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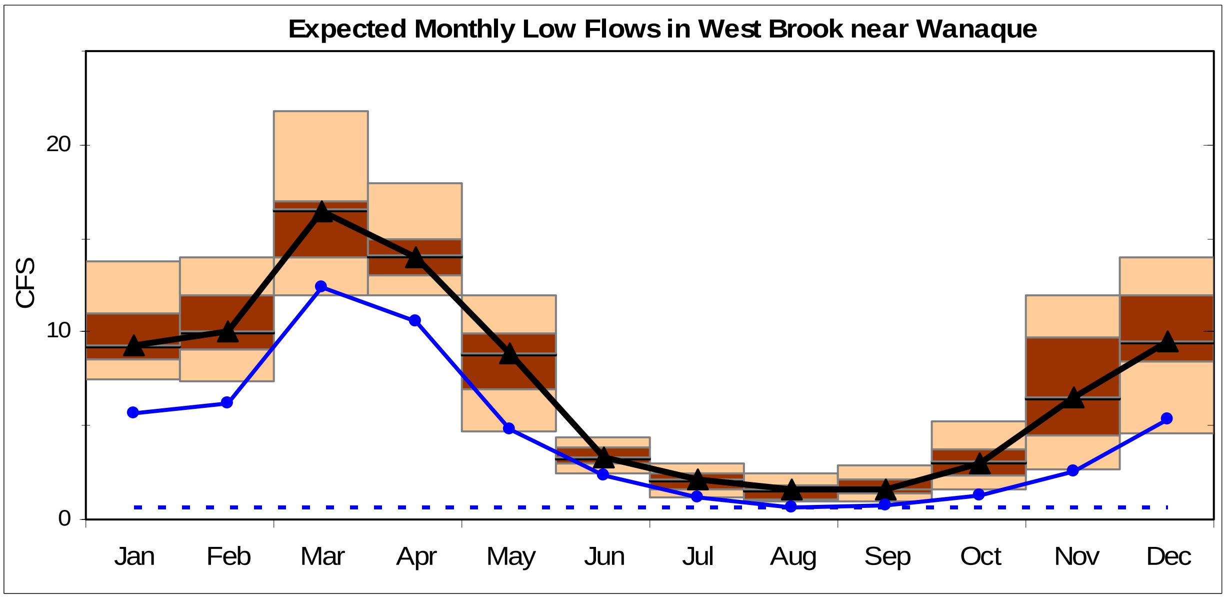
Technical Memorandum 09-3

The Hydroecological Integrity Assessment Process in New Jersey



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Cover:

The cover graph shows the statistical range of minimum daily flow reported in each month at the West Brook stream gage near Wanaque (USGS gage #01386000) in northern New Jersey for Water Years 1935-1978. The graph also shows annual and monthly 7Q10 flows. The data for this figure are in table 9 in appendix G of this report.

The top of the upper box and bottom of the lower box represent the 75-percent and 25-percent frequency of the minimum flow reported in each month, respectively. The top and bottom of the central, dark brown box represent the 60-percent and 40-percent frequency of monthly minimum flows, respectively. The black triangles and connecting black line is the median (50 percent) of reported monthly minimum flows.

The graph also shows the estimated annual 7Q10 streamflow at West Brook as a dotted blue line. The solid blue shows estimated monthly 7Q10 streamflows.

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The Hydroecological Integrity Assessment Process in New Jersey

by

Jeffrey L. Hoffman and Helen L.L. Rancan

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Land Use Management
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2009

Conversion Factors

Multiply inch-pound units	by	to obtain metric (SI) units		Multiply inch-pound units	by	to obtain metric (SI) units
VOLUME				**FLOW RATE**		
cubic inches (in^3)	16.39	cubic centimeters (cm^3)		million gallons/day (mgd)	0.04381	cubic meters/second (m^3/s)
cubic feet (ft^3)	0.02832	cubic meters (m^3)		cubic feet per second (cfs)	2,447.	cubic meters/day (m^3/d)
gallons (gal)	3.785	liters (L)		million gallons/year (mgy)	3,785.	cubic meters/year(m^3/y)
gallons (gal)	$3.785X10^{-3}$	cubic meters (m^3)		gallons/minute (gpm)	.06309	liters/second (L/s)

Note: In this report 1 billion = 1,000 million; 1 trillion = 1,000 billion

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Epigram

"The nation will not have a comprehensive view of water availability without assessing the needs of human and natural system uses, accounting for the effect of variability in the natural system on water supply, and recognizing how social and economic institutions affect water availability."
-- National Science and Technology Council, 2004

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The Hydroecological Integrity Assessment Process in New Jersey

Abstract

The newly-developed Hydroecological Integrity Assessment Process (HIP) provides a way to quantitatively characterize streamflow in non-tidal streams. It can help determine the acceptable yield of water from a watershed once limits on streamflow changes are set. The HIP can also help determine if a proposed water withdrawal or discharge will change streamflow beyond set limits. Maintaining natural streamflow patterns is a necessary step in preserving the natural aquatic ecosystem.

The ecology of a stream has evolved in response to a range of flows. High flows shape the stream channel and provide access to food sources and breeding sites in the flood plain. Average flows define the most common habitat. Low flows sustain the ecology in dry periods, but also, by limiting ecological niches, prevent invasive species from becoming established. Significantly disturbing the magnitude, timing, duration, frequency or rate of change of these flows will alter the ecological balance in the stream. The understanding that the aquatic ecosystem's integrity is dependent on maintaining the entire range of flows is termed the "natural flow paradigm." The natural flow paradigm is the basis of the HIP.

The New Jersey Department of Environmental Protection (NJDEP) proposes to use the HIP to determine acceptable limits of streamflow modification. It can be applied in regional planning studies (evaluating current or planned water losses in a watershed) or to set site-specific regulatory standards (passing flows on streams). These applications will require characterizing streamflow in a baseline period (which supported an unimpaired aquatic ecosystem) as well as current flows.

As a planning tool the HIP can provide hydrologic data to determine if streamflows have been significantly changed. This is done by comparing a statistical analysis of streamflow during a baseline period to an analysis of current flows. If present-day values for a range of hydrologic indices are too far from the baseline values, then streamflow has already been too greatly changed. In this case, additional withdrawals will probably shift the hydrologic indices even further from the baseline values. If the indices have not changed too much then a trial-and-error approach can determine how much additional streamflow alteration is acceptable and how much additional yield can be taken out of the basin. This planning approach was applied to the Toms River and West Brook watersheds in New Jersey. The HIP shows that the current rate of depletive and consumptive loss in the Toms River watershed is creating a significant change in streamflow variability. The relatively undeveloped West Brook watershed could sustain more water loss without showing unacceptable streamflow changes.

The HIP can be used as a regulatory tool to set permit conditions, such as passing flows. Passing flows are standards that define how much streamflow must pass a specified point. These standards can limit withdrawals during low-flow periods or set required releases from a reservoir. The HIP can provide a sequence of 12 monthly flows that are based on a consistent statistical analysis of low streamflow. These monthly flows follow the natural hydrology in New Jersey by being higher in the winter and spring and lower in the summer and fall, and could be applied as passing flows. The specific statistics used in setting the passing flows may vary depending on stream classification (to be more protective of sensitive streams) and water use (to allow critical water uses during droughts). Setting passing flows higher in the spring and lower in the summer is a more ecologically-based approach than one that is the same for every month. This method is applied to the West Brook watershed as a test case.

The Hydroecological Integrity Assessment Process is based on a research effort which started in 2000. The HIP and associated analysis software is the result of research by the U.S. Geological Survey.

This report presents an overview of the HIP and three case studies. The studies highlight the potential applications, decisions that must be made in order to apply the HIP to permits in a regulatory situation, and relevant data needs. Implementing the HIP in New Jersey will highlight the challenges in meeting the NJDEP's requirements under the Clean Water Act to protect the aquatic ecosystem, as well the Water Supply Management Act's requirements to provide a safe and assured water supply.

Introduction

The New Jersey Department of Environmental Protection (NJDEP) protects the ecology of the State. Its mandate includes regulating withdrawals and discharges so that they do not excessively alter streamflows. One tool in accomplishing this is to impose passing flows. A passing flow on a stream intake sets the flow at which the withdrawal must reduce or cease during a drought. A passing flow on a reservoir is the volume of water that must be continually released. As currently applied in New Jersey, passing flows are a constant value that is usually based on a statistical analysis of summer low flows. This has the disadvantage of applying a summer-drought standard to the entire year. Although these flows are a critical component of streamflow, other components are also vital for maintaining hydroecological integrity.

A better methodology for setting limits on streamflow changes would be more protective of the aquatic ecosystem, be more reflective of the natural hydrology of a stream, and be based on ecological principles. This better methodology would also use data that can be relatively easily obtained or generated, require only a reasonable amount of time to apply, have well defined and consistent guidelines that allow replication of work, and be numerically applicable in a regulatory situation. In 2000 the NJDEP and the United States Geological Survey's (USGS) New Jersey Water Science Center began work on such a methodology under a cooperative agreement. A Technical Advisory Committee (TAC) supervised the work and provided guidance. Appendix C lists TAC members.

The TAC's initial hope was that detailed flow requirements and habitat needs of all life cycles of all species of concern in New Jersey could be tabulated and serve as a basis for flow needs. However, the TAC quickly discovered that these flow-habitat relationships are not well understood. Seasonal flow requirements are available for trout but not for any other species (Stone, 1877; Crisp, 2000; Bovee and others, 2007). Developing detailed data for each additional species is the work of decades and millions of dollars.

The need to protect all species of concern in the absence of sufficient species-specific information led the TAC to the **natural flow paradigm** (Poff and others, 1997; Richter and others, 1998; Petts, 2009). It is a "more holistic view that the science is incapable of understanding the complexity of ecosystems, so management strategies must focus on restoring the fundamental drivers of ecosystem function rather than incrementally managing pieces" (Bencala and others, 2006). The natural flow paradigm states that streamflow is a master variable governing aquatic ecosystems and that the full range of flows are critical to sustaining a stream's ecology:

- High flows move sediment, thus scouring and shaping the stream channel. High flows also provide access to food sources and breeding sites in the flood plain that some species need.
- Average flows represent the normal condition that provide habitat most of the time and thus sustain the population.
- Low flows sustain the ecosystem in dry periods, but also, by limiting ecological niches, prevent invasive species from gaining a foothold.

In a natural state, a balanced ecology is the result of occasional high and low flows. Suppressing or exaggerating these infrequent extremes may drastically change the ecology. Just as important as the actual magnitude of extreme flows are their timing, duration, frequency and rate of change. Any significant alteration of these flows, by either natural climatic fluctuations or anthropogenic influences, will alter the balance of animal and plant species in the aquatic system. If the natural flows are not maintained, then the natural ecology is not sustained.

The HIP does not focus on the water needs of any individual species because optimizing flow for one species will adversely impact others (Sparks, 1995). Instead, the goal is to preserve a balanced ecosystem. The populations of different species undergo natural fluctuations in response to changing flows but over the long term they are in a dynamic equilibrium.

Maintaining the natural streamflow is not sufficient by itself to protect the aquatic ecosystem. Deviations of water quality, temperature and sedimentation from normal ranges will also affect what species can live in the stream. (Many NJDEP programs, including water monitoring & standards, stream classification, New Jersey Pollutant Elimination System regulations, and stormwater regulations, address these other concerns.) The natural flow paradigm can address these issues indirectly. Insufficient low flows may result in too little dilution of a discharge or too warm a temperature in the summer. Altered high flows may change normal sedimentation patterns. But to the natural flow paradigm, and methods built on it, cannot directly address these other issues.

The natural flow paradigm is the foundation of the Indicators of Hydrologic Alteration (IHA) method (Richter and others, 1996, 1997, 1998). An IHA analysis compares changes in 32 hydrologic indices from "pre-impact" to "post-impact" time frames. The Nature Conservancy (2006) provides software implementing the IHA approach. Poff and others (1997) and Olden and Poff (2002) expanded the number of indices from 32 to 171. They analyzed redundancy among the indices and correlated non-redundant indices with stream type in order to winnow out a smaller set of significant statistics that adequately characterize streamflow. This approach has recently been recharacterized as the ecological limits of hydrologic alteration (ELHOA) (Poff and others, 2009).

The USGS research project applied the work of Poff and Olden to develop the Hydroecological Integrity Assessment Process (HIP) (Kennen and others, 2007). This process compares streamflow during a baseline period to current flows for four stream types in New Jersey. The USGS also developed software tools (Hydrological Assessment Tool for New Jersey (NJHAT) and Stream Classification Tool (SCT)) to assist the analysis procedure (Henriksen, 2006; Henriksen and others, 2006).

The HIP can be used in two contexts - planning and regulation. In a planning context, an analysis of baseline streamflow yields the natural variability of a series of hydrologic indices. The regulatory agency must make a policy decision on the acceptable limits of streamflow change. Then the NJHAT software provides an estimate of how current water use has impacted the streamflow. This approach can determine how much additional water can be withdrawn from a stream without creating an unacceptable change in flow or how much water must be returned to restore normal flow variability.

In a regulatory context, the HIP approach can provide guidance on how to calculate low flows that minimize ecological stresses. A regulatory agency can use this as the basis for assigning passing flows. In New Jersey, passing flows historically have been based on a variety of standards, including statistically-defined low flows, dry-season base flows, water needed for downstream allocations, flows needed to dilute effluent discharge, and legislative mandates. Currently the most common method in New Jersey for setting passing flows is a stream's annual 7Q10 flow (N.J.A.C. 7:19-1.6 (e)). This is a 7-day-average low flow that has a 10 percent chance of occurring in a given year (Gillespie and Schopp, 1982). Annual 7Q10 flows are available for all active stream gages in New Jersey (Reiser and others, 2002), can be estimated for ungaged locations, are easy to apply as a standard in a permit, and have a successful history of protecting water quality. However, annual 7Q10 flows were not developed for protection of the aquatic ecosystem and have been criticized as allowing summer drought flows to occur year-round on a continual basis (Annear and others, 2004). One goal of the HIP is to develop passing flows that are reflective of the natural hydrograph and protective of the ecosystem.

As developed here, the HIP applies to nontidal streams in New Jersey. It should not be applied to the Delaware River because the Delaware River did not fall into any of the stream classification types (discussed below). Withdrawals from the Delaware River are also regulated under a multi-state Commission.

The NJDEP is applying the HIP to a series of test cases, three of which are reproduced in this report. This exercise has shown the need to address several policy issues before the HIP can be fully implemented. For example, the Clean Water Act (3 U.S.C. 1251 et seq) requires that the NJDEP protect the State's surface water. This is the regulatory basis of numerous NJDEP programs. The Water Supply Management Act (N.J.S.A. 58:2 – 1 et seq) requires the NJDEP provide a safe and assured water supply for the citizens of New Jersey. Balancing these requirements, especially during droughts, is an ongoing challenge. Undoubtedly, additional questions will arise as the HIP is implemented.

Other states working with the US Geological Survey on developing an application of the hydroecological integrity assessment process include Texas, Maryland, Missouri, and Pennsylvania. However, the HIP has yet to be implemented in a regulatory application in any state.

Other Approaches

There are three main approaches to setting passing flows: 1) analysis of historic streamflows; 2) hydraulic methods; and 3) habitat methods (Jowett, 1996).

Historic streamflow methods are based on a desktop analysis of reported flows. They tend to be quick to apply and do not require additional field work. The user must make assumptions as to the desirability of certain flow frequencies in order to set flows that are to be maintained. Examples of historic streamflow methods are annual 7Q10, Aquatic Base Flow (New England), and Tennant (Montana) methods. The HIP is also an example of this type of methodology.

Hydraulic methods relate flow to stream geometry. They require field measurements of stream cross sections and an established relationship between flow and ecological health. The wetted perimeter method is one example of a hydraulic method. These methods are more time and field intensive than historic streamflow methods.

Habitat methods are based on site-specific and species-specific studies of how changes in flow affect the amount of available habitat. They may also include the effects of land-use changes in the upstream watershed. Perhaps the most widespread example of this is the Physical Habitat Simulation System model (PHABSIM) (Milhous and others, 1984). These habitat models are very time and resource intensive due to their need for detailed data on stream geometry and species-specific ecological response.

Acknowledgements

Many NJDEP and USGS staff members were instrumental in the development of the HIP and its application to New Jersey. Members of the Technical Advisory Committee (Appendix C) were very helpful with their comments and suggestions. Special thanks to Karen Schaffer, formerly of the Division of Science, Research and Technology, who saw the need for this research, built support for it, lined up funding, shepherded the proposal through the approval process, and saw the project started. It took a workgroup consisting of Tom Belton, Jeffrey Hoffman, Helen Rancan, and Flavian Stellerine to replace her when she left. The workgroup expresses its thanks to the various division directors of the NJDEP who authorized funds and supported the research. Also, the workgroup thanks Steven Nieswand and Jonathan Kennen of the USGS, Water Resources Division, who oversaw the Federal efforts. And many thanks to Jim Henriksen of the USGS, Biological Resources Division, for guiding the TAC through its learning curve.

This report has also benefited from the thoughtful comments of several reviewers, including Michele Putnam, Ron Witte, Ray Bousenberry, and Butch Grossman of the NJ Department of Environmental Protection, Dan Van Abs of the New Jersey Water Supply Authority, Colin Apse of The Nature Conservancy, Steven Nieswand of the US Geological Survey, and Wendy Gordon of the Texas Commission on Environmental Quality.

Parameter Selection

A variety of hydrologic indices are available to characterize streamflow. These range in complexity from simple (average flow in August) to complex (standard deviation of the percentiles of the logs of the entire flow record divided by the mean of percentiles of the logs). Appendix H lists the 171 hydrologic indices Olden and Poff (2003) incorporated. The indices can be subdivided into groups that characterize different components of streamflow. There are ten principle components of streamflow as defined by Henriksen and others (2006):

- Magnitude of high flows (MH)
- Magnitude of average flows (MA)
- Magnitude of low flows (ML)
- Frequency of high flows (FH)
- Frequency of low flows (FL)
- Duration of high flows (DH)
- Duration of low flows (DL)
- Timing of high flows (TH)
- Timing of low flows (TL)
- Rate of change in flow (RA)

It is unnecessary to evaluate all 171 indices in order to sufficiently characterize the ten principal components. Many of the indices are closely associated. For example, average July low flows are highly correlated with average August low flows for a given stream. It is sufficient to examine "a parsimonious set of hydrologic indices that represent critical flow characteristics" (Olden and Poff, 2003). The HIP approach uses one hydrologic index from each of the ten components, resulting in a set of ten hydrologic indices that characterize streamflow.

Stream Types

As part of the process to determine which of the 171 hydrologic indices are the most informative, Olden and Poff (2003) classified streams according to flow properties. Based on a nation-wide analysis, they identified two major classes of streams, intermittent and perennial, with a total of six subtypes. Each subtype had a different set of ten hydrologic indices. Therefore, identifying a stream's subtype determines the most significant hydrologic indices.

Under this work, streams in New Jersey fell into two of the perennial subtypes (Olden and Poff, 2003). However, this national study used data from only seven New Jersey streams. Henriksen and others (2006) expanded this work to an analysis of 90 stream gages in New Jersey. They selected gages with long-term records (at least 20 years) that were, in their judgment relatively, unaffected by development in upstream watersheds, and were not affected by dams and reservoirs. This work classified New Jersey streams as one of four types based on flashiness (how quickly the stream rises and falls in response to precipitation), frequency of low-flow events, and watershed area. Table 1 and figure 1 show details and locations of the 90 gages (Henriksen and others, 2006). Appendix I lists the stream type determined for the gages.

Table 1. New Jersey stream types.

Stream type	Description	Watershed areas (sq mi)			Number of gages
		min	avg	max	
A	semi-flashy with moderately low base flow	25	165	786	31
B	stable with high base flows	47	86	141	13
C	moderately stable with moderately high base flow	8	21	37	20
D	flashy with low base flow	1	6	23	26
				sum:	90

(from Henriksen and others, 2006)

Henriksen and others (2006) developed the Stream Classification Tool (SCT) to analyze daily streamflows and to classify New Jersey's streams. In some cases, a stream's classification changes from upstream to downstream. For example, the Lamington River gage near Succasunna (USGS gage #01399190) has 7.4 square miles of watershed upstream from the gage. The SCT classifies the Lamington River as being type D stream at this point. Further downstream, at the Lamington River gage near Pottersville (USGS gage #01399500), the watershed area has increased to 32.8 square miles and the stream is classified as a type C.

The Delaware River did not fit into any of the four stream types (Jonathan Kennen, U.S. Geological Survey, oral communication, 2007) because its flow is ten times greater than that of the second largest river draining New Jersey, the Raritan River.

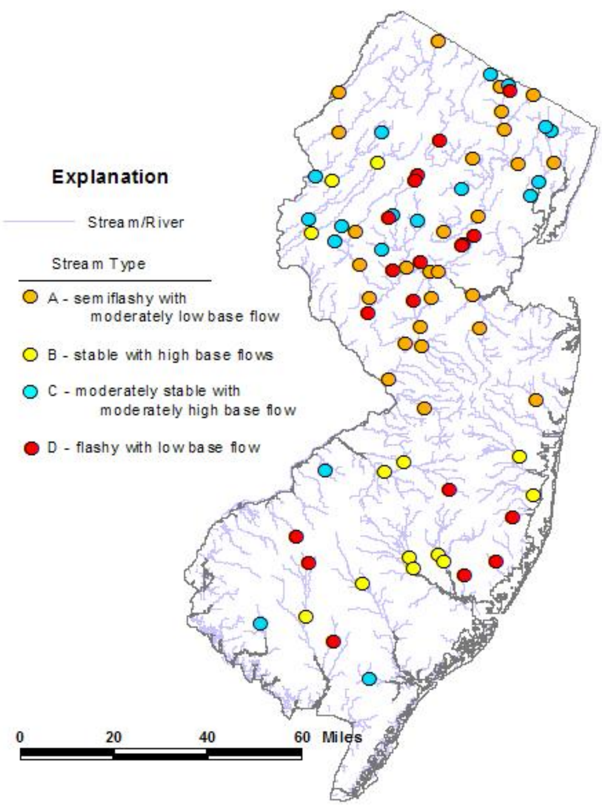

Figure 1. New Jersey stream types (after Henriksen and others, 2006).

New Jersey-specific hydrologic parameters

Kennen and others (2007) examined all 171 hydrologic indices for each stream gage. For each of the four stream types they selected the hydrologic index from each of the ten components that best characterized streamflow. Their analysis also identified which other indices were good surrogates for the primary index. Any of these secondary indices could be used in place of the primary index and still accurately characterize streamflow. Table 2 shows the set of indices for each stream type and flow component, with the first index being of primary importance and others being of secondary importance.

The primary indices recommended for use in New Jersey (table 3) differ from that recommended by Kennen and others (2007) (table 2). This change creates a consistent set of indices that appropriately characterizes streamflow and changes in streamflow in a way that can be applied in a regulatory setting. It allows all users of the HIP in New Jersey to know precisely how proposed changes in streamflow will be evaluated by State regulators. The indices are changed for three reasons: 1) calculation consistency when compensating for skewed data sets; 2) eliminating surrogate gages by analyzing variation in a stream using data only from that stream; and 3) and sensitivity to changes in the particular stream. These reasons are explained in more detail in Appendix D.

Table 2. Primary hydrologic indices defined by the U.S. Geological Survey for stream types and flow components in New Jersey[1]

Flow component	Stream type			
	A	B	C	D
Magnitude of average flows	MA18, MA39, MA26, MA37	MA9, MA15, MA33, MA32	MA24, MA11, MA43, MA40, MA45	MA39, MA13, MA44, MA40, MA9
Magnitude of low flows	ML6, ML13, ML16	ML20, ML4, ML21, ML16	ML3, ML19, ML20, ML13	ML20, ML13, ML15, ML21
Magnitude of high flows	MH5, MH16, MH20, MH18	MH24, MH4, MH18, MH26	MH14, MH17, MH12, MH13, MH16	MH16, MH2, MH21, MH3, MH1
Frequency of low flows	FL3, FL1	FL3, FL2, FL1	FL1, FL3, FL2	FL3, FL1, FL2
Frequency of high flows	FH4, FH3, FH1, FH9	FH4, FH10, FH1	FH7, FH3, FH4, FH11	FH3, FH9, FH5, FH10, FH11
Duration of low flows	DL4, DL12, FL16, DL6	DL15, DL1, DL16, DL12	DL16, DL14, DL5, DL9, DL17	DL4, DL16, DL11, DL7
Duration of high flows	DH2, DH13, DH20, DH8	DH12, DH2, DH20, DH24	DH11, DH14, DH1, DH9, DH23	DH14, DH2, DH17, DH12, DH23
Timing of low flows	TL1	TL2	TL2, TL1	TL1
Timing of high flows	TH1	TH2, TH3	TH3	TH3, TH2
Rate of change in flow	RA3, RA7, RA8, RA5	RA7, RA1, RA6, RA2	RA6, RA3, RA1, RA2, RA4	RA7, RA3, RA8, RA1, RA2

[1]The primary index is listed first, secondary indices follow. They are summarized in Appendix F and defined in Henriksen and others, 2006.

Table 3. Hydrologic indices selected by the N.J. Department of Environmental Protection for flow components and stream types in New Jersey.[1]

Flow component	Stream type			
	A	B	C	D
Magnitude of average flows	MA18	MA15	MA24	MA13
Magnitude of low flows	ML6	ML4	ML3	ML15
Magnitude of high flows	MH5	MH4	MH14	MH2
Frequency of low flows	FL1	FL1	FL1	FL1
Frequency of high flows	FH3	FH10	FH3	FH3
Duration of low flows	DL4	DL1	DL16	DL4
Duration of high flows	DH2	DH2	DH1	DH2
Rate of change in flow	RA3	RA7	RA6	RA7
Monthly low flows	ML1-ML12	ML1-ML12	ML1-ML12	ML1-ML12

[1]Hydrologic indices are summarized in Appendix F and defined in Henriksen and others, 2006.

Hydroecological Integrity Assessment Process Application

The hydroecological integrity assessment process (HIP) can be used for planning and regulatory activities. A planning activity refers to a watershed-wide analysis of water-use patterns, such as total upstream depletive and consumptive water loss. Ideally, such an analysis would be based on a lengthy record of stream flow. In contrast, a regulatory activity determines if a water withdrawal is creating an unacceptable impact on stream low flows. This analysis comes from instantaneous measurements of flow.

Baseline Period

A baseline period is necessary in order to apply the HIP. An analysis of streamflow during the baseline period provides the standard against which later flow changes are evaluated. The NJDEP is charged to "protect, restore and maintain the quality of New Jersey's water resources," (NJDEP, 2007). To help accomplish this, the NJDEP prefers to select a baseline period that represents a natural or relatively undisturbed condition.

Esralew and Baker (2008) analyzed selected New Jersey stream gages, in conjunction with timings of land-use changes and construction of water-supply facilities, to determine baseline periods. Their results are summarized in Appendix I. The appropriate baseline period is thus available for projects fortunate enough to be able to use data from one of these gages. The baseline period for an ungaged site on the same stream and close to one of the stream gages in Appendix I may be the same as that gage's. For other sites, a detailed analysis of hydromodifications and land-use changes in the watershed may be needed to define a baseline period. For a watershed with an extensive history of land-use changes and/or hydromodifications, there may not be a period in the available data record that would qualify as a baseline period. In this case a hydrograph may have to be developed based using nearby watersheds.

Planning application

As a planning tool, the HIP can be used to determine how much water could be withdrawn from a stream without creating an unacceptable change in flow. This is then compared to the volume of current depletive and consumptive water losses to determine how much additional loss, if any, may occur before streamflow is adversely affected. Such a planning application of the HIP includes the following steps:

1) Obtain daily streamflows at the site.
2) Determine the stream type.
3) Define the baseline period of streamflow.
4) Determine the natural variability for each hydrologic index associated with that stream type during the baseline period.
5) Set the acceptable range to define how much change in each index will be allowed.
6) Quantify current water-use patterns.
7) Determine if the current water-use patterns are having an unacceptable effect on the hydrologic indices.
8) Predict future water-use patterns.
9) Determine the potential effects of future water-use patterns on the selected hydrologic indices.
10) If necessary, investigate various scenarios to restore streamflow to acceptable flows.

Two examples of using this assessment methodology, the Toms River watershed and the West Brook watershed, are in Appendix E and F, respectively. The following section details the process that results in an estimate of the natural streamflow variability and the impacts of various acceptable ranges.

The process that generates the natural variability of all temporal indices begins by analyzing the underlying data to produces one value per year of the data record. This new sequence of annual data is then ranked from lowest to highest to yield a frequency distribution. This distribution then becomes the basis for determining the natural variability of each temporal hydrologic index.

This process is illustrated here for the hydrologic index ML6 (the magnitude of June low flows) for West Brook. The baseline period for West Brook is 1934-1978 (Esralew and Baker, 2008). Figure 2 shows the minimum daily streamflow in each of the 44 Junes in the baseline period[1]. Figure 3 shows a frequency distribution of these 44 values.

The vertical axis of figure 3 shows the expected frequency of each value. An expected frequency curve connects the observed data. This curve is read by selecting a streamflow value, moving vertically upwards to the curve, then horizontally left to a corresponding frequency value. The frequency value corresponds to that percent of the Junes that the minimum daily flow is expected to be less than that streamflow value. For example, 75 percent of the June monthly minimum flows are expected to be less than 4.4 cfs. The curve can also be read by selecting a frequency and determining the associated streamflow. Table 4 gives June minimum flows in West Brook for a range of frequencies.

The median June minimum flow is 3.3 cfs. Thus in half of the Junes (22 of them) the minimum daily flow was less than 3.3 cfs. In the other half of the Junes, the lowest observed daily flow was greater than 3.3 cfs. The 25-percent percentile flow is 2.6 cfs; in only a quarter of the Junes was lowest daily flow lower than this value. The 75-percent value is 4.4 cfs; three quarters of the Junes had a minimum daily flow less than 4.4 cfs. The range of 25 -75 percent is the central half of all values; half of all the Junes had a lowest daily flow between 2.6 and 4.4 cfs. And at the extremes the driest June day on record had a streamflow of 1.3 cfs while the wettest one had 18 cfs.

The acceptable range of variability must be set by the regulatory agency. This is a policy decision based on how protective the agency needs to be. The acceptable range defines the upper and lower limits, based on the natural variability, that define acceptable changes in the median value of that hydrologic index. Any project which alters streamflow may affect the frequency distribution of the hydrologic index. The median value of each hydrologic index calculated from the impacted hydrograph must fall within its acceptable

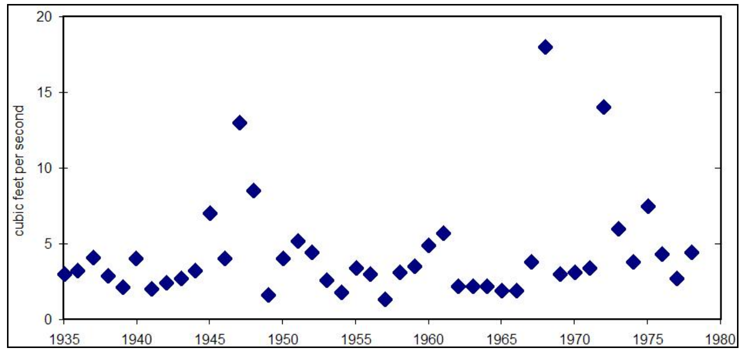

Figure 2. Annual minimum daily June flow, 1935-1978, West Brook, N.J.

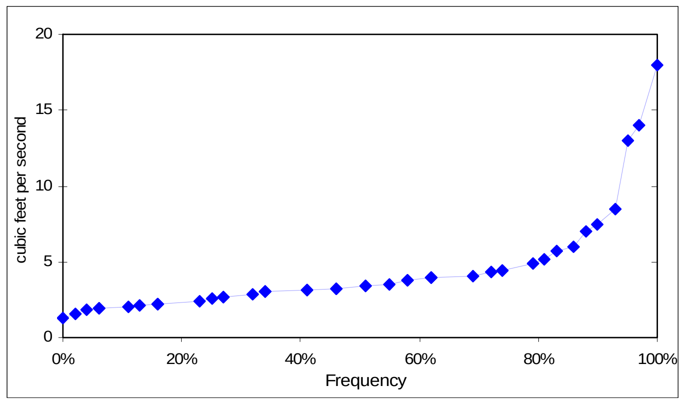

Figure 3. Frequency distribution of minimum June flows, 1935-1978, West Brook. (Some of the 44 data points coincide giving the impression of fewer than 44 years of data.)

Table 4. Expected frequencies[1] of June minimum flows in West Brook, New Jersey

Frequency (%)	Flow (cfs[2])	Frequency (%)	Flow (cfs[2])
1	1.4	55	3.5
5	1.8	60	3.8
10	1.9	65	4.0
15	2.1	70	4.1
20	2.2	75	4.4
25	2.6	80	5.0
30	2.7	85	5.9
35	3.0	90	7.4
40	3.0	95	12.3
45	3.1	99	16.3
50	3.3		

1. The frequency associated with each flow is the percentage of reported annual minimum monthly June flows lower than that flow.

2. cubic feet per second

[1] The data record begins in November 1934 so there is no July value for that year. This results in 44 instead of 45 values for computing ML6.

range. If the impacted median falls outside the acceptable range, then that project is judged to have an unacceptable impact on streamflow.

Richter and others (1997) recommend using a range of one standard deviation around the median if specific ecological information on how changes in streamflow variability affect the ecology is lacking. One standard deviation about the median is equivalent to a 16-84 percent range. The NJDEP is considering a 25 -75 percent acceptable range, which is slightly more conservative than Richter's recommendation.

If 25 -75 percent is the acceptable range for the West Brook example then, from table 4, this corresponds to a range of 2.6 cfs to 4.4 cfs in minimum June flows (fig. 4). This means that any proposed change in streamflows should not re-

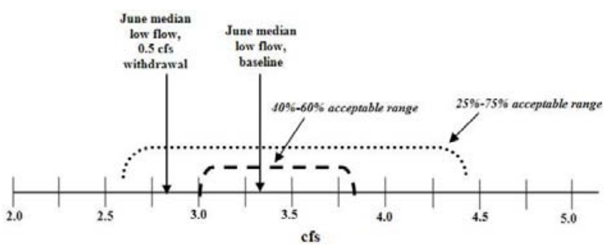

Figure 4. West Brook, N.J., June low-flow acceptable ranges with effect of 0.5 cubic-feet-per-second withdrawal on median minimum June daily flow.

sult in an alteration of the median June minimum flow outside this range. To continue this example, assume that a proposed project will create a constant decrease in streamflow of 0.5 cfs. This will reduce the median June minimum flow from 3.3 to 2.8 cfs. In this case the impacted median (2.8 cfs) is within the acceptable range of 2.6 to 4.4 cfs (fig. 4). Thus the proposed alteration does not have a significant impact on this particular hydrologic index.

The regulatory agency could decide that a stricter, more protective approach is appropriate for this stream. It may specify that 40-60 percent is the acceptable range. This range is 3.0 - 3.8 cfs for June minimum flows for this test case (table 4). A constant 0.5 cfs withdrawal would lower the June minimum flow median to 2.8 cfs, which is outside the 40-60 percent acceptable range (fig. 4). In this stricter example the proposed withdrawal would be judged to have an unacceptable impact on this hydrologic index.

This evaluation process is repeated for all hydrologic indices appropriate to the stream type (table 3). A proposed alteration may cause one or more impacted hydrologic indices to be outside of the acceptable range.

Regulatory Application

As a regulatory tool, the NJHAT software can provide flows that are representative of low flows in a stream at a location of interest. These flows can be the basis for establishing regulatory standards that apply to an intake. If streamflow declines to a rate less than the passing flows, then the withdrawal must stop. If applied to a reservoir, then water must be released to keep streamflow equal to or greater than the set passing flow.

Currently, passing flows are set in a variety of ways in New Jersey. The most common standard is the annual 7Q10 flow (N.J.A.C. 7:19-1.6 (e)). This is the 7-day-average low flow which has a 10 percent chance of occurring each year (Gillespie and Schopp, 1982). This is commonly interpreted as a summer drought flow which occurs for a sustained period, on average, once a decade. The USGS provides updated annual 7Q10 flows on its website (Reiser and others, 2002). Other methods used in New Jersey for setting passing flows for permit conditions include 125,000 gallons per day per square mile, average daily flow for the driest month, flows required to dilute a treated effluent discharge, and flows set by legislation. These passing flows are constant values, the same in every month.

These approaches to setting passing flows evolved from water-supply and water-quality concerns during a summer drought. However, from an ecological point of view, lower-than-normal flows in the winter may also cause a significant disruption. In New Jersey streams winter flows are normally greater than summer flows. A passing flow based on a summer drought flow may allow significant ecological disruption during the winter. Two widely-used methods for addressing this concern are the Tennant (or Montana) and Aquatic Base Flow (or New England) method (Annear and others, 2004). The Tennant method divides the year into two periods; the Aquatic Base Flow method into four. Each method applies a different passing flow to each period. The NJDEP is investigating setting a different passing flow in every month. These passing flows would be higher in the winter and lower in the summer, thus better reflecting the natural hydrological cycle in New Jersey. This would also be more protective of the aquatic ecosystem during seasonal low flows. The method proposed here is to use statistics produced by the NJHAT software to set variable monthly passing flows.

There are two NJHAT statistics which appear to be the most useful to this proposal. These are assessments of monthly median flows and monthly low flows.

The NJDEP approach uses the twelve indices MA12-MA23 to characterize monthly median flows for January through December. They are calculated by computing the median flow for each month in the data record followed by a frequency analysis of the median flows associated with each calendar month. For each calendar month, the median index value (defined as $MA_{50\%}$) is that median flow which occurs with a frequency of 50 percent. That is, in half of the months in the data record, the median monthly flow was less than this value. It is a statistic which represents what monthly flow in that calendar month that can commonly be expected to occur. The 25-percent median monthly flow ($MA_{25\%}$) represents a monthly median flow during a dry period which occurs, over a long period, in one year out of four.

In contrast, the twelve monthly low-flow statistics (ML1-ML12) are based on the lowest flow reported in each calendar month. They are calculated by selecting the lowest flow for each month in the data record followed by a frequency analysis of the flows associated with each calendar month. The monthly low-flow statistics are, by definition, lower than the monthly median-flow statistics for the same percentage. For each calendar month the 50-percent monthly low flow ($ML_{50\%}$) divides the reported flows, with half of the months having a lesser monthly low flow (and thus representing the drier months) and half having greater monthly low flows. The 25-percent monthly low flow ($ML_{25\%}$) represents a month that is experiencing a dry period that can be expected to occur in one year out of four.

For most streams the following relationship between the indices calculated for any given month:

$$MA_{50\%} > MA_{25\%} > ML_{50\%} > ML_{25\%} > \text{annual 7Q10}$$

For convenience, a passing flow based on $MA_{25\%}$ is abbreviated here as a H (high) passing flow, the M (moderate) passing flow is associated with the $ML_{50\%}$ value in each month, and the L (low) passing flows come from the $ML_{25\%}$ statistic (table 5). Figure 5 shows, for West Brook, the $MA_{25\%}$ (H), $ML_{50\%}$ (M), $ML_{25\%}$ (L), and annual 7Q10 monthly values.

These statistics provide an alternate way to set passing flows. Different passing-flow standards may be based on water quality or water use. For example, a stream that supports a threatened or endangered species may receive a higher passing flow (perhaps H or M). Passing flows associated with essential potable-supply needs may be re-

Table 5. Proposed monthly passing flow methodology.

Abbreviation	General description	Mathematical definition
H	Most restrictive. Monthly passing flows set to average flows in a dry month.	25-percent frequency of distribution of average monthly flow for each month - $MA_{25\%}$
M	Moderately restrictive. Monthly passing flows tied to low flows in an average month.	Median of observed monthly daily low flows - $ML_{50\%}$
L	Less restrictive. Monthly passing flows tied to low flows in a dry month.	25-percent frequency of observed monthly daily low flows - $ML_{25\%}$
7Q10	Least restrictive and the usual current approach. Flow in a summer drought.	7-Day mean low-flow that occurs, on average, once in 10 years

laxed based on this need (perhaps L or annual 7Q10).

Applying monthly passing flows would be more protective of stream ecology during low flow times. However, they are more complicated to compute and apply. Additionally, monthly passing flows based on the H, M, or L statistics will be more restrictive than an annual 7Q10 passing flow, especially during a winter drought. This makes the stream a less reliable source of water (Vogel and others, 2007). The regulatory agency must determine if the increased risk to the water supply is justified by the additional ecological protection.

Setting passing flows using HIP statistics requires the following steps:

1) Define baseline period of streamflow.
2) Calculate appropriate low-flow statistics for the baseline period.
3) For the given stream type and water use define what standards are appropriate for setting monthly passing flows.
4) Determine if the proposed passing flows will provide sufficient water for the intended use during low-flow times.
5) Apply the passing flows as permit conditions.

Appendix G presents a passing-flow analysis of West Brook. This analysis calculates the H-M-L statistics and compares them to results of both the Tennant and Aquatic Base Flow methodologies.

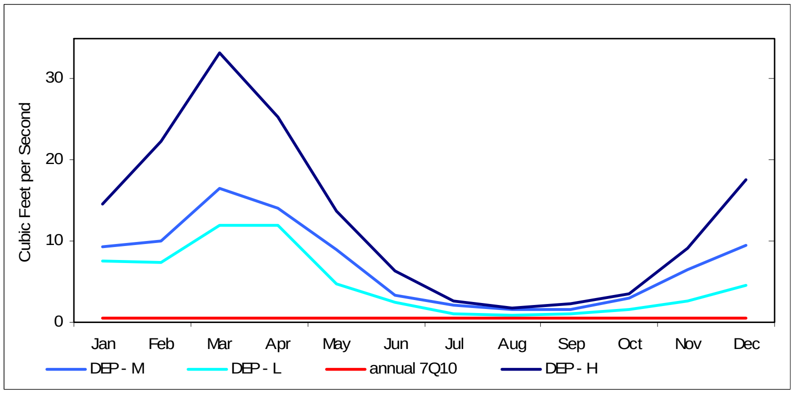

Figure 5. Possible passing flows, West Brook.

Groundwater interactions

The estimation of the impacts of current water use on streamflow implicitly assumes a 1:1 relationship between unconfined-aquifer withdrawals and a reduction in streamflow. That is, a gallon of water pumped from the unconfined aquifer creates a one gallon reduction of streamflow in the same month. This is a reasonable approach for the scope of this investigation. However, there may be some cases where the impacts of unconfined-aquifer withdrawals are delayed and affect a nearby stream days or weeks after the withdrawal occurs. Additionally, if water is coming out of storage in the aquifer then there may be less impact on streamflow than would otherwise be expected. These considerations are beyond the scope of this approach and will take a detailed hydrogeological investigation to quantify. As a conservative approach, the NJDEP prefers to assume that unconfined-aquifer withdrawals have a 1:1 correlation with streamflow losses and that streamflow losses occur in the same month as the groundwater withdrawal.

The HIP analysis assumes that withdrawals from a confined aquifer in a watershed have no direct affect on streamflow. However, drawdown due to confined aquifer withdrawals may induce leakage out of the overlying water table. The US Geological Survey has estimated the increased leakage rates out of Coastal Plain water-table aquifers due to increased confined-aquifer withdrawals (Alison Gordon, USGS, written communication, 2007). This is an indirect accounting for the effect of confined aquifer withdrawals. This effect is accounted for in the analysis of water loss in the Toms River watershed (appendix E).

Data Needs

The hydroecological integrity assessment (HIP) process requires a diverse data set:

1) Daily streamflows - The HIP analyzes daily streamflows. If the analysis is to be done for a location that lacks a stream gage then daily streamflows must be extrapolated to create a synthetic daily hydrograph. This process is more difficult if there are no nearby stream gages with watersheds of similar size and characteristics. The US Geological Survey is currently researching how to estimate daily hydrographs at an ungaged site based on upstream meteorology and land-use characteristics. Any such extrapolation method, other than a simple area-weighted approach, will require time, data, and professional expertise.

2) Baseline period - The HIP measures alterations in streamflow variability from a baseline period. The baseline period is available for a number of stream gages (Esralew and Baker, 2008; Appendix I). For locations near these gages this may be sufficient. At other locations, the user must determine an appropriate baseline period based on the timing of significant land-use changes and hydromodifications in the watershed.

3) Depletive and consumptive water use - The HIP requires the current rate of water loss attributable to exports and imports of water in the watershed in order to quantify the effects on current streamflow. These values are available for all HUC11 watersheds for the period 1990-1999 (Domber and Hoffman, 2004).

Implementation Issues

A number of issues arise in considering how to implement the HIP. A partial discussion of some of the more important ones follows.

Flows & Ecological Health

Any approach that sets passing flows based on annual or monthly 7Q10 flows, or uses the New England Aquatic Base Flow or Tennant methods, makes the implicit assumption that protecting the low flows protects the ecology. Statistical methods that characterize multiple flow components in baseline streams in order to evaluate changes, such as IHA (Richter and others, 1996) and HIP (Kennen and others, 2007), also use flows as a surrogate for aquatic health. This approach is valid because modifying flows modifies the aquatic ecology.

The aquatic flow regime is a 'master variable' which determines which aquatic species can survive in a stream reach (Poff and others, 1997; Beecher, 1990; Annear and others, 2004; Postel and Ricter, 2003). Lloyd and others (2004) conducted a literature review and found, that of 70 sites with reported modification of the flow regime, 87 percent exhibited ecological or geomorphological changes.

Bunn and Arthington (2002) define four principles to show how the natural variability of streamflows govern the aquatic ecosystem:

1. "Flow is a major determinant of physical habitat in streams, which in turn is a major determinant of biotic composition.
2. "Aquatic species have evolved life history strategies primarily in direct response to the natural flow regimes.
3. "Maintenance of natural patterns of longitudinal and lateral connectivity is essential to the viability of populations of many riverine species.
4. "The invasion and success of exotic and introduced species in rivers is facilitated by the alteration of flow regimes."

This approach does not focus on one species but instead is a holistic approach to protecting and maintaining the entire ecological web. Trying to manage streamflows for the benefit of one highly valued or charismatic species may have detrimental effects on other species (Sparks, 1995).

Analyzing the water needs of a particular species is a valid way to set adequate streamflows. Unfortunately, the research needed to determine the seasonal flow needs of a species is time and money intensive. After more than a century of study this level of detail is available only for one family of fish -- salmonids (Stone, 1877; Crisp, 2000). Kennen and Ayers (2002) examined population data for 43 species of fish, 170 invertebrates species, and 103 algae species in their analysis of urbanization effects on aquatic health in New Jersey. It is impractical to wait for studies to define the detailed flow needs of all of these species before trying to protect the aquatic ecosystem.

The TAC decided that tools which analyze changes in flow variability can help the NJDEP meet its goal of protecting, sustaining and restoring the natural aquatic ecosystem. Limiting changes in streamflow to an acceptable range is a much more achievable goal than analyzing the flow-habitat relationships of numerous aquatic species. The HIP is specifically designed to characterize changes in the different flow components quantitatively in order to facilitate achieving this goal. The HIP would not be appropriate if the goal were to optimize the population of one specific species.

New Passing Flow Standards

The need for passing flows is well established. A dry stream bed for a perennial stream means no aquatic ecosystem. But actually establishing a minimum flow is problematic. The widely-used annual 7Q10 flow has no biological support in the research literature other than that it is better than a zero flow. It does, however, have a history of successful implementation, is easy to obtain, and is widely referred to in regulation. Karr (1991) points out "… a narrow perspective on standards was imposed that was presumed to be effective because it was decisive, legally defensible, and enforceable in a regulatory context."

This report presents an alternate approach for setting monthly passing flows, based on observed monthly flow statistics, that is more reflective of the natural hydrograph in New Jersey. But there is a range of flow statistics that might be used. The H, M, and L passing flows (table 5) would all be more protective of the aquatic ecosystem than the annual 7Q10 method, but also more restrictive of on-stream withdrawals. The NJDEP must decide how conservative to be before this approach can be applied.

Water-Supply Streams

The surface-water reservoirs of northeastern New Jersey supply nearby cities. Some of these reservoirs have been a significant water source for more than a century, supporting the growth of these cities (Legislative Commission on Water Supply, 1955). Also, the aquatic ecosystem downstream of these reservoirs has had decades to adjust to the changed flow regime.

If the reservoirs begin to release greater passing flows, their ability to supply a sufficient volume of water, especially during droughts, will be affected (Vogel and others, 2007). Additionally, the restored flows may alter an ecology that has adapted to changed conditions. The NJDEP will have to consider how important a water supply is and the length of time streamflows have been altered when evaluating any changes in established passing flows.

Acceptable Range

This report suggests using an acceptable range of streamflow variation of 25 percent to 75 percent in a HIP application. For each hydrologic index a frequency analysis yields these values for the baseline period. The goal is then to make sure the 50-percent (median) value of that index for an altered streamflow falls within the baseline acceptable range. The 25-percent to 75-percent range was selected as the default range as it is slightly more conservative than the one standard deviation range (18 percent to 85 percent) recommended by Richter and others (1996).

Selecting the 25-percent to 75-percent range gives rise to the question of whether or not the range is sufficiently or overly conservative. Also, the range might be allowed to vary depending on water use. For example, a water withdrawal for potable supply might be evaluated with a wider range than a withdrawal for non-agricultural irrigation. The range might also depend on the stream ecology. Withdrawals from a stream of significant ecological sensitivity might be held to a narrower acceptable range than withdrawals on a less sensitive stream.

The HIP can give no insight into answering these questions other than concluding that a narrower range would limit streamflow changes while limiting water withdrawals. More data, linking flows to ecological health for more species, are needed to expand this argument beyond the rationale that less change in streamflow means less change in the ecosystem. This argument may suffice for stressed or environmentally-sensitive streams. It may also suffice for less-than-critical water uses. For critical water-supply streams additional justification may be needed to support a narrower acceptable range of streamflow variation.

Number of Hydrologic Index Violations

The HIP application in New Jersey uses the natural variability of 20 hydrologic indices with associated acceptable range of change. But should a violation of the acceptable range be a strict trigger? For example, assume a proposed flow alteration will move the median value of one hydrologic index to a value of 80 percent of the baseline acceptable range, while the 19 other indices remain well inside the acceptable 25-percent to 75-percent range. Is this worse than another flow alteration which moves all 20 indices to a value of 74.9 percent? These questions will have to be addressed by the NJDEP in order to implement the HIP. One possible approach is the way to DHRAM (Dundee Hydrological Regime Alteration Method) developed by Black and others (2005). This assigns a numerical score to each hydrologic index depending on how far it is from the baseline median value. The sum of scores for all indices then becomes a new evaluation parameters. An approach like this would have to be calibrated to New Jersey streams in order to be a useful tool.

Passing Flows and Discharge Limits

Several NJDEP regulatory programs use the annual 7Q10 passing flow as a basis to establish discharge limits. The discharge's impact on water quality is calculated assuming this flow is in the stream. When flows are greater the impact is lessened. If an alternate method for establishing passing flows becomes common in a watershed the net effect may be more water in the stream during low flow times. This might suggest that higher flows could be used to establish discharge limits. But this may be an unwise course of action. Low flows do occur. A higher passing flow applied to a withdrawal point does not mean flows will be kept above that passing flow, only that the withdrawal will stop at that time. Calculating permit discharge limits on lower flows appears to be the approach that is most protective of a stream's ecosystem.

Integrating Priorities

The State must meet different regulatory requirements. The Federal Clean Water Act requires the NJDEP to protect, maintain and restore the aquatic ecosystem of the State. Other Federal and State regulations impose additional restrictions on streamflow impacts. On the other hand the Water Supply Management Act requires that the State provide "an adequate supply and quality of water for the citizens of the State" in addition to "protect the natural environment of the waterways of the State."

Meeting these mandates requires an understanding of the effect a new withdrawal may have on the aquatic ecosystem. The HIP is one tool that can quantify this potential impact and add scientific insight that will allow decision makers to make better-informed policies and decisions.

Need for Ongoing Discussion

This paper attempts to apply the hydroecological integrity assessment process to New Jersey's water-supply regulatory environment. However, there needs to be continued discussions on the application of this approach to other NJDEP water programs. That discussion is beyond the scope of this document, but is vital to fully extend the potential benefits of the hydroecological integrity assessment approach to all water programs.

Summary

The natural flow paradigm recognizes that streamflow is a master variable that controls aquatic ecosystems. High flows shape the stream channel and provide access to breeding sites and food sources in the floodplain. Average flows represent the normal condition. Low flows sustain life in droughts but also limit ecological niches and suppress invasive species. If the extremes occur too frequently or too infrequently the natural ecological web is disrupted. The magnitude, timing, duration and frequency of all components of streamflow must be maintained in order to maintain an unimpaired ecology.

The U.S. Geological Survey developed the Hydroecological Integrity Assessment Process (HIP). The HIP provides a way to calculate the natural variability of a series of hydrologic indices. It can be applied to determine if a streamflow-changing project will alter flow variability by an unacceptable amount. The HIP can be applied in either planning or regulatory modes.

In a planning mode, the HIP is used to evaluate the effect of a proposed change in streamflow. The indices fully characterize the natural range of variability of streamflow during a baseline period. An acceptable range is then set for the hydrologic indices. An analysis of a projected impacted streamflow regime determines if hydrologic indices will be changed beyond the acceptable range by the proposed change.

In a regulatory mode, relevant HIP indices set monthly passing flows that govern reservoir releases or limit in-stream withdrawals Setting high passing flows is more protective of the aquatic ecosystem but limits the volume of water that can be withdrawn from the stream.

Applying the HIP to test cases has shown the need for additional research:

- HIP requires daily streamflows. If these are not available they must be generated to create a synthetic daily hydrograph. Any method that adequately addresses this problem is data intensive.
- For stream gages with a long-term record a recent USGS research project has determined appropriate baseline periods (Esralew and Baker, 2008). For other gages a baseline period must be set in a consistent fashion.
- For the HIP to be most accurate it requires an updated accounting of all depletive and consumptive water use in the watershed. This requires an ongoing effort to keep cumulative track of all activities which may affect streamflow.

The test cases have also highlighted some implementation issues. These include:

- What is the appropriate acceptable range for hydrologic indices? Using the 25 percent to 75-percent range could allow more withdrawals by allowing more streamflow alteration. A narrower range (such as 40 percent to 60 percent) would be more ecologically protective but also more limiting of withdrawals. Should the acceptable range be based on the designated use of the water, the ecological significance of the stream, or importance of the stream for water supply?
- Should a different passing flow be set for each month? If so, what flow statistics should be used?
- Should passing flows be set differently for reservoirs, where passing flows are required releases, than for on-stream intakes, where passing flows limit withdrawals at low streamflows. Some of the potential statistics are very protective of streamflow but could stop withdrawals if flows are only slightly lower than normal.
- Are the limits to the acceptable range absolute limits? If only one index is slightly out of bounds, is this significant? Are all violations of the acceptable range equally significant? Should the limits of the acceptable range be used in a regulatory context to develop permit limits?

It is expected that additional policy concerns will arise as the HIP is implemented throughout numerous programs of the NJDEP.

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GLOSSARY

Annual 7Q10 - The annual-minimum 7-day-average flow that has a recurrence interval of 10 percent (or once in ten years). It is calculated in four steps:

(1) For every day in the data record compute the 7-day-average flow (average of that day's flow and the previous six days).
(2) Pick out the minimum 7-day-average flow in each year to create a new data set that has as many entries as there are years in the data record.
(3) Create a frequency distribution of the new annual-minimum 7-day-average-flow data set using a Log-Pearson Type III statistical distribution.
(4) Determine which 7-day-average flow has a probability of occurrence of 10 percent per year (or once per ten years).

Acceptable Range - The central part of the natural variability of a hydrologic index. A regulatory agency determines that the median of a hydrologic index should not be moved outside of this range due to a change in streamflow.

Accretive - An accretive water use is one that adds water to the area being studied. Examples include the import of potable water or the import of sewage into a watershed.

Aquatic Base Flow method - A methodology developed in New England to estimate required flows in streams (U.S. Fish & Wildlife Service, 1981).

Aquatic Ecosystem_- Refers to the organisms (invertebrates, vertebrates and plants) living in or along the stream or river along with their interactions with each other and the environment. Some researchers may include energy and nutrient input sources outside of the water as well as terrestrial organisms that depend on the water for part of their life cycle or on aquatic organisms for food.

Baseline period - a period that represents a natural or relatively undisturbed condition.

Consumptive - consumptive water is that water that is evaporated or transpired during use. Basically it is water lost to the atmosphere by use. Examples include water lost during irrigation (either transpired by plants or evaporated during the spreading process) and water evaporated as it is used to cool an industrial process.

Depletive - A depletive water use is one that removes water from the area. Examples include the export of potable water and the export of sewage from a watershed.

Depletive and Consumptive - A shorthand way of referring to all of the processes that remove water from a watershed. This includes evaporation in the watershed and all exports.

Gaging station - A site on a stream where flow is measured. The U.S. Geological Survey maintains a national network of gaging stations. Information on New Jersey stream gages is at: http://nj.usgs.gov/sw/.

Hydroecological - A term that refers to the ecological processes that occur in a water environment.

Hydroecological Integrity - A term that refers to maintaining those processes that sustain a water-based ecological system in a natural or unimpacted state.

Hydrologic index - A numerical characterization of one component of streamflow. There are 171 hydrologic indices defined by Olden and Poff (2002).

Hydromodification - Alteration of the hydrologic characteristics of surface waters, which in turn could cause degradation of water resources. (US. Environmental Protection Agency, 1997)

HUC watershed - Hydrologic Unit Codes (HUCs) are assigned by the USGS to group drainage areas. They define the area that drains to a specific reach of a stream, excluding the area upstream of the upper end of the reach. The USGS has established a hierarchical set of HUCs, where a HUC11 consists of several HUC14s, and a HUC8 consists of several HUC11s. There are 921 HUC14s within the coastline of New Jersey with an average size of 8.5 square miles. There are 150 HUC11s within the coastline of New Jersey with an average size of 51.5 square miles. The boundaries of all New Jersey HUC14s and HUC11s stop at the boundaries of the State; they do not extend into Pennsylvania or New York even if the actual drainage area does. The HUC classification system in New Jersey is described by Ellis and Price (1995). A current GIS coverage of the HUC11s is given by Hoffman (2000).

Instream Flows - see Passing Flows.

Natural Flow Paradigm - An approach to aquatic ecology that assumes that the aquatic ecosystem has evolved in response to all streamflow components. If any streamflow component changes significantly then the aquatic ecosystem will change.

Natural Variability - The observed frequency distribution of a hydrologic index observed during a baseline (unimpacted) period.

Non-tidal - That portion of a stream or river sufficiently far from the coast that water flow is not affected by tidal rise and fall in the ocean.

On-stream Withdrawal - A water intake that withdraws water directly from a stream or river without benefit of a significant dam.

Passing Flows - The water flow rate that must remain in the stream to support the aquatic ecosystem and other downstream users. This term is used only in New Jersey. Most other users refer to these flows as instream flows.

Salmonids - Fish belonging to the salmonidae family of ray-finned fish. This includes trout and salmon.

Streamflow Component - One major grouping of hydrological indices. There are ten streamflow components dealing with magnitude of high, average and low flows; frequency of high and low flows; duration of high and low flows, timing of high and low flows; and rate of change in flow.

Tennnant method - A method to estimate required flows in streams in Montana. (Tennant, 1976).

Watershed - All the area that drains to a defined point, usually along a stream.

Appendix A. Selected Internet Links

Instream Flow Council

http://www.instreamflowcouncil.org/

The Nature Conservancy

Indicators of Hydrologic Alteration (IHA):
http://www.nature.org/initiatives/freshwater/conservationtools/

Ecological Limits of Hydrologic Alteration (ELOHA):
http://conserveonline.org/workspaces/eloha

New Jersey Department of Environmental Protection

Division of Water Supply home web page:
http://www.nj.gov/dep/watersupply/

New Jersey Geological Survey home web page:
http://www.njgeology.org/

U.S. Geological Survey Biological Resources Division, Fort Collins, CO

The hydroecological integrity assessment process home web page:
http://www.fort.usgs.gov/resources/research_briefs/HIP.asp

New Jersey hydrologic tools (NJHAT and NJSCT) (Henriksen and others, 2006):
http://www.fort.usgs.gov/Products/Software/NJHAT/Default.asp

NJHAT users manual (Henriksen and others, 2006):
http://www.fort.usgs.gov/Products/Publications/pub_abstract.asp?PubID=21598

U.S. Geological Survey Water Resources Division, Trenton, NJ

Streamflow statistics (Reiser and others, 2002):
http://nj.usgs.gov/flowstatistics/

NJ Streamflow characteristics and trends (Watson and others, 2005):
http://pubs.usgs.gov/sir/2005/5105/

Streamflow gaging stations in New Jersey:
http://waterdata.usgs.gov/nj/nwis/current/?type=flow

Note: All Internet links active as of December 2009.

Appendix B. Acronyms

Acronym	Stands For
7Q10	7-Day mean low-flow that occurs, on average, once in 10 years
ABF	Aquatic Base Flow
DH	Duration of high flows
DL	Duration of low flows
ELOHA	Ecological Limits Of Hydrologic Alteration
FH	Frequency of high flows
FL	Frequency of low flows
GIS	Geographical Information System
HIP	Hydroecological Integrity assessment Process
IBI	Index of Biological Integrity
IHA	Index of Hydraulic Alteration
MA	Magnitude of average flows
MH	Magnitude of high flows
ML	Magnitude of low flows
NJDEP	New Jersey Department of Environmental Protection
NJGS	New Jersey Geological Survey
NJHAT	Hydrological Assessment Tool for New Jersey
QAA	Average annual flow
RA	Rate of change in flow
RVA	Range of Variability Analysis
SCT	Stream Classification Tool
TAC	Technical Advisory Committee
TH	Timing of high flows
TL	Timing of low flows
USGS	United States Geological Survey

Appendix C. Members of the Technical Advisory Committee

The Technical Advisory Committee (TAC) was set up to provide guidance for the U.S. Geological Survey's Hydroecological Integrity Assessment Process research project. The TAC did not have an official voting membership. The first TAC meeting was held on September 6, 2001. The last meeting, the 14th, was held on June 23, 2004.

The following alphabetical membership list consists of individuals who attended one or more meetings. Each member is listed with his or her affiliation at that time.

Academy of Natural Science
Camille Flinders, Rich Horowitz

New Jersey Department of Environmental Protection
Division of Fish and Wildlife: Andy Didun, Pat Hamilton, Jeanette Bowers-Altman
Division of Science, Research & Technology: Tom Belton, Marjorie Kaplan, Karen Schaffer
Division of Water Quality: Flavian Stellerine
Division of Water Supply: Mike Bleicher, Jan Gheen, Michele Putnam, Fred Sickels
Division of Watershed Management: Kevin Berry, Tom Brand, Ambrosia Collier, Jim Gaffney, Barbara Hirst, Bob Kecskes, Joe Mattle, Donna Milligan, Harold Niebling, Helen Rancan, Liz Semple
New Jersey Geological Survey: Jeff Hoffman

New Jersey Pinelands Commission
Nick Procopio, Bob Zampella

New Jersey Water Supply Authority
Dan Van Abs

Pennsylvania Department of Environmental Protection, Fish and Boat Commission
Leroy Young

United States Geological Survey - Biological Resources Division - Boulder Office
Jim Henriksen

United States Geological Survey - Water Resources Division - West Trenton Office
Mark Ayers, Ming Chang, Jack Gibbs, Jonathan Kennen, Pierre Lacombe, Steve Nieswand, Bob Reiser, Bob Schopp, Dave Steadfast, Steve Tessler, Kara Watson

Note: Some TAC members have changed their affiliation since 2004.

Appendix D. Selection Details for New Jersey-Specific Hydrologic Indices

Kennen and others (2007) examined 171 hydrologic indices for each stream gage. For each of the four stream types they selected the hydrologic index from each of the ten components that best characterized streamflow. Their analysis also identified other indices that were acceptable surrogates for the primary index. Any of these secondary indices could be used in place of the primary index and still accurately characterize streamflow. Table 2 shows the set of indices for each stream type and flow component, arranged so that the first index is of primary importance and the others are of secondary importance.

The primary indices recommended for use in New Jersey (table 3) differ from that recommended by Kennen and other (2007). This modification is required for three reasons: 1) calculation consistency when compensating for skewed data sets; 2) eliminating surrogate gages by analyzing variation in a stream based on data solely from that stream; and 3) sensitivity to changes in the particular stream. Each of these reasons is explained in detail in Appendix I.

Calculation Consistency

For each hydrologic index the HIP compares a single number that characterizes current or impacted flows to an acceptable range of natural variability during a baseline period. All of the numbers must be calculated in a consistent manner in order for this comparison to be valid.

Each hydrologic index's acceptable range of natural variability is based on annual values of a statistical characterization of streamflow during a baseline period. A ranking of the annual values yields a percentile distribution. The acceptable range is based on a preset frequency range, 25 percent to 75 percent for example, that bounds acceptable changes in that hydrologic index. A more detailed example of this is in the section 'Hydroecological Integrity Assessment Process Application.'

The acceptable range is generated by a frequency analysis and is a nonparametric statistic. When it is used as a standard in a regulatory, it is necessary that the evaluation parameter be generated in a consistent manner. For example, the median of a data set is that value with a 50 percent frequency occurrence. It comes from a percentile ranking of the underlying data and is also a nonparametric statistic. Thus, comparing the impacted median value to the baseline 25-percent to 75- percent range is a consistent comparison. In contrast, the mean (average) of a data set is not a percentile; it is a parametric statistic. It implicitly assumes that the underlying data follow a distribution curve such that the mean is a defining factor of the curve. In a skewed data set, such as is the case for most streamflow data sets, the mean may differ significantly from the median.

For example, West Brook in northern New Jersey is in stream type C, with a baseline period of 1935-1978. The hydrologic index ML3 is used to evaluate the magnitude of low flows (table 3). For ML3 the 25-percent to 75-percent acceptable range is 12.0 - 21.8, whereas the 40-percent to 60-percent range is 14.0 - 17.0. The median value of ML3 during the baseline period is 16.5. The mean of FH3 during the baseline period is 17.2, which is outside the 40-percnet to 60-percent range. If the 40-percent 60-percent range were the acceptable range for ML3 and the mean were the evaluation parameter, the baseline period would show an unacceptable change in variability in this stream. This nonsensical result arises from comparing the standards generated by a nonparametric statistic (the frequency distribution) to a parameter generated by a parametric statistic (the mean).

For these reasons, comparing the mean value to a range based on a percentile analysis is not logically consistent. This inconsistency is a problem in a regulatory setting. To overcome this inconsistency, the software Hydrologic Assessment Tool for New Jersey (NJHAT) provides the option of using the mean or median (Henriksen and others, 2006). In regulatory applications in New Jersey the median should be specified for consistency.

Eliminating Surrogate Gages

For regulatory applications, the HIP will be used to evaluate flow changes in a specific stream at a specific location. It is necessary that all of the indices in this evaluation (both the baseline observed range and the impacted index) be based on this specific location.

There are two categories of hydrologic indices - temporal and spatial. Temporal indices are calculated based on streamflows observed at a single gage and yield both a value and a frequency distribution. For example, ML1 is based on a frequency analysis of annual January low flows. The underlying frequency distribution has as many values as there are Januarys in the data record. Spatial values, however, yield only a single value. For example, ML13 is the variability across minimum monthly flows. It is based on the mean and standard deviation of all monthly minimum flows across the data record (Kennen and others, 2007). Each stream gage has only one value, rather than a series of annual values. This means that for ML13, and all other spatial indices, a natural variability range cannot be generated. Henriksen and others (2006) suggest using data from nearby streams of the same type to generate an observed baseline variability range appropriate to that stream type. The consequence of this approach is that some of the streams will have an unimpacted spatial hydrologic index outside the baseline range. This would imply that the baseline flow shows a significant change from the baseline condition. This invalid result is a statistical artifact that does not help evaluate streamflow changes in that particular stream. For this reason, spatial indices may not consistently provide useful results in regulatory situations. NJDEP does not recommend using the spatial indices. Where a spatial index is listed as the primary index (table 2) a secondary index is used instead. Table 6 lists the hydrologic indices for which the NJHAT software enables the user to specify using either the mean or median value in comparisons.

Eliminating spatial indices leaves no index for two flow components - timing of low flow and timing of high flows[2]. This report recommends adding an analysis of monthly low flows in order to retain an evaluation of the timing of low flows. Most flow alterations (except for those caused by major dams) do not significantly affect high flows. Low-flow changes are usually a greater concern. In order not to change the ecology, low flows should not occur significantly more frequently, be significantly lower, or last significantly longer than before the flow alteration. The 12 monthly magnitude of low-flow indices (ML1 through ML12, representing January through December) are useful for showing the effects of a project's impact on low flows. These indices have the additional benefit of being intuitive and quickly showing, in a natural sense, the distribution of low flows throughout a year. Figure 6 shows not only the median (50-percent frequency) value but also the 25- percent to 75-percent range of each index. Figure 6 shows the normal hydrograph of an unmodified New Jersey stream -- lower flows in late summer/early fall and higher flows in the spring.

Sensitivity to Changes

In order to be useful, the calculated statistic must show a change in response to changing flows. The hydrologic index FL3 was selected by USGS as the preferred index characterizing low-flow frequency for stream types A, B and D (table 2). However, in many test cases this index was equal to 0 for the 25-percent, 50-percent and 75-percent frequencies. Thus it is not a useful analysis tool. For these stream types the next appropriate low-flow index is FL1. (For stream type B, FL2 is the first secondary index but this is a spatial index and was removed for the reasons described above.)

Similarly, the preferred high-flow-frequency indices FH4 (for stream types A and B) and FH7 (for stream type C) also proved to be equal to 0 in most test cases. The next highest spatial high-flow index was FH3 for stream types A and C, and FH10 for stream type B.

For the above reasons the USGS-recommended set of hydrologic indices for each stream type was modified to a set more suitable for regulatory application in New Jersey. The indices recommended for regulatory use are listed in table 3.

[2] In the HIP each flow component is characterized by multiple temporal and/or spatial hydrologic indices. All indices that characterize the flow components 'timing of low flows' and 'timing of high flows' are spatial, that is, they depend on flow observations at multiple gages indices (Olden and Poff, 2003). Thus the counterintuitive result that there are no temporal indices available for timing of low or high flows.

Table 6. Hydrologic indices for which NJHAT software allows option of calculating either median or mean

Flow component	Hydrologic Indices
Magnitude of average flows	MA3, MA12 - MA35
Magnitude of low flows	ML1- ML12, ML14, ML15, ML17, ML19
Magnitude of high flows	MH20
Frequency of low flows	FL1, FL3
Frequency of high flows	FH1, FH3 - FH11
Duration of low flows	DL1 - DL5, DL18
Duration of high flows	DH17 - DH24
Rate of change in flow	RA1, RA3, RA8

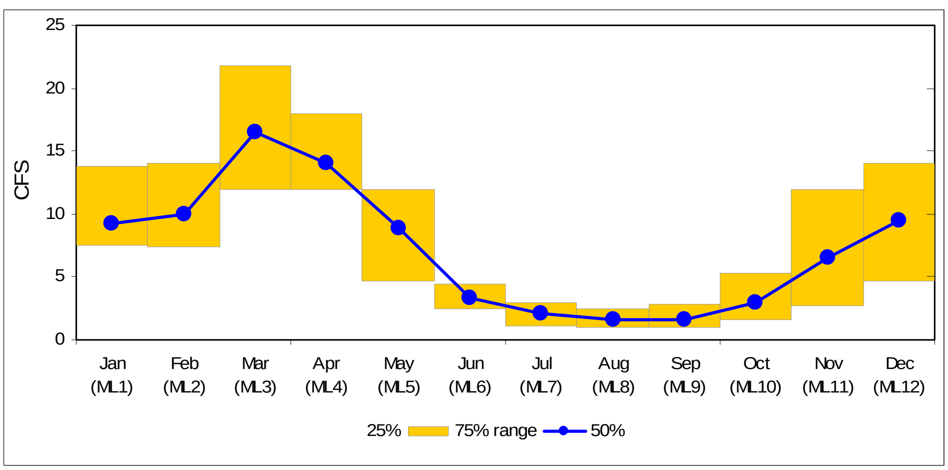

Figure 6. Monthly-low-flow hydrologic indices (ML1-ML12), West Brook, N.J.

Appendix E: Planning Example - Toms River watershed

This appendix shows an application of the hydroecological integrity assessment process (HIP) to the Toms River watershed in order to evaluate the effects of the current rate of depletive and consumptive water use on streamflow. Additionally, it includes an analysis to determine if the hydrologic indices could be restored to the acceptable range by not exporting sewage from the watershed.

The Toms River watershed in southern New Jersey covers approximately 123 square miles upstream from the stream gage near Toms River (USGS gage 01408500). Figure 7 depicts the watershed and shows locations of withdrawals, by magnitude, source, and use of water. The withdrawal volumes are averages for the 1990's. Population in this watershed increased from about 5,000 in 1940 to 73,000 in 2000, with a marked increase starting in the 1960's (fig. 8).

Daily streamflows for the Toms River are available for 1928-2004 (fig 9). An SCT analysis of these data classifies the Toms River as stream type B, stable with high base flows (appendix I). In the 1990's, low flows were close to 100 cubic feet per second (cfs), whereas high flows were greater than 1,000 cfs.

The baseline period for this gage is 1928-1963 (appendix I). The 25-percent, 50-percent (median) and 75-percent frequency values of appro priate hydrologic indices for a B stream (from table 3) are in table 7. This table also shows the

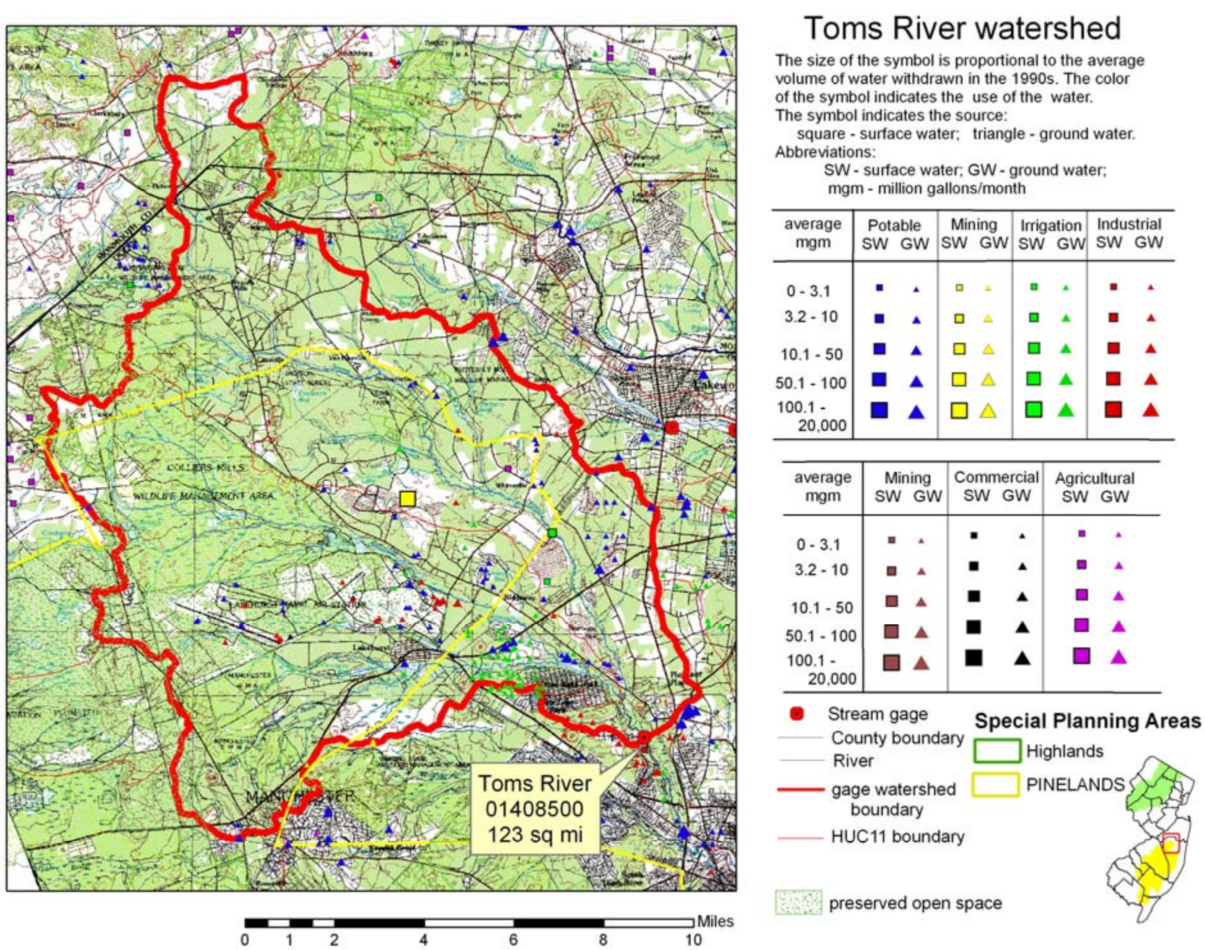

Figure 7. Toms River, N.J., watershed and average 1990's withdrawals.

median values of the indices based on 1980-2004 flows. If the baseline 25-percent to 75-percent values form the acceptable range of variability then current median values of the hydrologic indices DL1, ML1, ML3, ML6 and ML11 are outside of this range. This implies that the current pattern of streamflow in the Toms River is significantly different from the baseline period.

Water losses in the watershed is defined for this approach as all water lost due to anthropogenic activities, either by evaporation or by export. Any imports of water into the watershed help to offset these losses. The analysis assumes there is a 1:1 relationship between water loss and streamflow decreases.

This analysis assumes that the surface water and unconfined groundwater systems are one hydrologic system. Water pumped from an unconfined aquifer creates a direct and immediate decrease in streamflow with a 1:1 relationship. The confined aquifer system, however, is a separate system. It may be recharged outside of the watershed and water withdrawn from it may have no effect on streamflows. To account for this, withdrawals of confined groundwater within the watershed are considered to be an import.

An additional potential loss is the change in vertical leakage between the water-table aquifer and an underlying unit. Increased confined aquifer withdrawals may decrease the water flowing upwards to the water table, or may induce outward leakage. The U. S. Geological Survey has estimated the change in this leakage due to confined aquifer pumpage (Alison Gordon, USGS, written communication, 2007). This change from baseline conditions is incorporated in the net water-loss analysis.

In order to analyze the effect of current water losses it is important to separate out any impact of climatic change. If the past few decades have been wetter (or drier) than the baseline period than this will complicate analysis of the impacts of current water losses. For this reason, current water losses are applied to the baseline daily hydrograph in order to estimate what flow would have been had the current pattern of water losses been in effect then. This allows a direct comparison of how current loss rates alter the baseline streamflow variation.

Domber and Hoffman (2004) provide data on water use and transfer patterns during the 1990's on a watershed basis. These data allow an estimate of the steady-state impact of current depletive and consumptive water losses on streamflow. This is done in a three-step process: (1) quantify average monthly losses and offset this by average monthly gains; (2) convert average monthly losses to an equivalent daily value and apply this to observed baseline daily streamflows; and (3) analyze the synthetic hydrograph to determine if the impacted hydrologic indices are outside of the baseline acceptable range of variability. The following section applies these three steps to the Toms River.

Monthly withdrawals by source -- confined groundwater, unconfined groundwater and surface water -- for the 1990's are in figure 10. Total monthly withdrawals peaked at over 600 million gallons per month (mgm) in the summer in the late 1990's.

Generally 100 to 150 mgm of wastewater was exported from the watershed in the 1990's (fig. 11). This wastewater is conveyed to sewage treatment plants outside of the watershed. Since all of the wastewater exported is a loss to the watershed, there is an assumed 1:1 relation to streamflow loss. There are no treated-effluent imports into the watershed.

Figure 12 shows monthly consumptive loss, exports and imports. Because this graph is aimed at quantifying net losses, an action that results in a loss of water from the watershed upstream from the stream gage is a positive number. In contrast, an accretive transfer, an action that results in a gain of water, such as imports of water from outside the watershed and confined aquifer withdrawals in the watershed, is treated as a negative number. The consumptive losses are calculated by multiplying each water use in the watershed by the estimated evaporative loss associated with that use in that month (Domber and Hoffman, 2004). Peak exports are as high as 385 mgm in July 1998 and peak imports are 188 mgm in July 1999. Exports of water from the watershed (fresh water and sewage) dominate the losses.

The monthly consumptive losses in figure 12 are averaged by month and shown in figure 13. Maximum losses of 370 mgm occur in July. Maximum average imports of 175 mgm also occur in July. Figure 14 shows the net monthly loss through the 1990's for the Toms River watershed. This represents the loss associated with exports and consumptive use in the watershed as balanced by imports. The net monthly losses peak around 200 mgm in the summer. The net monthly losses are averaged for each month in the 1990s, converted to cubic feet per second (cfs) and shown in figure 15. Net losses reach a high of 9.9 cfs in July and a low of 5.3 cfs in the winter.

The net monthly losses in figure 15 are assumed to represent the net impact on streamflow of the current water-use pattern. The volumes of water shown for each month were converted into daily equivalents and subtracted from the daily hydrograph at the Toms River gage for the period 1928-1963. This creates an impacted hydrograph that estimates what streamflow would have been if the 1990's average pattern of monthly water use had been in place during the baseline period. This analysis scenario, where 100 percent of the 1990's monthly depletive and consumptive use pattern is assumed to reduce streamflow, is called DC100. Figure 16 shows what streamflow would have been in July 1965 under scenario DC100 along with observed streamflow. This drought year is chosen to visually highlight the differences between the observed and impacted hydrographs.

The NJHAT software is used to analyze the DC100 hydrograph. In order to be consistent with the baseline period, this analysis was done on estimated flows for the period 1928-1963. In this example, the acceptable range of the natural variability is set at 25 percent to 75 percent. The median value (50-percent frequency) for each hydrologic index, based on the impacted hydrograph, is shown in table 7. This table also shows the 25-percent, 50-percent, and 75-percent values for the unimpacted, baseline period. The relevant comparison is between the median value from the impacted period and the baseline 25-percent to 75-percent range. When the impacted median is outside the unimpacted range then the water-withdrawal pattern used to create that scenario is considered to have created an unacceptable change in streamflow. In table 7, those impacted medians that are outside of the acceptable 25-percent to 75-percent range are in bold. Under the DC100 scenario, the hydrologic indices DL1, ML6, ML7 and ML8 show significant impacts. DL1 measures the duration of low flows and ML6-ML8 low flows for the period June-August. It is clear that the 1990's pattern of depletive and consumptive use is creating low flows that are lower and longer lasting than during the baseline period. This is consistent with the analysis of observed flow for the period 1980-2004.

As alternatives, two additional scenarios were investigated. These scenarios assume that some or all of the sewage currently exported from the watershed is instead treated and discharged in the watershed. The 'Sewage50' scenario assumes that 50 percent of the sewage is treated to standards and discharged upstream from the stream gage. The 'Sewage100' scenario assumes no export of sewage from the basin, all of it is treated and discharged in the watershed. The average 1990's monthly depletive and consumptive use under all three scenarios is shown in figure 17.

The results of a NJHAT analysis of the synthetic hydrographs for these two additional scenarios are in table 7. Under scenario Sewage50, no hydrologic indices have been altered outside of the acceptable range. This implies that if half of the sewage currently exported from the watershed is instead treated and discharged inside it then the streamflow indices will return to within the acceptable range. If no sewage is exported from the basin then the hydrologic indices are closer to the baseline median value.

The above analysis of the Toms River watershed shows that streamflow from 1928-1963 is significantly altered under the 1990's patterns of depletive and consumptive use and falls outside a 25-percent to 75-percent acceptable range. One way to restore the hydrologic indices to within the acceptable range is to reduce waste water exports by 50 percent.

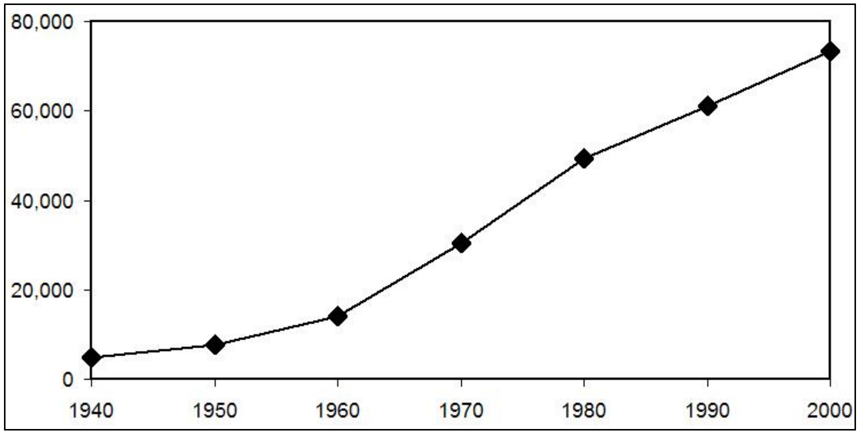

Figure 8. Population of the Toms River watershed, N.J.

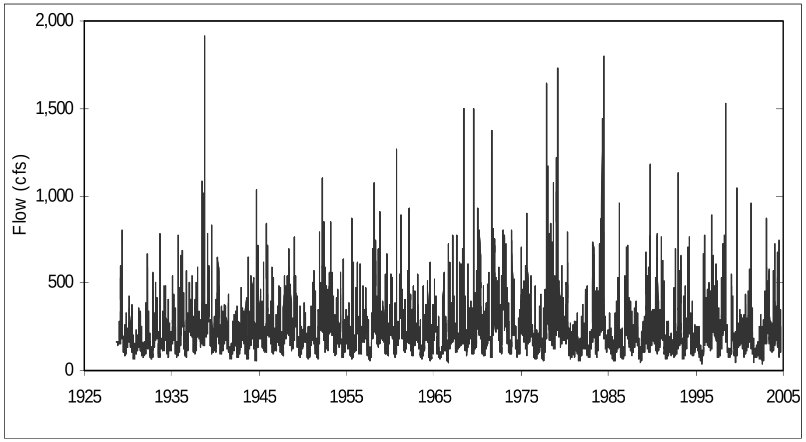

Figure 9. Daily streamflow, Toms River, N.J.

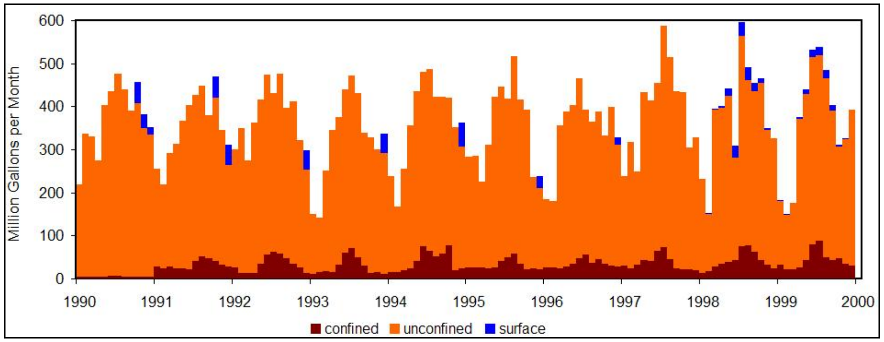

Figure 10. Withdrawals of confined and unconfined groundwater, and of surface water in the Toms River, N.J. watershed, 1990-1999.

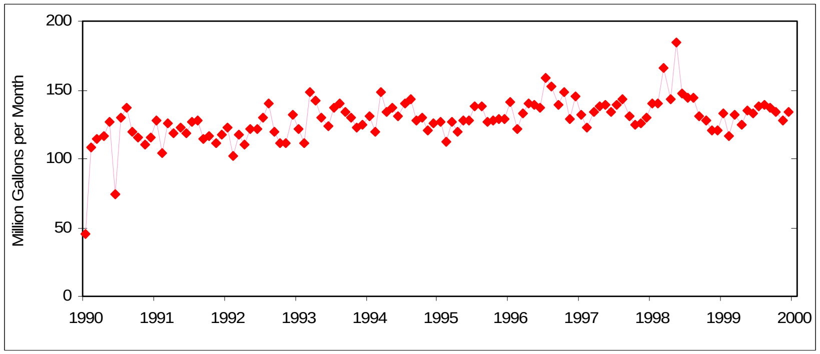

Figure 11. Toms River, N.J., watershed sewage exports, 1990-1999.

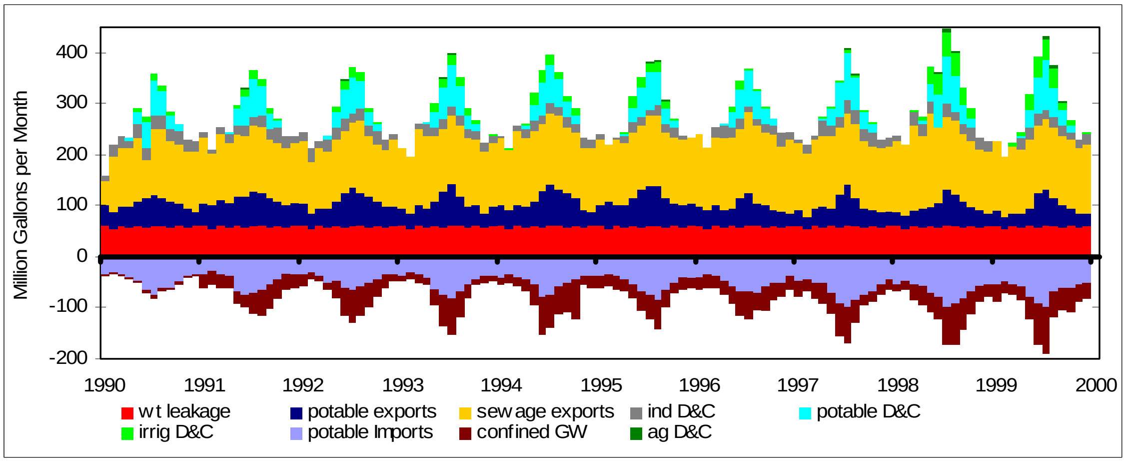

Figure 12. Toms River, N.J., monthly exports & consumptive losses (positive numbers) with imports (negative numbers), 1990-1999.

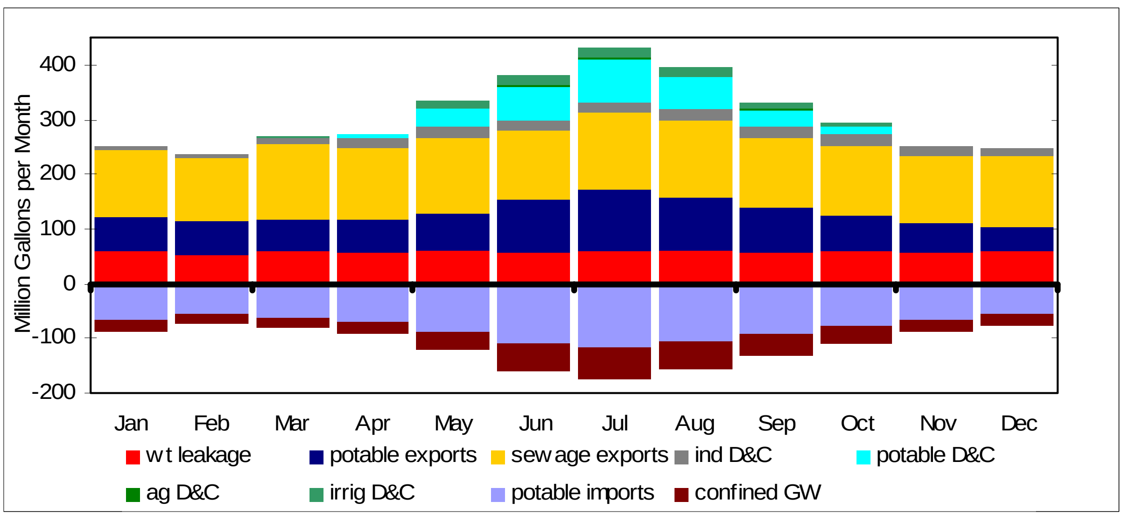

Fig 13. Toms River, N.J., watershed average monthly depletive/consumptive losses, 1990-1999.

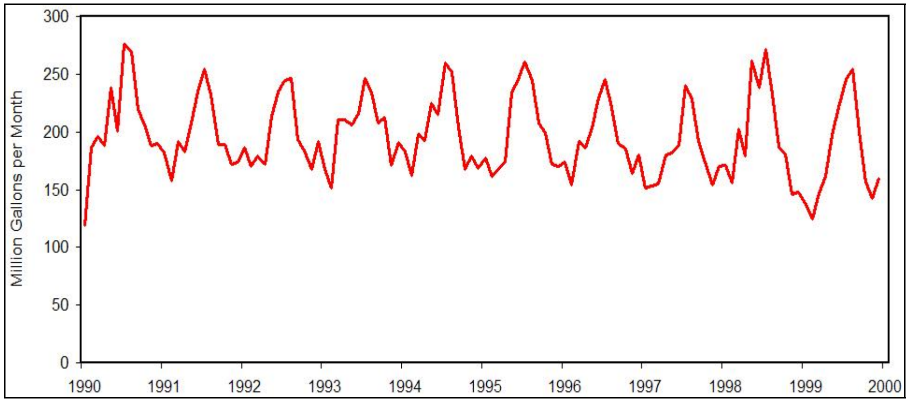

Figure 14. Net monthly water loss, Toms River, N.J., watershed 1990-1999. (exports + consumptive losses - imports).

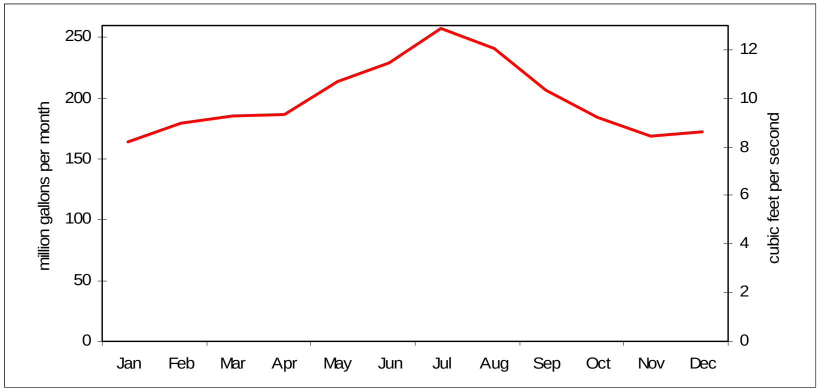

Figure 15. Average net monthly water loss, Toms River, N.J., watershed, 1990-1999 (exports + consumptive losses - imports)

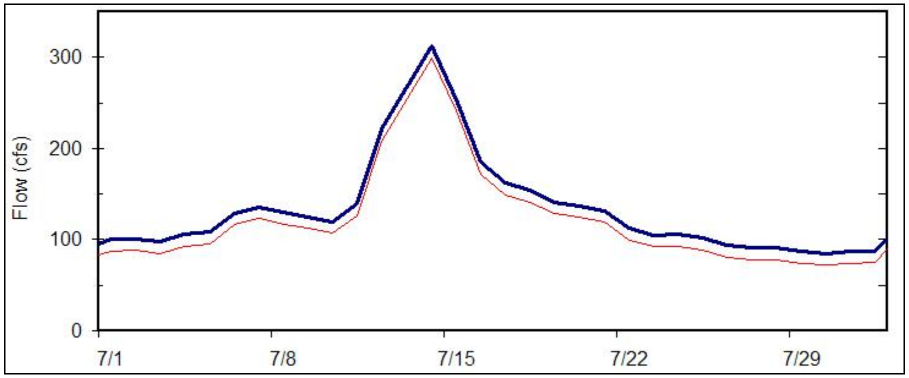

Figure 16. Toms River, N.J., observed and estimated DC100 daily flows for July, 1965.

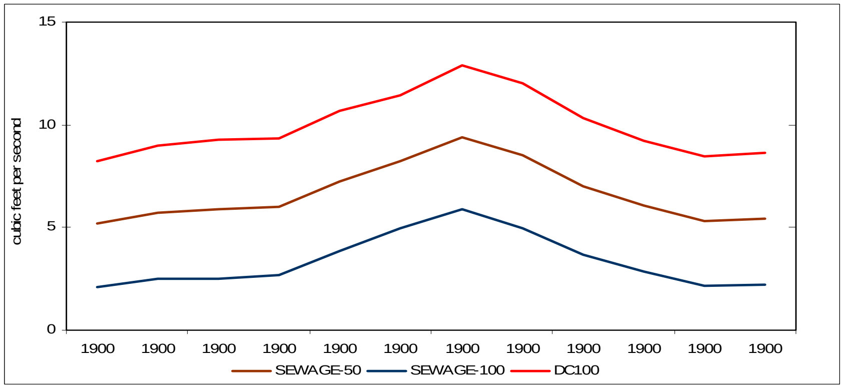

Figure 17. Average-net-monthly water-loss scenarios, Toms River, N.J., watershed.

Table 7. Toms River, N.J., hydrologic indices - baseline, current and scenarios.

Hydrologic index		Baseline, 1928-1963			Current, 1980-2004	50-percent value of scenarios		
		25%	50%	75%	50%	DC100	Sewage50	Sewage100
NJHAT index	MA15	211.4	285.6	318.1	285.0	279.2	282.6	285.9
	ML4	161.0	186.0	215.0	174.0	179.6	183.0	186.3
	MH4	328.0	434.0	561.0	459.0	427.6	431.0	434.3
	FL1	6.0	7.0	11.0	9.0	7.0	7.0	7.0
	FH10	1.0	1.0	3.0	2.0	1.0	1.0	1.0
	DL1	68.0	75.0	91.0	***66.0***	***65.9***	69.5	73.0
	DH2	464.3	620.0	775.3	690.0	614.7	617.8	620.9
	RA7	-0.1	-0.1	0.0	-0.1	-0.1	-0.1	-0.1
monthly low flows	ML1	146.0	170.0	192.0	***143.0***	164.7	167.8	170.9
	ML2	155.0	179.0	202.0	159.0	173.0	176.2	179.5
	ML3	169.0	196.0	231.0	***165.0***	189.7	193.1	196.5
	ML4	161.0	186.0	215.0	174.0	179.6	183.0	186.3
	ML5	137.0	162.0	202.0	143.0	154.3	157.7	161.1
	ML6	102.0	116.0	142.0	***101.0***	107.5	110.8	114.0
	ML7	80.0	94.0	108.0	82.0	84.1	87.6	91.1
	ML8	74.0	83.0	103.0	89.0	***73.9***	77.5	81.0
	ML9	75.0	90.0	107.0	88.0	82.6	86.0	89.3
	ML10	83.0	111.0	122.0	95.0	104.7	107.9	111.1
	ML11	119.0	135.0	154.0	***115.0***	129.5	132.6	135.8
	ML12	120.0	149.0	167.0	140.0	143.4	146.6	149.8

Note: Shaded values are outside of the 25-percent to 75-percent baseline acceptable range.

Appendix F: Planning Example - West Brook watershed

West Brook is a mostly undeveloped watershed in northern New Jersey (fig. 18). In 2002, forest covered 90 percent of the watershed. Its population has remained roughly constant since 1980 at a little over 4,000 people (fig. 19). There are no major water intakes in the 11.8 square mile watershed.

Figure 20 shows streamflows at the gage for the period October 1, 1934 to September 30, 1978, at which time measurements were discontinued. Flow measurements resumed on May 11, 2002. Using the stream classification tool, West Brook at the base of the watershed is classified as a type C stream. The baseline period for West Brook is 1935-1978 (appendix G).

As a planning tool, the HIP can determine if the current rate of water losses has too great an impact on streamflow variability. If the current impact is not too great then the HIP can determine how much additional water loss can occur without violating the baseline acceptable variability.

The current impacts are defined as all water lost from the watershed (by evaporation during use or by export) counterbalanced by any imports. However, streamflow data are not available to enable a direct analysis of this impact. To account for this, the average depletive and consumptive water use rate for the 1990's is estimated and then applied to streamflows during the baseline period.

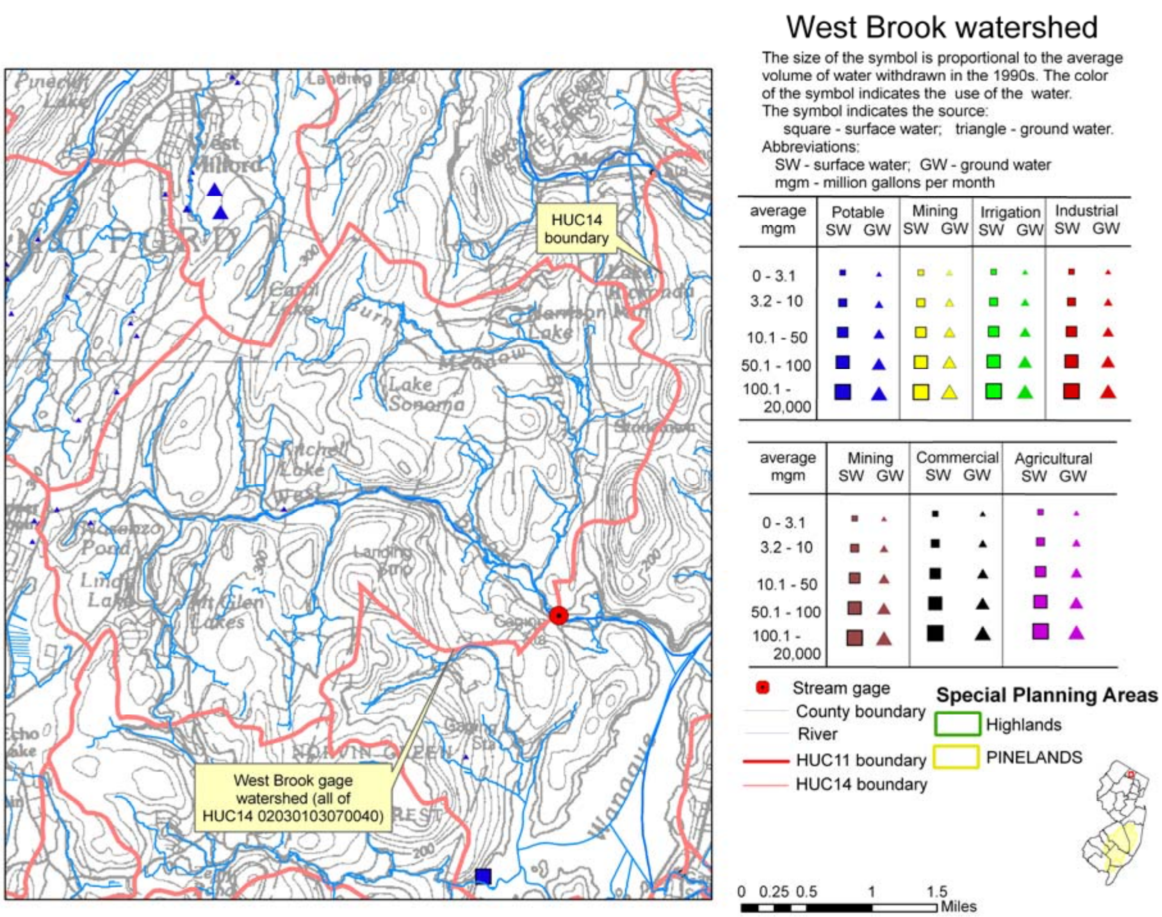

Figure 18. West Brook, N.J., watershed with average 1990's withdrawals.

Figure 19. Population of the West Brook, N.J., watershed.

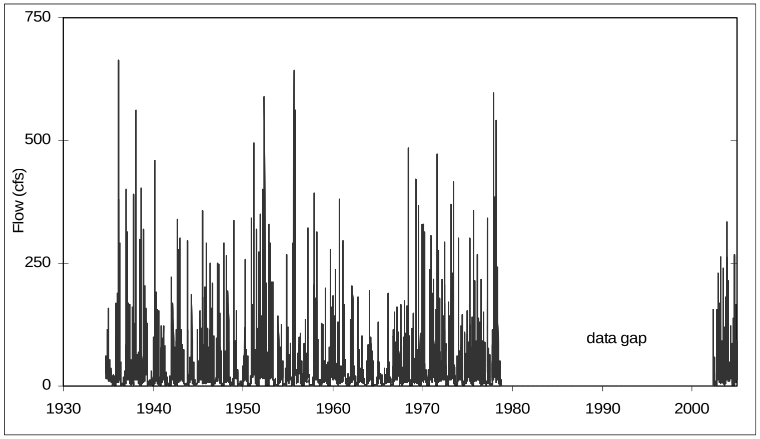

Figure 20. West Brook, N.J., daily streamflow.

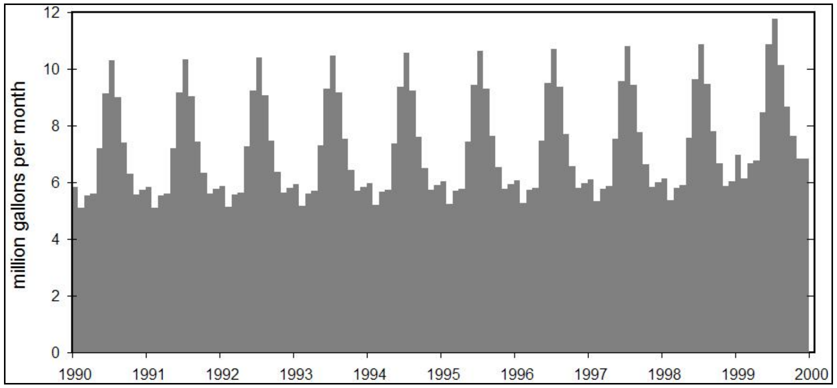

Figure 21. West Brook, N.J., unconfined aquifer withdrawals, 1990-1999.

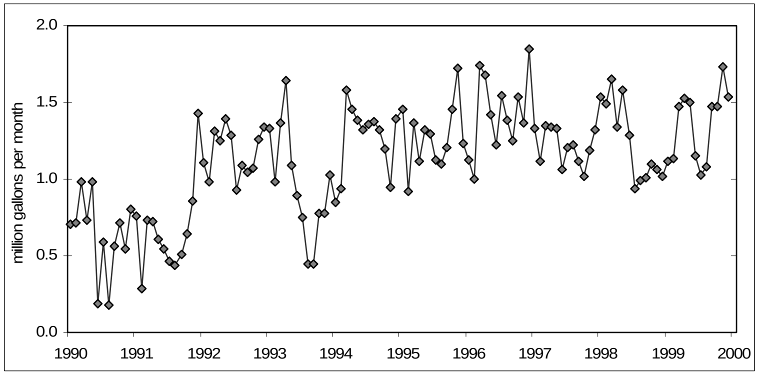

Figure 22. West Brook, N.J., sewage exports, 1990-1999.

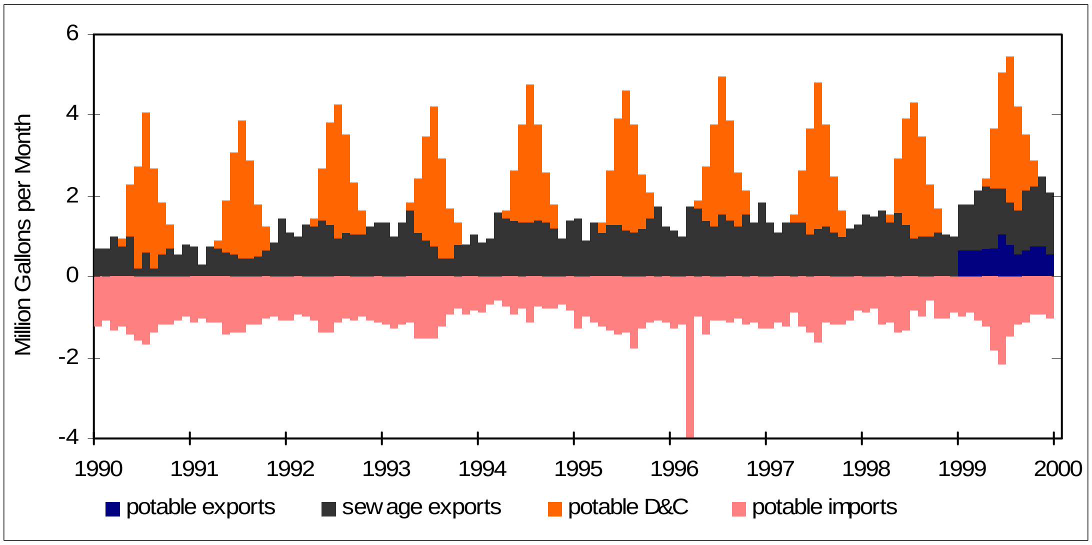

Figure 23. West Brook, N.J., monthly exports, consumptive losses, and imports, 1990-1999.

Figure 21 shows monthly withdrawals. No surface water or confined aquifer withdrawals are in the watershed. All withdrawals are from unconfined aquifers and range from nearly 12 million gallons per month (mgm) in the summer to 6 mgm in the winter.

Figure 22 shows monthly wastewater exports from the watershed in the 1990's. Exports rose during the 1990's, with rates of 1.0 to 1.5 mgm in the late 1990's. The wastewater is exported to a treatment plant that discharges outside of the watershed. Inasmuch as all of the waste water exported is a loss to the watershed, there is an assumed 1:1 relation to streamflow loss. There are no wastewater imports into the basin.

Figure 23 shows monthly consumptive loss as well as exports and imports of freshwater and wastewater. Because this graph is designed to quantify net losses, an action that results in a loss of water from the watershed above the stream gage is a positive number. In contrast, an action that results in a gain of water is a negative number. Consumptive losses are calculated by multiplying each water use in the basin by the estimated evaporative loss associated with that use in that month (Domber and Hoffman, 2004). Maximum losses are about 5 mgm in the summer in 1999. Maximum imports are about 2 mgm. The value of 4 mgm of potable imports of fresh water in March 1996 is probably a data reporting error because it is so different from other reported values.

The consumptive, export and import data are averaged by calendar month and shown in figure 24. July displays the greatest average monthly loss, 4.5 mgm. Average monthly potable water imports are relatively constant around 1 mgm. These data show that exports of water from the basin is the primary way the watershed loses water.

Figure 25 shows the net monthly loss through the 1990's for the West Branch watershed. This represents the losses associated with exports and consumptive use in the watershed as balanced by imports. Summer peak losses rose from a little over 2 mgm in 1990 to 4 mgm in 1999.

Average net monthly losses for the 1990s are in figure 26. These losses are assumed to represent the net impact on streamflow of 1990's consumptive losses, exports and imports. The maximum average net monthly loss is 0.16 cfs in July. Net losses fall to near zero in January, February and March.

The volumes of water shown for each month in figure 26 were subtracted from the daily hydrograph at the West Brook gage for the period 1935-1978. This creates an impacted hydrograph that estimates what streamflow would have been had the 1990's average pattern of water use been in place during the baseline period. This analysis scenario, where 100 percent of the 1990's depletive and consumptive use is assumed to reduce streamflow, is called DC100. Figure 27 compares what streamflow would have been in July

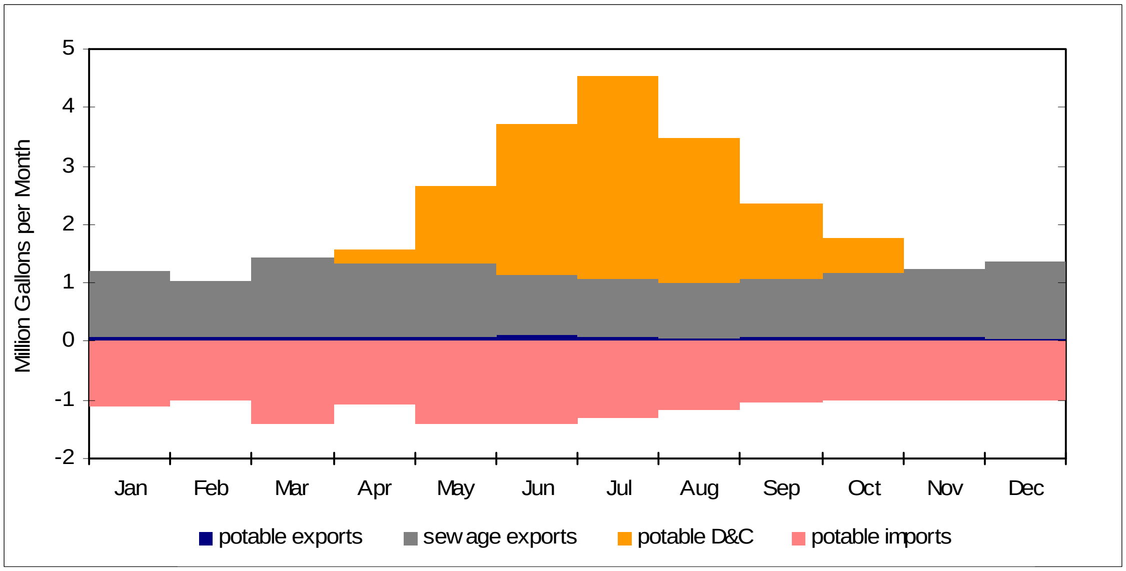

Fig 24. West Brook, N.J., average monthly exports, consumptive losses, and imports, 1990-1999.

1965 under scenario DC100 to observed streamflow. This month is selected to emphasize the change in flow. If the total range of streamflows is depicted (up to 700 cfs as shown in fig. 20) then there is no visual difference between the observed and DC100 hydrographs.

The impacted hydrograph for the DC100 scenario was then analyzed using the NJHAT software for the baseline period 1935-1978. Table 8 shows the median value of each hydrologic index as well as the 25-percent, 50-percent, and 75-percent values for the baseline period. Assume that the regulatory agency decided that the acceptable range of the natural variability is 25 percent to 75 percent. When the impacted median is outside the acceptable range, then the water withdrawal pattern used to create that scenario is considered to have created an unacceptable change in streamflow. This analysis shows that the 1990's depletive and consumptive use is not creating an unacceptable change in streamflow when compared to the baseline 25-percent to 75-percent range.

The 25-percent to 75-percent range does not need to define the acceptable range for all water types. Table 8 also shows the 40-percent to 60-percent range of each hydrologic index. This is a more conservative standard. Comparing the median values of the indices based on the impacted hydrograph to the 40-percent to 60-percent acceptable range shows that the 1990's pattern of depletive and consumptive use does not create a significant change in streamflow.

For comparison, four additional scenarios investigate the impacts of increasing the 1990's pattern of water usage. Increases are by a factor of two, three, four or five; resulting in scenarios labeled 2xDC100, 3xDC100, 4xDC100 and 5xDC100, respectively. Figure 28 shows the monthly impacts on streamflow of average 1990's depletive and consumptive use under all four scenarios.

Synthetic hydrographs were created for each scenarios and analyzed using NJHAT. The median values of the hydrologic indices are shown in table 8. The median value of all flow indices fall within each index's baseline 25-percent to 75-percent range. However, the median values of summer low flows fall outside the 40-percent to 60-percent range for the 4xDC100 and 5xDC100 scenarios.

The results indicate that the current rate of depletive and consumptive use in the watershed could be increased fivefold without creating an unacceptable change in indices if the 25-percent to 75-percent range is the appropriate standard against which to judge acceptable change. If the allowable change is tightened to a 40-percent to 60-percent standard, then a fourfold increase in water loss results in unacceptably low streamflow in the summer.

Current water use in the West Brook watershed is very low. It is this low starting rate that allows the conclusion that water losses could be increased fivefold without creating an unacceptable change in indices. Peak summertime water losses in the 12-square-mile West Brook watershed averaged about 3.2 million gallons per month in the 1990's. In contrast, the 123-square-mile Toms River watershed, which is 10 times larger and with 17 times the population, showed peak net losses of 375 million gallons per month, about 100 times greater than those in the West Brook watershed.

Table 8. West Brook,N.J., hydrologic indices - baseline and scenarios.

Hydrologic index		Flow component percentages - baseline[1]					Flow component 50% value, by scenario[1]				
							scenarios				
		25%	40%	50%	60%	75%	DC100	2DC100	3DC100	4DC100	5DC100
NJHAT index	MA24	49.8	62.2	71.5	80.0	89.3	71.5	71.5	71.5	71.6	71.6
	ML3	12.0	14.0	16.5	17.0	21.8	16.5	16.5	16.5	16.5	16.5
	MH14	18.2	22.0	23.5	26.2	33.7	23.7	23.8	23.9	24.1	24.1
	FL1	6.0	7.0	8.0	9.0	10.0	7.5	8.0	8.0	8.0	8.0
	FH3	36.5	46.0	48.5	57.0	72.5	49.5	49.5	49.5	49.5	49.5
	DL16	7.9	9.2	10.7	13.8	17.1	11.4	11.4	11.4	11.6	11.6
	DH1	252.0	297.0	325.5	342.	419.0	325.5	325.5	325.5	325.4	325.4
	RA6	0.12	0.19	0.27	0.40	0.66	0.27	0.28	0.28	0.28	0.30
monthly low flows	ML1	7.5	8.5	9.3	11.0	13.8	9.3	9.2	9.2	9.2	9.2
	ML2	7.4	9.1	10.0	12.0	14.0	10.0	10.0	10.0	10.0	10.0
	ML3	12.0	14.0	16.5	17.0	21.8	16.5	16.5	16.5	16.5	16.5
	ML4	12.0	13.0	14.0	15.0	18.0	14.0	14.0	13.9	13.9	13.9
	ML5	4.7	6.9	8.9	9.9	12.0	8.8	8.7	8.7	8.6	8.5
	ML6	2.5	3.0	3.3	3.8	4.4	3.2	3.1	***2.9***	***2.8***	***2.7***
	ML7	1.1	1.6	2.1	2.5	3.0	1.9	1.8	1.6	***1.5***	***1.3***
	ML8	0.9	1.1	1.6	1.8	2.5	1.4	1.3	1.2	1.1	*1.0*
	ML9	1.0	1.4	1.6	2.1	2.9	1.5	1.5	1.4	***1.3***	***1.3***
	ML10	1.6	2.4	3.0	3.7	5.3	3.0	2.9	2.9	2.9	2.8
	ML11	2.7	4.5	6.5	9.7	12.0	6.5	6.5	6.5	6.5	6.4
	ML12	4.6	8.4	9.5	12.0	14.0	9.5	9.5	9.5	9.4	9.4

[1] See the text for a description of baseline and scenarios.

Note: Shaded values are outside the 40-percent to 60-percent baseline acceptable range.

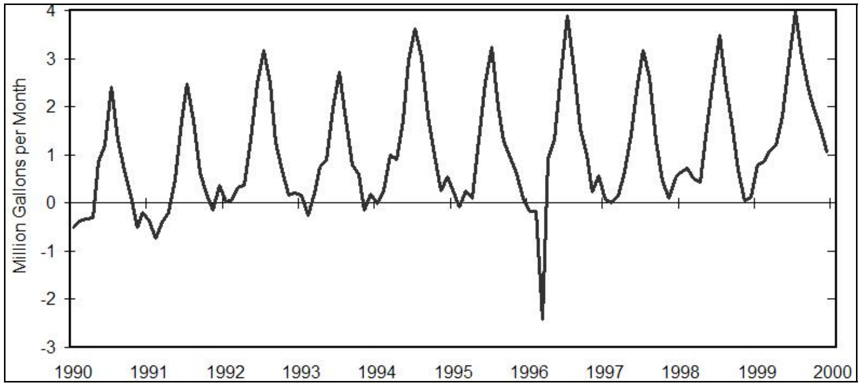

Figure 25. Net monthly water loss, West Brook, N.J., watershed, 1990-1999.

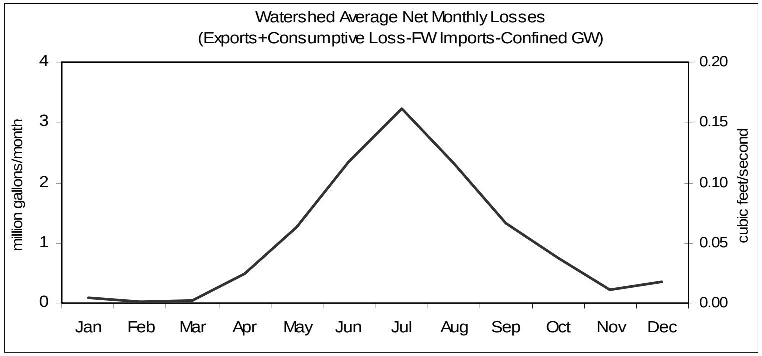

Figure 26. Average net monthly water loss, West Brook, N.J., watershed, 1990-1999.

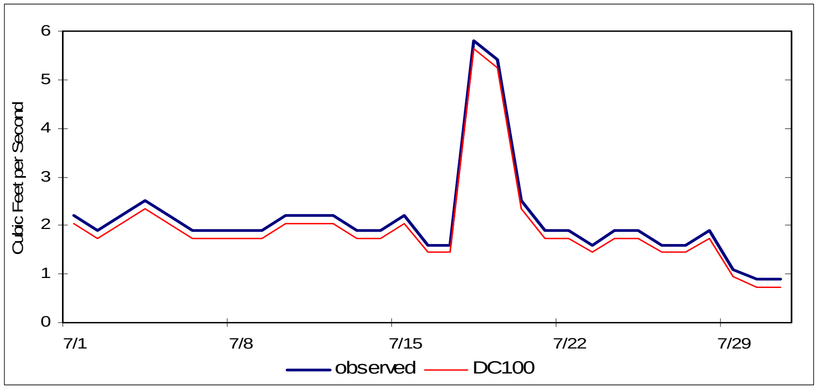

Figure 27. West Brook, N.J., observed and DC100 daily flows for July, 1965.

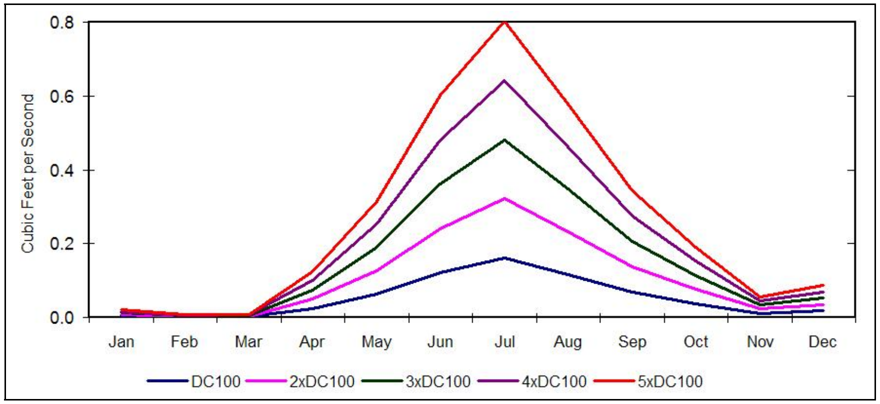

Figure 28. Average-net-monthly water-loss scenarios, West Brook, N.J

Appendix G. Regulatory Example - West Brook Watershed

The West Brook planning example (appendix D) shows how the hydroecological integrity assessment process can approximate how much additional water can be withdrawn from the watershed without creating an unacceptable change in streamflow. This approach does not directly give guidance on passing flows. A passing flow, which is set by permit, requires withdrawals to temporarily cease when streamflow declines to that flow. Passing flows are set to prevent withdrawals from exacerbating a dry condition and adversely affecting the aquatic ecosystem and downstream water users.

The H-M-L approach to passing flows, developed in the Regulatory Application section of the 'Hydroecological Integrity Assessment Process Application' discussed previously, is applied below to West Brook. These results are then contrasted to results from two other popular standard-setting approaches, the Tennant method and the Aquatic Base Flow method. The results are also compared to an expansion of the annual 7Q10 approach to monthly 7Q10 values.

H-M-L passing flows

The 'Hydroecological Integrity Assessment Process Application' section above laid out an approach to setting monthly passing flows based on selected statistics associated with some hydrologic indices (table 5). The H (high) passing flow is defined by the 25-percent frequency average monthly flow ($MA_{25\%}$). The M (medium) passing flow is associated with the 50-percent frequency (median) of the monthly low flow ($ML_{50\%}$). The L (low) passing flows are from the 25-percent frequency of the median monthly low flow ($ML_{25\%}$).

For the West Brook watershed, these statistics are shown in table 9. Figure 29 shows these monthly passing flows along with the annual 7Q10 flow for the USGS West Brook stream gage. At this gage, the H, M and L values are all higher than the annual 7Q10 flow. In August, the L monthly passing flow falls to 0.9 cfs and the H value falls to 1.8 cfs. In the wettest month, March, the H monthly passing flow is 33.3 cfs, the L value is 12.0 cfs. The annual 7Q10 flow is a constant 0.59 cfs in all months.

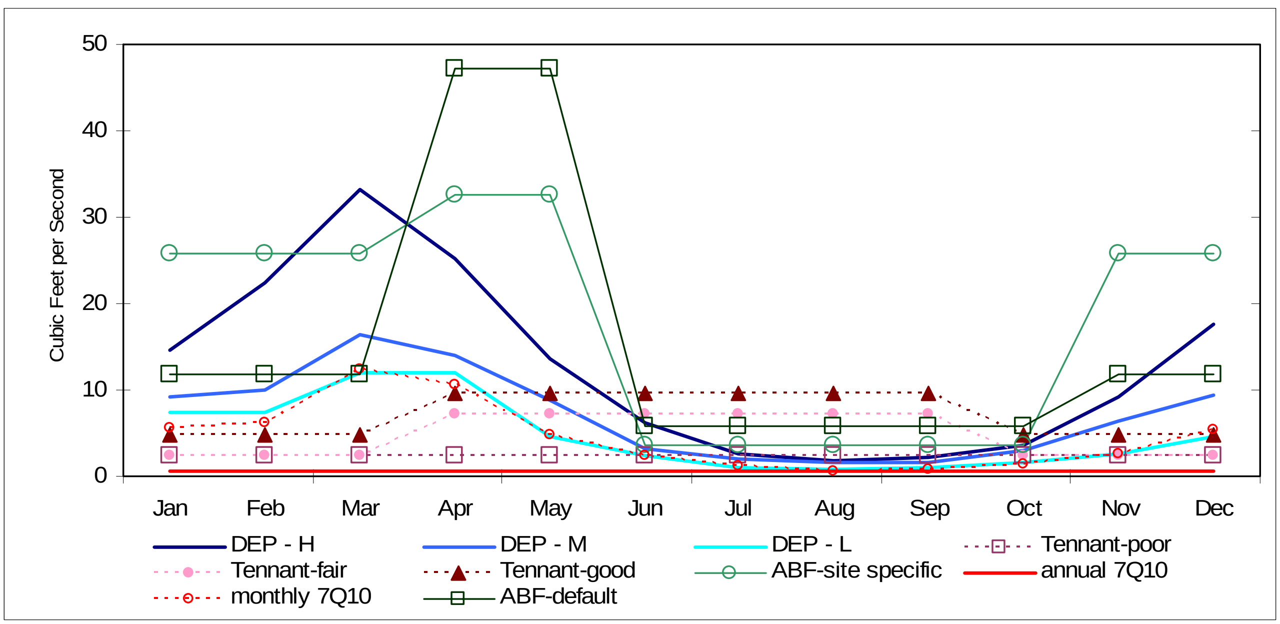

Figure 29. West Brook, N.J., monthly passing flows based on the proposed NJDEP, Tennant, aquatic base flow, and 7Q10 methodologies.
(see text for description of the DEP -H, - M and - L values)

The H passing flow is based on average flow in a month that occurs in one year out of four. This is a relatively frequent occurrence, especially compared to how often the annual 7Q10 flow occurs. Figure 30 shows for the period 1934-1978 the number of days each year in which observed flow in West Brook was lower than each monthly passing flow. In 1966, during the drought of record in New Jersey, flows were lower than the H monthly passing flow on 204 days, lower then the M flows 118 days, lower than L flows 52 days, and lower than the annual 7Q10 flow on 24 days. If there had been a withdrawal on West Brook in 1966 with the H monthly passing flow as a permit condition it would have not been able to pump for 204 days. Over the 45-year period the daily flows were lower than the H monthly passing flow on 39 percent of the days, 18 percent for the M passing flows, 6 percent for L passing flows, and 0.4 percent for the annual 7Q10 passing flow.

As formulated here, the H monthly passing flows are very restrictive. Any withdrawal operating under a H passing flow would probably not be a reliable source of water. A proposed withdrawal on the West Brook would have to be evaluated in consideration of any passing flow permit condition to determine if it was a reliable source of water during seasonal low flows.

Tennant Methodology

The Tennant (or Montana) method assumes a relationship between a percentage of the average annual flow (QAA) and habitat quality during two periods of the year (Tennant, 1976). It assumes that 10 percent of QAA must be retained in the stream year-round to support a 'poor' habitat and to prevent severe degradation. Streamflow must be maintained at 30 percent of the QAA during the period April-September and 10 percent for October-March in order to support a 'fair' habitat. To support a 'good' aquatic habitat 40 percent of the QAA is needed for April-September and 20 percent for October March. At the West Brook gage the average annual flow during water years 1935-1978 was 24.15 cfs. The Tennant method would then say that during the months April to September, 2.41 cfs must be maintained in the stream at a minimum to support a poor habitat, 7.24 cfs for fair, and 9.66 cfs for a good habitat. During October to March, at least 2.41 cfs must be maintained in the stream to support a poor or fair habitat and 4.83 cfs for a good habitat.

Table 9 and figure 29 show the Tennant results for West Brook in comparison to the H-M-L values. In August and September, the monthly H-M-L values are all below the Tennant-poor value. This indicates that passing flows set using the H-M-L approach would allow more water to be taken out of the stream during this dry month than the Tennant method would. For other months one or more of the H-M-L values are above Tennant values, some-

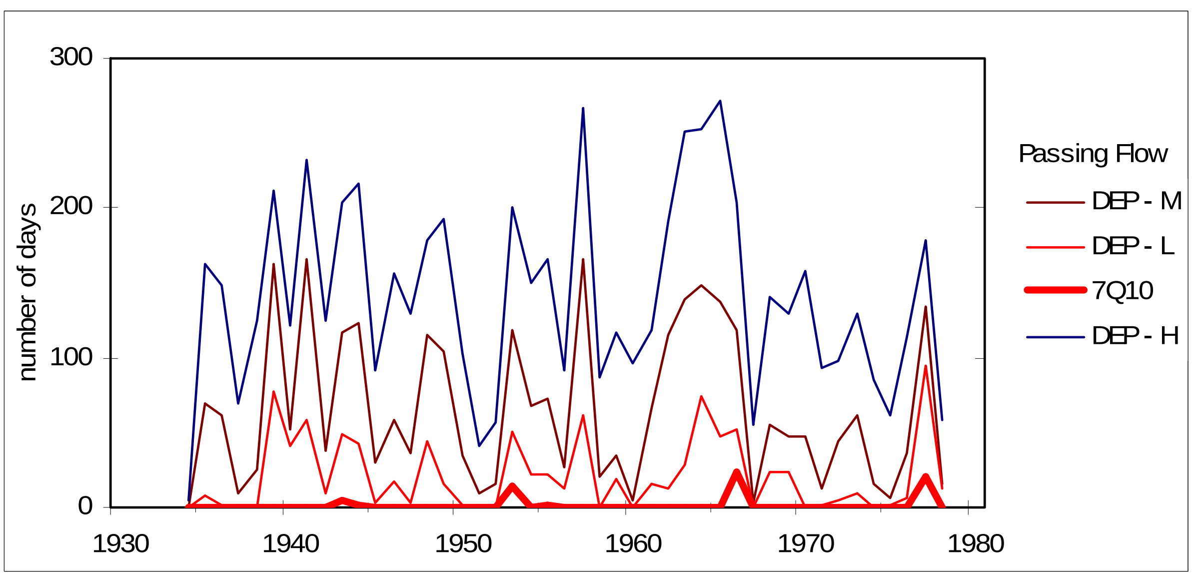

Figure 30. Number of days per year on which observed flow was lower than monthly-passing-flow standards in West Brook, N.J.
(see the text for a description of the DEP - H, - M and - L values)

times significantly so. In general, the H-M-L approach for setting passing flows would allow slightly more water to be taken out in the very driest months, but would be more restrictive in the wetter months.

Aquatic Base Flow Methodology

The Aquatic Base Flow (ABF) method, also known as the New England method, uses the median of selected annual monthly flows to determine required passing flows during different seasons (U. S. Fish and Wildlife Service, 1981). The median annual August monthly flow is used to estimate necessary summer flows. Summer is defined as mid-June to mid-October. The fall/winter period is mid-October to March and required flows are defined by the median of annual February flows. Spring is April to mid-June and required flows are defined by the median of annual April and May flows. This method was developed using data from 48 gaging stations in New England, each with more than 25 years of reliable flow records and with a watershed at least 50 square miles.

The U.S. Fish and Wildlife Service recommends developing ABF values for any site that meets these requirements. At other sites default values of 0.5, 1.0 and 4.0 cubic feet per second per square mile for the summer, fall-winter and spring time periods, respectively, may be appropriate.

Site-specific ABF monthly passing flows for the West Brook stream gage are shown in table 10 and figure 29. These also show ABF monthly passing flows calculated using the recommended default values.

During August and September, the ABF values (both site specific and default) are greater than the H-M-L values. This indicates that passing flows set using the H-M-L approach would allow more water to be taken out of the stream during these dry months than the ABF method would. This is also the case in April and May, when the ABF values are significantly higher than the H-M-L values. This difference in the spring perhaps reflects a regional climate difference. New England typically receives more snow than New Jersey and it melts later in the spring. This snow melt sustains the spring high-flow period longer than is typical for New Jersey streams. It may be necessary to adapt the timings of the seasons used in the ABF approach in order to more accurately reflect the natural flow characteristics of New Jersey streams. Kulik (1990) recommends a region-specific ABF analysis to develop more accurate default values to account for differences in precipitation and basin characteristics. Connecticut and Rhode Island are applying region-specific ABF approachs (Colin Apse, The Nature Conservancy, written communication, 2007).

Annual and Monthly 7Q10 values

The annual 7Q10 flow is the average weekly flow that has a 10 percent chance of occurring in a given year. This is commonly interpreted as occurring, on average, once every 10 years. Current values for active stream gages in New Jersey are made available by the U.S. Geological Survey over the internet at http://nj.usgs.gov/flowstatistics/ (Reiser and others, 2002).

The annual 7Q10 value is based on all reported flows at a gage. The same approach can be applied to monthly flows. In this case, only the flows in each calendar month over the period of record are considered for each month's 7Q10 value. In Georgia, monthly 7Q10s are now one option for setting regulatory instream flows (Georgia Board of Natural Resources, 2001; Caldwell, 2005).

At the West Brook gage, the reported annual 7Q10 flow value is 0.59 cfs. Monthly 7Q10 flows range from a high of 12.43 cfs in March to a low of 0.65 cfs in August (table 9). The monthly 7Q10 flows are shown in figure 28. The monthly 7Q10 flows are very close to the DEP's L flows (the 25-percent frequency of the median monthly low flow -- $ML_{25\%}$) (table 9, fig. 29).

Figure 31 shows the 25-75% and 40-60% range of monthly low flows, along with median monthly low flow in West Brook. This figure also shows annual and monthly 7Q10 flows. This graphic emphasizes the normal range of monthly flow flows and the degree to which the annual 7Q10 is lower than expected monthly low flows during the winter and spring.

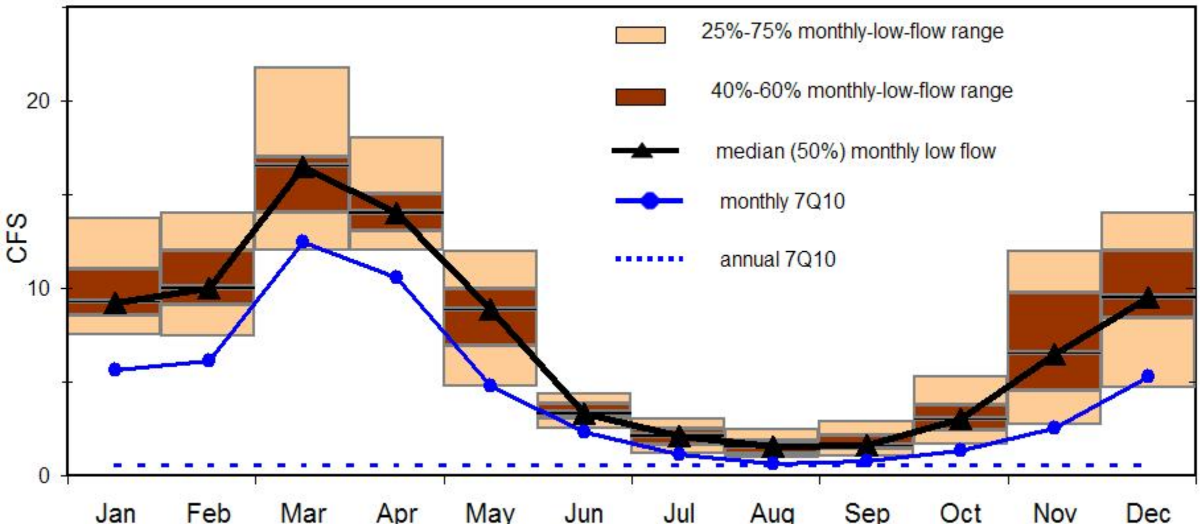

Figure 31. Expected range of monthly low flows in West Brook, with 7Q10 flows.

Table 9. Possible West Brook, N.J., monthly passing flows calculated by different methodologies.

Month	Passing Flows (cfs)									
	7Q10		New Jersey proposed method[1]			Tennant habitat			Aquatic Base Flow	
	Annual	Monthly	L	M	H	poor	fair	good	site specific[2]	default[3]
Jan	0.59	5.65	7.5	9.3	14.6	2.41	2.41	4.83	25.86	11.8
Feb	0.59	6.16	7.4	10.0	22.4	2.41	2.41	4.83	25.86	11.8
Mar	0.59	12.43	12.0	16.5	33.3	2.41	2.41	4.83	25.86	11.8
Apr	0.59	10.56	12.0	14.0	25.3	2.41	7.24	9.66	32.63	47.2
May	0.59	4.81	4.7	8.9	13.7	2.41	7.24	9.66	32.63	47.2
Jun	0.59	2.35	2.5	3.3	6.3	2.41	7.24	9.66	32.63[a] / 3.68[a]	5.90
Jul	0.59	1.13	1.1	2.1	2.6	2.41	7.24	9.66	3.68	5.90
Aug	0.59	0.65	0.9	1.6	1.8	2.41	7.24	9.66	3.68	5.9
Sep	0.59	0.80	1.0	1.6	2.2	2.41	7.24	9.66	3.68	5.90
Oct	0.59	1.33	1.6	3.0	3.6	2.41	2.41	4.83	3.68[a] / 25.86[a]	5.90
Nov	0.59	2.54	2.7	6.5	9.2	2.41	2.41	4.83	25.86	11.8
Dec	0.59	5.31	4.6	9.5	17.6	2.41	2.41	4.83	25.86	11.8

[1]See table 5 for description of each passing flow methodology.
[2] Calculated using Aquatic Base Flow methodology. Time periods are April to mid-June, mid-June to mid-October, and mid-October to March.
[3] Default aquatic base flow values are 4.0, 0.5 and 1.0 cfs/sq mi for April/May, August and February flow periods, respectively. See table 11.
[a] Values for June and Oct are split due to evaluation period. See note 2 above.

Table 10. Aquatic base flow seasons, default flows, and West Brook, N.J., specific flows.

Aquatic base flow default values[1]				West Brook flows (cubic feet per second)	
Season	duration	defined by flows in	flow (cfs per square mile)	based on default flows[2]	based on observed flows
summer	mid-June to mid-October	August	0.5	5.90	3.68
fall/winter	mid-October to March	February	1.0	11.8	25.86
spring	April to mid-June	April/May	4.0	47.2	32.63

1. U.S. Fish and Wildlife Service, 1981.
2. Watershed area is 11.8 square miles.

Appendix H. Definition of Hydrologic Indices[1]

(all notes at end of appendix)

Hydro-logic index	Tempo-ral/ spatial[2]	USGS primary/secondary indices by stream type[3]					NJDEP selected indi-ces, by stream type[4]				Flow component evaluated by hydrologic Index[5] (with measurement units)
		A	B	C	D	all	A	B	C	D	
Magnitude of Average Flows											
MA1	T										Mean of the entire flow record (cubic feet per second)
MA2	T										Median of the entire flow record (cubic feet per second)
MA3	T										Mean of the coefficients of variation for each year. (percentage)
MA4	S										Standard deviation of the percentiles of the logs of the entire flow record divided by the mean of percentiles of the logs. (percentage)
MA5	S										Skewness of the entire flow (dimensionless**)**
MA6	S										Range in daily flows - 10%/90% exceedence values. (dimensionless)
MA7	S										Range in daily flows - 20%/80% exceedence values. (dimensionless)
MA8	S										Range in daily flows - 25%/75% exceedence values. (dimensionless)
MA9	S		P		S						Spread in daily flows is the ratio of the difference between the 90^{th} and 10^{th} percentile of the logs of the flow data to the log of the median of the entire flow record. (dimen-sionless)
MA10	S										Spread in daily flows is computed like MA9 except for the 20^{th} and 80^{th} percentiles. (dimensionless)
MA11	S			S							Spread in daily flows is computed like MA9 except for the 25^{th} and 75^{th} percentiles. (dimensionless)
MA12	T										Means or medians (user choice) of January flow values. (cubic feet per second)
MA13	T				S					✓	Same as MA12 except for February.
MA14	T										Same as MA12 except for March.
MA15	T		S					✓			Same as MA12 except for April.
MA16	T										Same as MA12 except for May.
MA17	T										Same as MA12 except for June.
MA18	T	P					✓				Same as MA12 except for July.
MA19	T										Same as MA12 except for August.

Appendix H. Definition of Hydrologic Indices (cont.)[1]

(all notes at bottom of appendix)

Hydro-logic index	Tempo-ral/ spatial[2]	USGS primary/secondary indices by stream type[3]					NJDEP selected indi-ces, by stream type[4]				Flow component evaluated by hydrologic Index[5] (with measurement units)
		A	B	C	D	all	A	B	C	D	
MA20	T					P					Same as MA12 except for September.
MA21	T										Same as MA12 except for October.
MA22	T										Same as MA12 except for November.
MA23	T										Same as MA12 except for December.
MA24	T			P					✓		Variability (coefficient of variation) of January flow values. (percentage)
MA25	T										Same as MA24 except for February.
MA26	T	S									Same as MA24 except for March.
MA27	T										Same as MA24 except for April.
MA28	T										Same as MA24 except for May.
MA29	T										Same as MA24 except for June.
MA30	T										Same as MA24 except for July.
MA31	T										Same as MA24 except for August.
MA32	T		S								Same as MA24 except for September.
MA33	T		S								Same as MA24 except for October.
MA34	T					S					Same as MA24 except for November.
MA35	T										Same as MA24 except for December.
MA36	S										Variability across monthly flows. (dimensionless)
MA37	S	S				S					Variability across monthly flows. (dimensionless)
MA38	S										Variability across monthly flows. (dimensionless)
MA39	S	S			P						Variability across monthly flows. (percent)
MA40	S			S	S	S					Skewness in the monthly flows. (dimensionless)
MA41	T										Annual runoff. (cubic feet per second/square mile)
MA42	T										Variability across annual flows. (dimensionless)
MA43	T			S							Variability across annual flows. (dimensionless)
MA44	T				S						Variability across monthly flows. (dimensionless)
MA45	T			S							Skewness in the annual flows. (dimensionless)

Appendix H. Definition of Hydrologic Indices (cont.)[1]

(all notes at bottom of appendix)

Hydro-logic index	Tempo-ral/ spatial[2]	USGS primary/secondary indices by stream type[3]					NJDEP selected indi-ces, by stream type[4]				Flow component evaluated by hydrologic Index[5] (with measurement units)
		A	B	C	D	all	A	B	C	D	
Magnitude of Low Flows											
ML1	T						✓	✓	✓	✓	Mean or median (user choice) of January minimum flow values. Determine the minimum flow for each January over the entire flow record. (cubic feet per second)
ML2	T						✓	✓	✓	✓	Same as ML1 except for February.
ML3	T			P			✓	✓	✓	✓	Same as ML1 except for March.
ML4	T		S				✓	✓	✓	✓	Same as ML1 except for April.
ML5	T						✓	✓	✓	✓	Same as ML1 except for May.
ML6	T	P					✓	✓	✓	✓	Same as ML1 except for June.
ML7	T						✓	✓	✓	✓	Same as ML1 except for July.
ML8	T					P	✓	✓	✓	✓	Same as ML1 except for August.
ML9	T						✓	✓	✓	✓	Same as ML1 except for September.
ML10	T						✓	✓	✓	✓	Same as ML1 except for October.
ML11	T						✓	✓	✓	✓	Same as ML1 except for November.
ML12	T						✓	✓	✓	✓	Same as ML1 except for December.
ML13	S	S		S	S	S					Variability (coefficient of variation) across minimum monthly minimum flow values. (percent)
ML14	T										Minimum annual flow/median annual flow. (dimensionless)
ML15	T				S	S				✓	Low flow index. (dimensionless)
ML16	T	S	S								Median of annual minimum flows. (dimensionless)
ML17	T										Base flow. (dimensionless)
ML18	S										Variability in base flow. (percent)
ML19	T			S		S					Base flow. (dimensionless)
ML20	S		P	S	P						Base flow. (dimensionless)
ML21	S		S		S						Variability across annual minimum flows. (percent)
ML22	T										Specific mean annual minimum flow. (cubic feet per second/square mile)

Appendix H. Definition of Hydrologic Indices (cont.)[1]

(all notes at bottom of appendix)

Hydro-logic index	Tempo-ral/ spatial[2]	USGS primary/secondary indices by stream type[3]					NJDEP selected indi-ces, by stream type[4]				Flow component evaluated by hydrologic Index[5] (with measurement units)
		A	B	C	D	all	A	B	C	D	
											Magnitude of High Flows
MH1	T				S						Mean or median (user choice) of January maximum flow values. Determine the maximum flow for each January over the entire flow record. (cubic feet per second)
MH2	T				S					✓	Same as MH1 except for February.
MH3	T				S	S					Same as MH1 except for March.
MH4	T		S					✓			Same as MH1 except for April.
MH5	T	P					✓				Same as MH1 except for May.
MH6	T										Same as MH1 except for June.
MH7	T										Same as MH1 except for July.
MH8	T										Same as MH1 except for August.
MH9	T										Same as MH1 except for September.
MH10	T										Same as MH1 except for October.
MH11	T										Same as MH1 except for November.
MH12	T			S							Same as MH1 except for December.
MH13	S			S							Variability (coefficient of variation) across maximum monthly minimum flow values. (percent)
MH14	T			P					✓		Median of annual maximum flows. (dimensionless)
MH15	S										High flow discharge index. (dimensionless)
MH16	S	S		S	P						High flow discharge index. (dimensionless)
MH17	S			S							High flow discharge index. (dimensionless)
MH18	S	S	S								Variability across annual maximum flows. (percent)
MH19	S										Skewness in annual maximum flows. (dimensionless)
MH20	T	S				P					Specific mean annual maximum flow. (cubic feet per second/square mile)
MH21	T				S						High flow volume index. (days)
MH22	T										High flow volume. (days)
MH23	T					S					High flow volume. (days)
MH24	T		P								High peak flow. (dimensionless)

Appendix H. Definition of Hydrologic Indices (cont.)[1]

(all notes at bottom of appendix)

Hydro-logic index	Tempo-ral/ spatial[2]	USGS primary/secondary indices by stream type[3]					NJDEP selected indi-ces, by stream type[4]				Flow component evaluated by hydrologic Index[5] (with measurement units)
		A	B	C	D	all	A	B	C	D	
MH25	T										High peak flow. (dimensionless)
MH26	T		S								High peak flow. (dimensionless)
MH27	T										High peak flow. (dimensionless)
Frequency of Low Flows											
FL1	T	S	S	P	S	S	✓	✓	✓	✓	Low flood pulse count. (number of events/year)
FL2	S		S	S	S	S					Variability in low pulse count. (percent)
FL3	T	P	P	S	P	P					Frequency of low pulse spells. (number of events/year)
Frequency of High Flows											
FH1	T	S	S								High flood pulse count. (number of events/year)
FH2	S					S					Variability in high pulse count. (number of events/year)
FH3	T	S		S	P	S	✓		✓	✓	High flood pulse count. (number of days/year)
FH4	T	P	P	S							High flood pulse count. (number of days/year)
FH5	T				S						Flood frequency. (number of events/year)
FH6	T										Flood frequency. (number of events/year)
FH7	T			P		P					Flood frequency. (number of events/year)
FH8	T										Flood frequency. (number of events/year)
FH9	T	S			S	S					Flood frequency. (number of events/year)
FH10	T		S		S			✓			Flood frequency. (number of events/year)
FH11	T			S	S						Flood frequency. (number of events/year)
Duration of Low Flows											
DL1	T		S					✓			Annual minimum daily flow (cubic feet per second)
DL2	T										Annual minimum of 3-day moving average flow (cubic feet per second)
DL3	T					P					Annual minimum of 7-day moving average flow. (cubic feet per second)
DL4	T	P			P		✓			✓	Annual minimum of 30-day moving average flow. (cubic feet per second)
DL5	T			S							Annual minimum of 90-day moving average flow. (cubic feet per second)

Appendix H. Definition of Hydrologic Indices (cont.)[1]

(all notes at bottom of appendix)

Hydro-logic index	Tempo-ral/ spatial[2]	USGS primary/secondary indices by stream type[3]					NJDEP selected indi-ces, by stream type[4]				Flow component evaluated by hydrologic Index[5] (with measurement units)
		A	B	C	D	all	A	B	C	D	
DL6	S	S				S					Variability of annual minimum daily average flow. (percent)
DL7	S				S						Variability of annual minimum of 3-day moving average flow. (percentage)
DL8	S										Variability of annual minimum of 7-day moving average flow. (percentage)
DL9	S			S							Variability of annual minimum of 30-day moving average flow. (percentage)
DL10	S										Variability of annual minimum of 90-day moving average flow. (percentage)
DL11	T				S						Annual minimum daily flow divided by the median for the entire record. (dimen-sionless)
DL12	T	S	S			S					Annual minimum of 7-day moving average flow divided by the median for the entire record. (dimensionless)
DL13	T										Annual minimum of 30-day moving average flow divided by the median for the entire record. (dimensionless)
DL14	S			S							Low exceedence flows. (dimensionless)
DL15	S		P								Low exceedence flows. (dimensionless)
DL16	T	S	S	P	S	S			✓		Low flow pulse duration. (number of days)
DL17	S			S							Variability in low pulse duration. (percent)
DL18	T										Number of zero-flow days. (number of days/year)
DL19	S										Variability in the number of zero-flow days. (percent)
DL20	T										Number of zero-flow months. (percentage)
											--- Duration of High Flows ---
DH1	T			S							Annual maximum daily flow. (cubic feet per second)
DH2	T	P	S		S	S					Annual maximum of 3-day moving average flows. (cubic feet per second)
DH3	T										Annual maximum of 7-day moving average flows. (cubic feet per second)
DH4	T										Annual maximum of 30-day moving average flows. (cubic feet per second)
DH5	T										Annual maximum of 90-day moving average flows. (cubic feet per second)
DH6	S										Variability of annual maximum daily flows. (percent)
DH7	S										Variability of annual maximum of 3-day moving average flows. (percent)
DH8	S	S				S					Variability of annual maximum of 7-day moving average flows. (percent)

Appendix H. Definition of Hydrologic Indices (cont.)[1]

(all notes at bottom of appendix)

Hydro-logic index	Tempo-ral/ spatial[2]	USGS primary/secondary indices by stream type[3]					NJDEP selected indi-ces, by stream type[4]				Flow component evaluated by hydrologic Index[5] (with measurement units)
		A	B	C	D	all	A	B	C	D	
DH9	S			S							Variability of annual maximum of 30-day moving average flows (percent)
DH10	S										Variability of annual maximum of 90-day moving average flows. (percent)
DH11	T			P		P					Annual maximum of 1-day moving average flows divided by the median of the entire record. (dimensionless)
DH12	T		P		S						Annual maximum of 7-day moving average flows divided by the median of the entire record. (dimensionless)
DH13	T	S									Annual maximum of 30-day moving average flows divided by the median of the entire record. (dimensionless)
DH14	T			S	P						Flood duration. (dimensionless)
DH15	T					S					High flow pulse duration. (days/year)
DH16	S										Variability in high flow pulse duration. (percent)
DH17	T				S						High flow duration. (days)
DH18	T										High flow duration. (days)
DH19	T										High flow duration. (days)
DH20	T	S	S								High flow duration. (days)
DH21	T										High flow duration. (days)
DH22	T										Flood interval. (days)
DH23	T			S	S						Flood duration. (days)
DH24	T		S								Flood-free days. (days)
------ Timing of Average Flows ------											
TA1	S	P	P	S	P	P					Constancy. (dimensionless)
TA2	S				S						Predictability. (dimensionless)
TA3	S	S		S							Seasonal predictability of flooding. (dimensionless)
------ Timing of Low Flows ------											
TL1	S	S		S							Julian date of annual minimum. (Julian day)
TL2	S		S	S							Variability in Julian date of annual minima. (Julian day)
TL3	S					S					Seasonal predictability of low flow. (dimensionless)

Appendix H. Definition of Hydrologic Indices (cont.)[1]

(all notes at bottom of appendix)

Hydro-logic index	Tempo-ral/ spatial[2]	USGS primary/secondary indices by stream type[3]					NJDEP selected indi-ces, by stream type[4]				Flow component evaluated by hydrologic Index[5] (with measurement units)
		A	B	C	D	all	A	B	C	D	
TL4	S										Seasonal predictability of non-low flow (dimensionless)
------ Timing of High Flows ------											
TH1	S										Julian date of annual maximum. (Julian day)
TH2	S		S		S	S					Variability in Julian date of annual maxima. (Julian days)
TH3	S		S	P	S						Seasonal predictability of non-flooding. (dimensionless)
------ Rate of Change of Flows ------											
RA1	T		S	S	S						Rise rate. (cubic feet per second/day)
RA2	S		S	S		S					Variability in rise rate. (percent)
RA3	T	P		S	S	S	✓				Fall rate. (cubic feet per second/day)
RA4	S			S							Variability in fall rate. (percent)
RA5	S	S									Number of day rises. (dimensionless)
RA6	T		S	P	S	P			✓		Change of flow. (cubic feet per second)
RA7	T	S	P		P			✓		✓	Change of flow. (cubic feet per second/day)
RA8	T	S			S	S					Number of reversals. (days)
RA9	S										Variability in reversals. (percent)

Notes:

1. Table summarized from Henriksen and others (2006).
2. Temporal indices defined using only data from one stream gage. Spatial indices are defined using information from multiple gages. See the 'Parameter Selection' section of this report for more information.
3. P indicates the primary hydrologic index and S the secondary hydrologic indices for each stream type. The 'all' stream type is based on an analysis of all streams, not breaking them into types. See Henriksen and others (2006) for more details on stream types. See table 2 of this report for a condensed list of USGS-designated principal and secondary hydrological indices.
4. A check mark means this hydrologic index is selected for this stream type. See table 3 of this report for a condensed list of NJDEP designated principal hydrological indices.
5. See Henriksen and others (2006) for details on how each hydrologic index is calculated.

Appendix I. Baseline Periods for Selected New Jersey Streams[1]

(all notes at the end of appendix)

Stream Gage Number[2]	Stream Gage Name[2]	Stream Type[3]	Drainage Area (mi^2)	Continuous Period of Record[4]	Baseline Period[5]	Baseline Period Rating[6]
			Passaic River Basin			
01379000	Passaic River near Millington, NJ	A	55.4	1903-1906, 1921-2004	1921-1979	good
01379500	Passaic River near Chatham, NJ	A	100	1903-1911, 1938-2004	1938-1964	good
01379773	Green Pond Brook at Picatinny Arsenal, NJ	D	7.65	1983-2005	1983-2005	poor
01380500	Rockaway River Above Reser-voir at Boonton, NJ	A	116	1937-2005	1937-1959	good
01381500	Whippany River at Morristown, NJ	C	29.4	1921-2005	1921-1952	good
01383500	Wanaque River at Awosting, NJ	C	27.1	1919-2005	1919-1968	good
01384000	Wanaque River at Monks, NJ	A	40.4	1935-1985	1934-1985	good
01384500	Ringwood Creek near Wanaque, NJ*	C	19.1	1934-2005	1934-2005	good
01385000	Cupsaw Brook near Wanaque, NJ	D	4.37	1936-1958	1934-1958	good
01386000	West Brook near Wanaque, NJ*	C	11.8	1935-1978	1934-1978	good
01386500	Blue Mine Brook near Wanaque, NJ	D	1.01	1935-1958	1934-1958	good

Appendix I. Baseline Periods for Selected New Jersey Streams (cont.)[1]

(all notes at the end of appendix)

Stream Gage Number[2]	Stream Gage Name[2]	Stream Type[3]	Drainage Area (mi^2)	Continuous Period of Record[4]	Baseline Period[5]	Baseline Period Rating[6]
01387000	Wanaque R at Wanaque, NJ	A	90.4	1911-1914, 1918-2005	1918-1928	very poor
01387450	Mahwah River near Suffern, NY	C	12.3	1958-1995	1958-1995	good
01387500	Ramapo River near Mahwah, NJ	A	120	1903-1906, 1923-2005	1923-1964	good
01388000	Ramapo River at Pompton Lakes, NJ	A	160	1921-2005	1921-1953	good
01390500	Saddle R at Ridgewood, NJ	C	21.6	1954-2005	1954-1964	good
01391000	Hohokus Brook at Ho-Ho-Kus, NJ	C	16.4	1954-2005	1954-1965	fair
01391500	Saddle River at Lodi, NJ	A	54.6	1923-2005	1923-1957	fair
01392000	Weasel Brook at Clifton, NJ	D	4.45	1936-1962	1937-1950	very poor
01392210	Third River at Passaic, NJ	C	11.8	1976-1997	1977-1986	very poor
01392500	Second River at Belleville, NJ	C	11.6	1936-1964	1937-1964	poor
Raritan River Basin						
01396000	Robinsons Branch at Rahway, NJ	D	21.6	1939-1999	1973-1996	very poor
01396500	South Branch Raritan River near High Bridge, NJ	A	65.3	1918-2005	1918-1970	good
01396580	Spruce Run at Glen Gardner, NJ	C	11.3	1977-1988, 1991-2005	1978-2005	good

Appendix I. Baseline Periods for Selected New Jersey Streams (cont.)[1]

(all notes at the end of appendix)

Stream Gage Number[2]	Stream Gage Name[2]	Stream Type[3]	Drainage Area (mi^2)	Continuous Period of Record[4]	Baseline Period[5]	Baseline Period Rating[6]
01396660	Mulhockaway Creek at Van Syckel, NJ	C	11.8	1976-2005	1977-2005	good
01397000	South Branch Raritan River at Stanton, NJ	A	147	1903-1905 1919-2005	1919-1963	good
01397500	Walnut Brook near Flemington, NJ	D	2.24	1935-1961	1936-1961	good
01398000	Neshanic River at Reaville, NJ	A	25.7	1930-2005	1930-1962	good
01398045	Back Brook Tributary near Ringoes, NJ	D	1.98	1977-1988	1977-1988	very poor
01398107	Holland Brook at Readington, NJ	D	9	1979-1996	1978-1996	very poor
01398500	North Branch Raritan River near Far Hills, NJ	C	26.2	1921-2005	1921-2004	good
01399190	Lamington (Black) River at Succasunna, NJ	D	7.37	1977-1987	1976-1987	very poor
01399200	Lamington (Black) River near Ironia, NJ	D	10.9	1976-1987	1975-1987	very poor
01399500	Lamington (Black) River near Pottersville, NJ	C	32.8	1921-2005	1921-1950	good
01399510	Upper Cold Brook near Pottersville, NJ	D	2.18	1972-1996	1982-1996	very poor
01399525	Axle Brook near Pottersville, NJ	D	1.22	1978-1988	1978-1988	very poor
01399670	South Branch Rockaway Creek at Whitehouse Station, NJ	C	12.3	1976-2005	1977-2005	good
01400000	North Branch Raritan River near Raritan, NJ	A	190	1923-2005	1923-1962	good

Appendix I. Baseline Periods for Selected New Jersey Streams (cont.)[1]

(all notes at the end of appendix)

Stream Gage Number[2]	Stream Gage Name[2]	Stream Type[3]	Drainage Area (mi^2)	Continuous Period of Record[4]	Baseline Period[5]	Baseline Period Rating[6]
01400350	Macs Brook at Somerville, NJ	D	0.77	1982-1995	1982-1992	very poor
01400500	Raritan River at Manville, NJ	A	490	1903-1907, 1921-2005	1921-1963	fair
01400730	Millstone River at Plainsboro, NJ	A	65.8	1964-1975	1964-1975	very poor
01401000	Stony Brook at Princeton, NJ	A	44.5	1953-2005	1953-1980	good
01401500	Millstone River near Kingston, NJ	A	171	1934-1949	1933-1949	very poor
01401650	Pike Run at Belle Mead, NJ	D	5.36	1979-2005	1980-1995	poor
01402000	Millstone River at Blackwells Mills, NJ	A	258	1921-2005	1921-1960	good
01402600	Royce Brook Tributary near Belle Mead, NJ	C	1.2	1966-1975, 1980-1996	1966-1975	very poor
01403060	Raritan River Below Calco Dam at Bound Brook, NJ	A	785	1903-1909, 1945-2005	1945-1963	very poor
01403400	Green Brook at Seeley Mills, NJ	D	6.23	1978-2005	1979-2005	fair
01403535	East Branch Stony Brook at Best Lake at Watchung, NJ	D	1.57	1979-2000	1980-2000	good
01403540	Stony Brook at Watchung, NJ	D	5.51	1974-2005	1974-1991	very poor
	Atlantic Coastal River Basins					
01405300	Matchaponix Brook at Spots-wood, NJ	A	43.9	1957-1967	1957-1967	very poor

Appendix I. Baseline Periods for Selected New Jersey Streams (cont.)[1]

(all notes at the end of appendix)

Stream Gage Number[2]	Stream Gage Name[2]	Stream Type[3]	Drainage Area (mi^2)	Continuous Period of Record[4]	Baseline Period[5]	Baseline Period Rating[6]
01408000	Manasquan River at Squankum, NJ	A	44	1931-2005	1931-1956	good
01408120	North Branch Metedeconk River near Lakewood, NJ	C	34.9	1972-2005	1972-2004	poor
01408500	Toms River near Toms River, NJ	B	123	1928-2005	1928-1963	good
01409000	Cedar Creek at Lanoka Harbor, NJ	B	53.3	1931-1958,1969-1971,2003-2005	1932-1956	poor
01409095	Oyster Creek near Brookville, NJ	D	7.43	1966-1985	1966-1985	very poor
01409280	Westecunk Creek at Stafford Forge, NJ	D	15.8	1974-1988	1973-1988	very poor
01409400	Mullica River near Batsto, NJ	B	46.7	1956-2005	1957-2005	good
01409500	Batsto River at Batsto, NJ*	B	67.8	1927-2005	1927-2005	good
01409810	West Branch Wading River near Jenkins, NJ	B	84.1	1974-1996	1974-1996	good
01410000	Oswego River at Harrisville, NJ*	B	72.5	1930-2005	1930-2005	good
01410150	East Branch Bass River near New Gretna, NJ	D	8.11	1977-2005	1978-2005	poor
01411000	Great Egg Harbor River at Folsom, NJ	B	57.1	1924-2005	1925-1970	good
01411300	Tuckahoe River at Head of River, NJ	C	30.8	1969-2005	1969-2005	good
01411456	Little Ease Run near Clayton, NJ	D	9.77	1989-2005	1989-2005	very poor

Appendix I. Baseline Periods for Selected New Jersey Streams (cont.)[1]

(all notes at the end of appendix)

Stream Gage Number[2]	Stream Gage Name[2]	Stream Type[3]	Drainage Area (mi^2)	Continuous Period of Record[4]	Baseline Period[5]	Baseline Period Rating[6]
01411500	Maurice River at Norma, NJ	B	112	1932-2005	1932-2005	good
01412000	Menantico Creek near Millville, NJ	D	23.2	1930-1985	1931-1957	good
01412800	Cohansey River at Seeley, NJ	C	28	1978-1988	1978-1988	good

Delaware River Basin

Stream Gage Number	Stream Gage Name	Stream Type	Drainage Area (mi^2)	Continuous Period of Record	Baseline Period	Baseline Period Rating
01437500	Neversink River at Godeffroy, NY	A	307	1937-2005	1937-1953	very poor
01440000	Flat Brook near Flatbrookville, NJ*	A	64	1924-2005	1923-2005	good
01443500	Paulins Kill at Blairstown, NJ*	A	126	1921-2005	1921-2005	good
01445000	Pequest River at Huntsville, NJ	C	31	1939-1962	1939-1962	good
01445500	Pequest River at Pequest, NJ	B	106	1921-2005	1921-1958	good
01446000	Beaver Brook near Belvidere, NJ	C	36.7	1922-1961	1922-1951	good
01456000	Musconetcong River near Hack-ettstown, NJ	B	68.9	1921-1972	1921-1972	good
01457000	Musconetcong River near Bloomsbury, NJ	B	141	1903-1907, 1921-2005	1921-1972	good
01464000	Assunpink Creek at Trenton, NJ	A	91	1923-2005	1923-1956	good

Appendix I. Baseline Periods for Selected New Jersey Streams (cont.)[1]

(all notes at the end of appendix)

Stream Gage Number[2]	Stream Gage Name[2]	Stream Type[3]	Drainage Area (mi^2)	Continuous Period of Record[4]	Baseline Period[5]	Baseline Period Rating[6]
01464500	Crosswicks Creek at Extonville, NJ	A	81.5	1939-2005	1940-1979	poor
01465850	South Branch Rancocas Creek at Vincentown, NJ	B	64.5	1962-1975	1961-1975	good
01466000	Middle Branch Mt Misery Brook In Lebanon State Forest, NJ	D	3	1953-1964	1952-1964	very poor
01466500	Mcdonalds Branch in Lebanon State Forest, NJ*	D	2.35	1953-2005	1953-2005	good
01467000	North Branch Rancocas Creek at Pemberton, NJ	B	118	1921-2005	1921-2005	good
01467081	South Branch Pennsauken Creek at Cherry Hill, NJ	C	8.98	1967-2005	1967-1978	poor
01475000	Mantua Creek at Pitman, NJ	D	6.05	1940-1976, 2003-2005	1940-1972	good
01477120	Raccoon Creek near Swedes-boro, NJ	C	26.9	1965-2005	1966-2005	good

* An index site is considered to be relatively "pristine" (least urbanization, less than 15% urban land use) for a long period of record (at least 50 years). The entire period of record for these sites is considered baseline.

1 Information from Esralew and Baker, 2008.

2 Assigned by US Geological Survey.

3 See Henriksen and others (2006) for a description of stream types and assignments.

4 Continuous Period of Record: This is the period of record when gage data are continuous (including estimated periods).

5 Baseline Period: This is the period of record determined by the USGS to be the best period of record to calculate baseline index values. This period is estimated to have the least urbanization, the least anthropogenic activity in the basin (including regulation, diversion, and withdrawal), no statistically significant changes in annual streamflow patterns (not attributed to climate changes), and contains a minimum number of years to avoid excessive variability in index values. Details on the methods of baseline period and minimum period of record calculation are in Esralew and Baker, 2008.

[6] Baseline Period Rating: This is a rating assigned to each baseline period by the U.S. Geological Survey that designates the quality of the baseline period determined by the criteria listed above. The baseline period is the period that contains the "least anthropogenic activity" affecting streamflow and/or drainage basin, and contains a minimum number of years. A baseline period was selected even if most of the period of record contained significant anthropogenic activity, and if the continuous period of record was less than the minimum period of record. The purpose of the baseline period rating was to identify those gaging stations that had a baseline period under conditions that were not considered ideal given the years of existing record, and to assign a level of quality to the best available baseline period. Details on the methods used to determine the rating for each baseline period are in Esralew and Baker, 2008