. Bankfull-channel width was measured as the distance between stream banks perpendicular to the stream channel (Figure 2). Bankfull channel depth-measurements were determined at three locations across each transect, including the thalweg (the deepest point along the transect) and two points on either side of the thalweg midway to the edge of water. Bankfull depth and associated bankfull stage were determined by adding the height of the water column or staff-gage water level at the time of assessment to the height of the lowest bank above the water column. The edge of the bank was established at each transect by identifying the point along the stream bank where the bank slope changed to nearly horizontal (Gordon et al. 1992, Fitzpatrick et al.

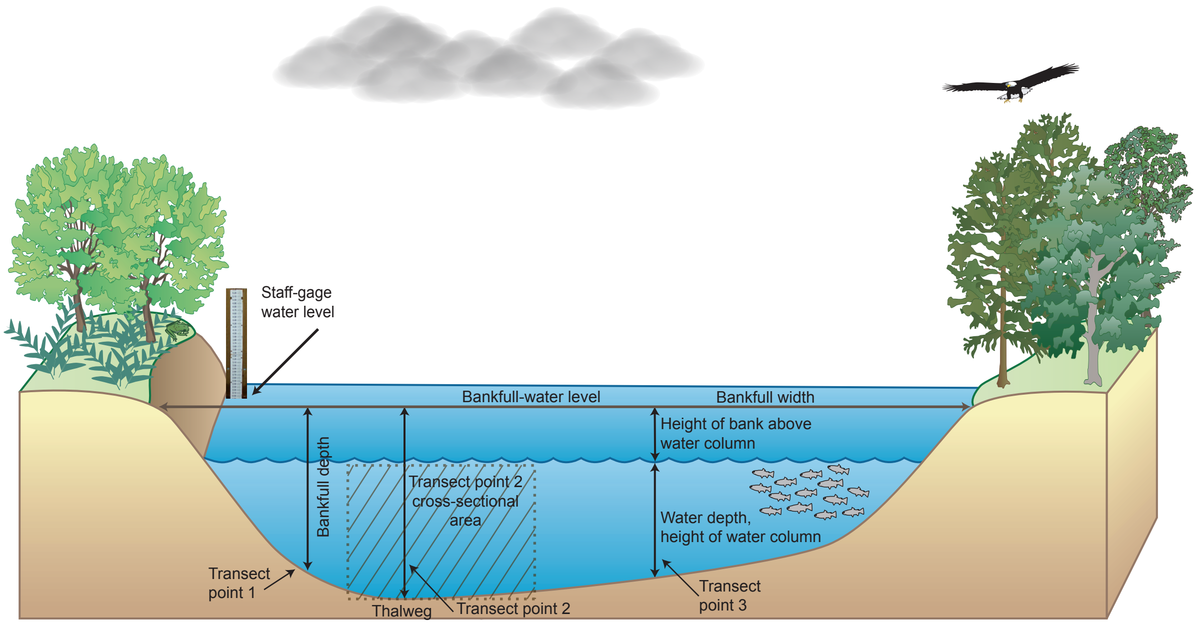

Figure 2. Stream cross-section illustrating terminology used in computing the geomorphic assessments.

1998). The habitat metrics associated with average flow and low flow water levels were related to the respective stream discharge level using simple linear regression of log-transformed data in order to evaluate the predictability of each.

Simulated Streamflow-reduction Scenarios

Streamflow-reduction scenarios of 5, 10, 20, and 30 percent of average annual discharge and the seven-day low flow were chosen to estimate the potential loss of aquatic habit that may occur concomitantly with reduced streamflows. The stage-discharge rating tables developed for each study site were used to determine the stage height of the average flow and seven-day low flow and stage height associated with simulated reductions to each.

Morphologic and velocity profiles were developed for each site based on the average streamflow value and the seven-day low-flow value (Table 1) as well as for four streamflow reduction scenarios of each. For each transect and desired stage reading, the bankfull-water level at each point along the transect was lowered by subtracting a calculated incremental drop between bankfull stage and desired stage reading in order to derive a simulated water depth. Stream width was then proportionately recalculated along the edges. Stream cross-sectional area was calculated by summing the area around each section using the calculated stream depth at each point along the transect and half the distance from the preceding point to half the distance to the next point (Rantz 1982) (Figure 2). Average stream depth was calculated as the stream cross-sectional area divided by the stream width (Leopold and Maddock 1953, Gregory and Walling 1973). Velocity was calculated at each transect stage reading by dividing the discharge value estimated from the stage-discharge rating table for the specific stage reading by the cross-sectional transect area. Stream-reach volume was calculated by multiplying the average cross-sectional area of the upstream and downstream transects of each of the four sections within each reach by the distance between the transects and summing the four component volumes. Stream width, average stream depth, stream cross-sectional area, and stream velocity were each averaged over the ten transects to produce average morphologic and velocity measures for all desired streamflow levels. Stream-reach volume from the two reaches at each site were averaged to acquire a mean reach volume for each desired streamflow level. Changes from baseline conditions for each hydrogeomorphic metric were calculated and used to determine the percentage change.

Flow-ecology response models relating coastal plain fish-species richness and total aquatic-invertebrate taxa richness (Table 2) to a measure of average annual flow developed by Kennen and Riskin (2010) were used to estimate potential changes to each ecologic metric concomitant with reduced streamflows. Average annual streamflow was used to estimate a baseline richness value for each study site. Subsequent richness values were estimated based on simulated streamflow reductions of 5, 10, 20, and 30 percent of average annual flow. Changes from baseline conditions were calculated and used to determine the percentage change. Percentage changes for each simulated streamflow reduction scenario were averaged among the study sites.

Results

Table 2. Flow-ecology response models developed by Kennen and Riskin (2010) used to estimate changes to ecological structure. AAF refers to average annual flow in m^3s^{-1}.

Coastal plain fish species richness	y = 13.222*log(AAF+1) + 5.0168
Aquatic-invertebrate taxa richness	y = -23.352*(AAF)^2 + 41.86*(AAF) + 22.623

Streamflow Conditions

Among the fourteen study sites, average flow and the seven-day low flow ranged from 0.012 to 1.026 m^3s^{-1} and 0.001 to 0.287 m^3s^{-1}, respectively (Table 1). Median average flow and low flow were 0.39 (0.51 iqr) m^3s^{-1} and 0.07 (0.10 iqr) m^3s^{-1}, respectively. Values of the two datasets were correlated (Pearson r = 0.759, p = 0.002). The low-flow values averaged 19.2% (± 3.1% s.e.) of the average streamflow values.

Pinelands-wide Streamflow and Basin Area Relationships

Regression results comparing the study date average to the average of the study period daily values for the twelve USGS stations showed strong agreement between the two sets of discharge values (R^2 = 0.997, p < 0.001) with a slope coefficient of 0.951 (± 0.017 s.e.) (Figure 3). The average discharge values based on the 46 study dates averaged 5.8% lower than those determined from the daily data. The absolute differences between the partial-record average and the daily average were positively related to basin size (Pearson r = 0.732, p = 0.007), but the percentage differences between the two metrics were not. Greater differences between the two average datasets generally occurred at the larger basins, especially at basins much larger than the fourteen study sites used in this study. The relationship between basin area and average discharge values calculated using the 46 study dates for the twelve USGS stations was strong (R^2 = 0.873, p < 0.001), as was the relationship between basin area and low flow (R^2 = 0.666, p < 0.002).

Similar to the results using the twelve USGS stations, average flows and low flows of the fourteen study sites were significantly related to basin area (R^2 = 0.948, p < 0.001 and R^2 = 0.426, p = 0.012, respectively). While statistically significant, the relatively low R^2 value for the low-flow basin-area relationship among the study sites was primarily due to four study sites. These included two study sites on the same stream having considerably lower than expected low-flow values and two other sites on the same stream having considerably higher than expected low-flow values relative to their respective basin sizes.

Region-wide relationships between basin area and average and low flows, which used the USGS stations and study sites collectively, were also strong (R^2 = 0.927 and 0.790, respectively) and significant (p < 0.001) (Figure 4). Additionally, significant relationships were observed between each of the habitat metrics and associated average flow and low flow values among the fourteen study sites (Figures 5 and 6).

Simulated Streamflow-reduction Scenarios

The average percentage decrease and variability of each habitat metric increased with successive simulated streamflow reductions (Figure 7).

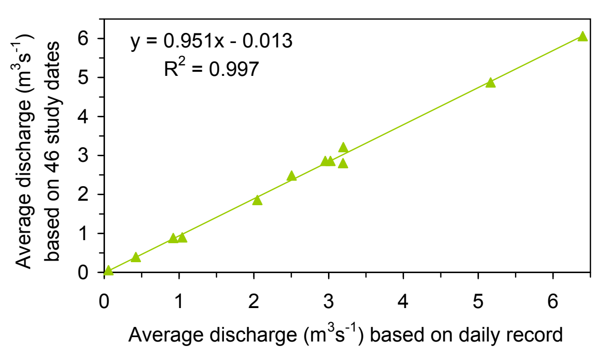

Figure 3: The relationship between average discharge calculated from 46 study dates and the daily record for the twelve regional USGS index stations during the November 2004 through September 2006 study period.

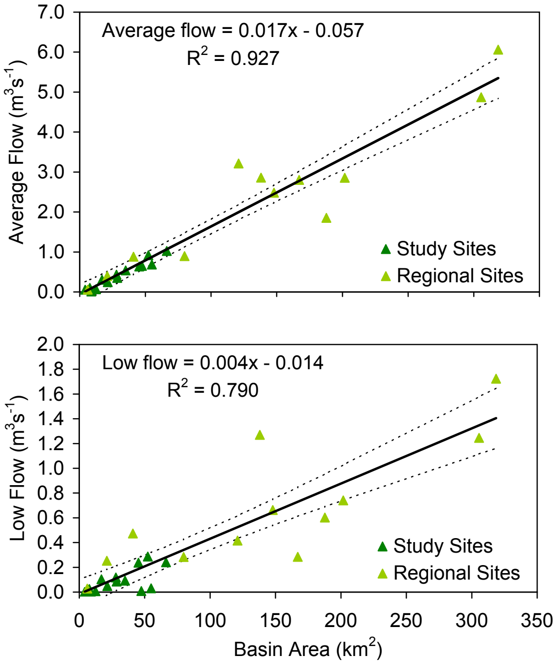

Figure 4. Region-wide relationships between basin area and average discharge (top) and low-flow discharge (bottom) including the twelve USGS stations and the fourteen study sites, collectively. The dashed lines represent the 95% confidence intervals around the regression line (solid black).

Simulated reductions in average streamflow led to nearly identical percentage decreases in stream-reach volume and stream cross-sectional area. Based on simulated flow declines, average reductions to stream-reach volume and stream cross-sectional area ranged from 3.0% to 17.7% and 3.0% to 17.9%, respectively (Figure 7). Simulated reductions to low flow also produced similar changes in stream-reach volume and stream cross-sectional area, but the percentage decreases of each were less than half of that for average streamflow. Based on simulated low-flow reductions, average declines in stream-reach volume and stream cross-sectional area ranged from 1.4% to 7.4% and 1.4% to 7.5%, respectively (Figure 7).

Impacts to stream depth were slightly greater than those to stream width for simulated reductions of both average flow and low flow (Figure 7). Based on the four reduction scenarios of average flow, average decreases in stream depth ranged from 1.8% to 11.0%, while average decreases in stream width ranged from 1.4% to 8.5%. Impacts to stream width and depth were much less pronounced for the simulated reductions of low flow. Decreases to stream depth were again greater than those to stream width. Based on the four reduction scenarios for low

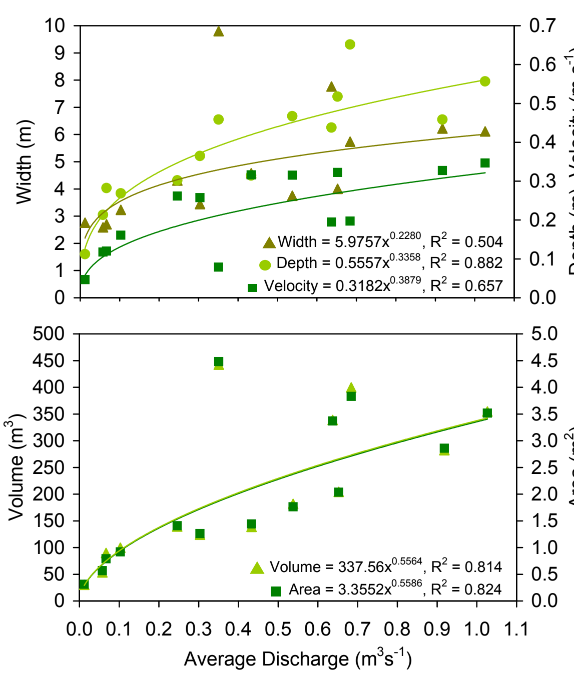

Figure 5. Relationships between five habitat metrics and average streamflow. Each power function relationship is significant ($p < 0.001$). Power functions were determined from the results of simple linear regression of log-transformed data.

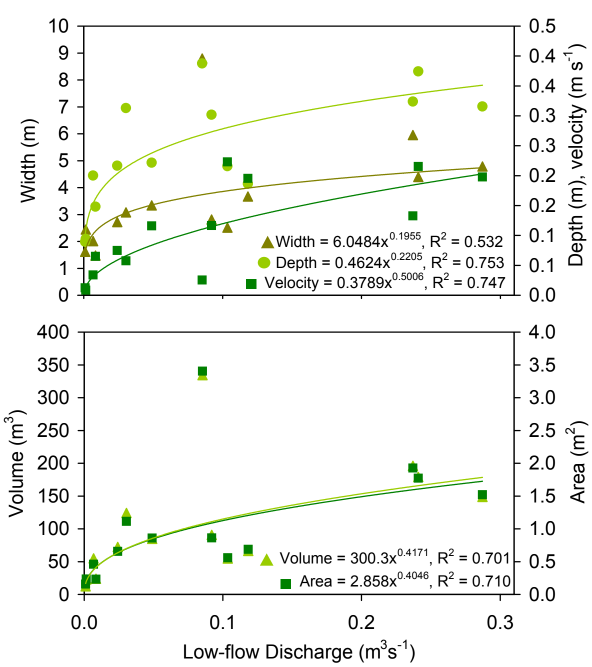

Figure 6. Relationships between five habitat metrics and low flow. Each power function relationship is significant ($p < 0.005$). Power functions were determined from the results of simple linear regression of log-transformed data.

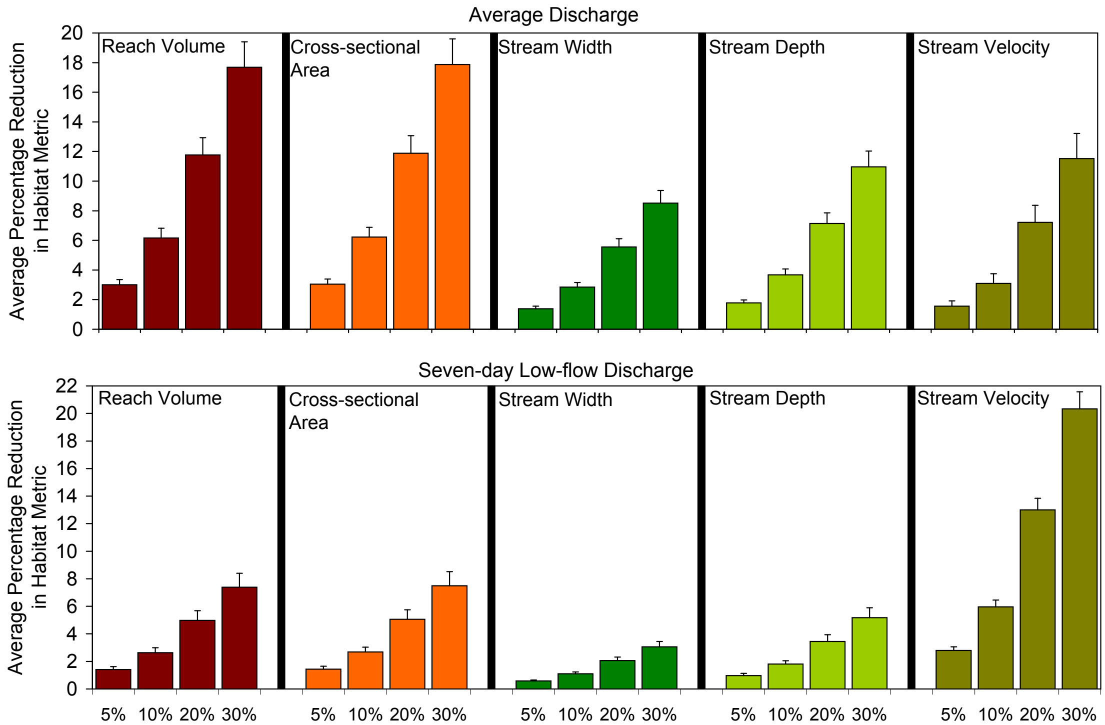

Figure 7. The average percentage (+1 s.e.) declines of each habitat metric relative to a simulated 5, 10, 20, and 30% reduction in average streamflow (top) and seven-day low flow (bottom).

flow, average decreases in stream depth ranged from 1.0% to 5.2%, while stream width decreased by 0.6% to 3.1% (Figure 7). Of the four morphologic variables, stream width showed the least amount of impact under average and low flow simulations.

In contrast to the morphological variables, stream velocity was impacted more severely when low flows were reduced than when average flows were reduced. Stream velocity also showed the greatest percentage change for all four low-flow simulations compared to the morphological variables. Based on the four manipulation scenarios to average flow and low flow, stream velocity decreased by an average of 1.6% to 11.5% and 2.8% to 20.3%, respectively (Figure 7).

Some of the decreases in the five aquatic-habitat metrics were related to basin area, average flow, or low flow. The percentage decreases in stream width resulting from the 10%, 20%, and 30% streamflow reductions to average discharge were positively related to basin area. Similarly, the percentage decreases in stream width resulting from the 20% and 30% streamflow reductions to low-flow discharge and decreases in stream cross-sectional area resulting from the 20% streamflow reduction of low-flow discharge were positively related to basin area. In no other instance was the percentage decrease of any of the variables under either of the scenarios related to basin area. The percentage decrease of four of the five habitat metrics under one or more of the average discharge reduction scenarios were positively related to average discharge, but consistent trends were absent. With the exception of velocity, the percentage decreases to each of the habitat metrics resulting from reductions applied to low flows were positively related to the low-flow discharge under each scenario.

For fish and macroinvertebrates, both richness metrics showed considerable response to reductions in average annual streamflow. Based on simulated flow declines, aquatic-invertebrate taxa richness and coastal plain fish-species richness decreased by an average of 0.75% to 5.7% and 1.4% to 10.1%, respectively (Figure 8). The percentage reductions in coastal plain fish-species richness for each scenario were inversely related to basin area (Spearman rho = -0.965, p < 0.001, respectively). Trends between basin area and aquatic-invertebrate taxa richness were not detected.

For two study sites, the stream was estimated to be dry across one transect at the calculated low-flow

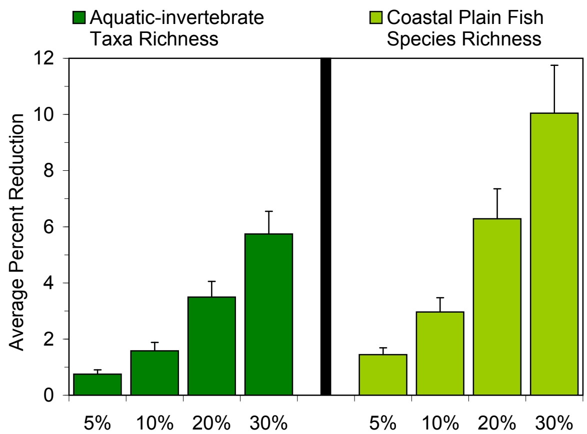

Figure 8. The average percentage (+1 s.e.) declines of aquatic-invertebrate taxa richness and coastal plain fish-species richness relative to a simulated 5%, 10%, 20%, and 30% reduction in average streamflow.

discharge level. Consequently, the same transects were estimated to be dry under the four low-flow reduction scenarios. No other transects were estimated to be dry after applying the simulations.

Discussion

Niadas (2005) recommended that 25–48 discharge measurements are needed to adequately represent the streamflow regime in small watersheds and avoid the need to create a synthetic daily-record dataset to generate flow statistics. The fact that this study included 46 partial-record (study date) discharge measurements and that the study date and daily averages of the twelve USGS index stations were comparable indicated that the study-date average discharge values were preferable for data analyses. Additionally, the strength of the relationships between basin area and stream discharge for the twelve USGS index sites and fourteen study sites (Figure 4) indicated that basin area can be used to estimate average or low flow discharge for a wide range of watershed sizes distributed throughout the Pinelands region that lack sufficient streamflow data.

Patterns in the rates of change of each habitat metric (average stream width, stream depth, stream cross-sectional area, stream-reach volume, and stream velocity) have been shown to be fairly consistent over a range of streamflow conditions (Leopold et al. 1964, Rhodes 1977). Since discharge and wetted-channel dimensions tend to decrease at a slower rate at lower stage levels, it can be expected that changes in reach volume, cross-sectional area, wetted width, and depth would be less dramatic for reductions to low flow than to average flow. Percentage decreases in stream velocity tend to be more pronounced when low flows are reduced. These observed patterns in velocity can be explained by the fact that percentage changes in stream cross-sectional area, respective to reductions in discharge, were smaller under low flow conditions than under average flow conditions.

Possible consequences of reduced in-stream habitats include changes to resource availability, stream temperature regimes, dissolved oxygen, and other water-quality characteristics. Such changes could lead to alterations to the in-stream ecosystem dynamics and lead to shifts in community structure (Gordon et al. 1992, Allan and Castillo 2007). Furthermore, reduced streamflows may decrease aquatic-habitat volume causing downstream reaches to mimic shallower headwater reaches (Poff and Allan 1995).

Impacts associated with reductions of in-stream habitats include modifications to food availability (Vannote et al. 1980) and species composition and diversity (Poff and Allan 1995, Resh et al. 1988, Bunn and Arthington 2002), along with an increased potential of nonnative species invasions (Moyle and Light 1996, Marchetti and Moyle 2001). Changes in hydrogeomorphic conditions have been documented to influence fish-habitat complexity and availability (Bain et al. 1988, Pusey et al 2000, Lamouroux and Cattanéo 2006, Remshardt and Fisher 2009), available refugia (Schlosser 1982, Schlosser 1995, Townsend et al. 1997, Lake 2000) as well as fish-community structure (Poff and Allan 1995, Lamouroux and Cattanéo 2006, Zorn et al. 2008). Vannote et al. (1980) described how changes in habitat and resource availability can force changes to macroinvertebrate communities. Additionally, changes to baseline hydrologic conditions were shown to alter benthic macroinvertebrate community composition, density, and richness (Dewson et al. 2007, DeGasperi et al. 2009), including those of Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa (Wills et al. 2006). Changes in stream velocity have been shown to have direct impacts to fish species abundance and growth rates (Pusey et al

2000, Harvey et al. 2006) while declines in annual streamflow have been shown to result in reduced fish species richness (Xenopoulos et al. 2005).

Based on the flow-ecology models used in this study, aquatic-macroinvertebrate taxa and coastal plain fish-species richness would decrease if persistent reductions in streamflow were to occur. Although these flow-ecology models do not estimate biological responses to reductions in low flow, the significant inverse relationships between basin area and percent reduction in coastal plain fish-species richness suggest that the smaller streams are more vulnerable to species losses. It is anticipated that impacts to richness will be more dramatic if low flows are persistently reduced (Poff and Allan 1995, Dewson et al. 2007). This would be of special concern in headwater reaches where prolonged withdrawals may dry the stream.

In this study, the few stream transects that were dry at low-flow and under simulated reduction scenarios leads to a direct loss in stream connectivity. A loss of connectivity between stream sections restricts the ability of aquatic species to move freely throughout the stream network and may lead to a direct loss of organisms associated with those dry reaches (Bunn and Arthington 2002, Ladle and Bass 1981). Depending on the duration of the dry period, the viability of certain populations of fish and macroinvertebrates may be impaired (Ward and Stanford 1995, Bunn and Arthington 2002, Lake 2003). Lowered or dry streamflow conditions may favor the survival and colonization of certain macrophyte species (Ladle and Bass 1981) and ultimately allow for increased plant growth throughout the year (Bunn and Arthington 2002). Despite the fact that the results of this study indicate that changes to some of the habitat metrics are less dramatic as low flow values are reduced, it is important to keep in mind that in-stream conditions are already stressed and habitat availability and channel connectivity are already compromised under low-flow conditions.

Management Applications

The relationships between streamflow, basin area, habitat metrics, and richness measures developed in this study can be used to estimate the potential effects of groundwater pumping on available aquatic habitat and aquatic assemblages in Pinelands streams. With the establishment of an average or a low-flow streamflow value estimated from basin area (Figure 4) upstream from a proposed water withdrawal, one could estimate any of the habitat metrics using the relationships presented in Figures 5 and 6. Subsequent reductions to each habitat metric can then be predicted within the range of the streamflow-reduction scenarios using the information presented in Figure 7. Likewise, estimated average annual flow could be used to estimate either aquatic macroinvertebrate taxa richness or coastal plain fish-species richness (Table 2) and subsequent reductions to each ecologic metric can then be predicted within the range of the streamflow-reduction scenarios using the information presented in Figure 8.

The results of this study can be used in conjunction with watershed-wide hydrologic models that were developed as part of the larger Kirkwood-Cohansey Project (Pinelands Commission 2003). Models developed from the larger study will be used to estimate the potential effects of groundwater pumping on hydrologic and ecological attributes of Pinelands wetlands and aquatic systems, as well as to help determine the optimum location, depth, and pumping rates for water-supply wells. Some of the general well-siting criteria determined from the Kirkwood-Cohansey project may also be applicable to other coastal plain regions.

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