# A Method for Assessing Hydrologic Alteration within Ecosystems

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**Abstract:** *Hydrologic regimes play a major role in determining the biotic composition, structure, and function of aquatic, wetland, and riparian ecosystems. But human land and water uses are substantially altering hydrologic regimes around the world. Improved quantitative evaluations of human-induced hydrologic changes are needed to advance research on the biotic implications of hydrologic alteration and to support ecosystem management and restoration plans. We propose a method for assessing the degree of hydrologic alteration attributable to human influence within an ecosystem. This method, referred to as the "Indicators of Hydrologic Alteration," is based upon an analysis of hydrologic data available either from existing measurement points within an ecosystem (such as at stream gauges or wells) or model-generated data. We use 32 parameters, organized into five groups, to statistically characterize hydrologic variation within each year. These 32 parameters provide information on ecologically significant features of surface and ground water regimes influencing aquatic, wetland, and riparian ecosystems. We then assess the hydrologic perturbations associated with activities such as dam operations, flow diversion, groundwater pumping, or intensive land-use conversion by comparing measures of central tendency and dispersion for each parameter between user-defined "pre-impact" and "post-impact" time frames, generating 64 Indicators of Hydrologic Alteration. This method is intended for use with other ecosystem metrics in inventories of ecosystem integrity, in planning ecosystem management activities, and in setting and measuring progress toward conservation or restoration goals.*

Un Métro para Evaluar Alteraciones Hidrológicas dentro de Ecosistemas

**Resumen:** *Los regímenes hidrológicos juegan un papel importante en la determinación de la composición de la biota, la estructura y función de ecosistemas acuáticos inundables y riparios. Sin embargo, el uso de la tierra y agua por parte del hombre está alterando substancialmente regímenes hidrológicos. Se requieren mejores evaluaciones cuantitativas de los cambios hidrológicos inducidos por el hombre para avanzar en la investigación de las implicaciones de la alteración hidrológica sobre la biota y para soportar planes de manejo y restauración del ecosistema. Proponemos un método para evaluar el grado de alteración hidrológica atribuible a impactos humanos dentro de un ecosistema. Este método, denominado Indicadores de Alteración Hidrológica, se basa en el análisis de datos hidrológicos disponibles ya sea de puntos de muestreo dentro de un ecosistema (tales como mediciones de corrientes o pozos) o generados por modelos. Utilizamos 32 parámetros organizados en cinco grupos, para caracterizar estadísticamente la variación hidrológica de cada año. Estos 32 parámetros proporcionan información de `rasgos ecológicamente significativos de los regímenes de aguas superficiales y subterráneas que influyen en ecosistemas acuáticos, inundables y riparios. Se evaluaron las perturbaciones hidrológicas asociadas con actividades tales como operación de presas, desviación de flujos, bombeo de agua subterránea o cambios en el uso intensivo del suelo mediante la comparación de medidas de tendencia central y dispersión para cada parámetro, entre rangos de tiempo difini-*

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*dos como "pre-impacto" y "post-impacto," lo que generó 64 Indicadores de Alteración Hidrológica. Se pretende que este método sea utilizado en conjunto con ostros en inventarios de integridad de ecosistemas, en la planeación de actividades de manejo de ecosistemas y en la definición y medición de avances en las metas de conservación o restauración.*

## Introduction

A goal of ecosystem management is to sustain ecosystem integrity by protecting native biodiversity and the ecological (and evolutionary) processes that create and maintain that diversity. Faced with the complexity inherent in natural systems, achieving that goal will require that resource managers explicitly describe desired ecosystem structure, function, and variability; characterize differences between current and desired conditions; define ecologically meaningful and measurable indicators that can mark progress toward ecosystem management and restoration goals (Keddy et al. 1993); and incorporate adaptive strategies (Holling 1978) into resource management plans.

The biotic composition, structure, and function of aquatic, wetland, and riparian ecosystems depend largely on the hydrologic regime (Gorman & Karr 1978; Junk et al. 1989; Poff & Ward 1990; National Research Council 1992; Sparks 1992; Mitsch & Gosselink 1993). Intra-annual variation in hydrologic conditions is essential to successful life-cycle completion for many aquatic, riparian, and wetland species; variation in these conditions often plays a major role in the population dynamics of these species through influences on reproductive success, natural disturbance, and biotic competition (Poff & Ward 1989). Modifications of hydrologic regimes can indirectly alter the composition, structure, or function of aquatic, riparian, and wetland ecosystems through their effects on physical habitat characteristics, including water temperature, oxygen content, water chemistry, and substrate particle sizes (Stanford & Ward 1979; Ward & Stanford 1983, 1989; Bain et al. 1988; Lillehammer & Saltveit 1984; Dynesius & Nilsson 1994).

Collectively, limnology research suggests that the full range of natural intra- and inter-annual variation of hydrologic regimes is necessary to sustain the native biodiversity and evolutionary potential of aquatic, riparian, and wetland ecosystems. This emerging paradigm is expressed in numerous recent statements about the necessity of protecting or restoring "natural" hydrologic regimes (National Research Council 1992; Sparks 1992; Doppelt et al. 1993; Dynesius & Nilsson 1994; Noss & Cooperrider 1994). For example, Sparks (1992) suggested that rather than optimizing water regimes for one or a few species, "a better approach is to approximate the natural flow regime that maintained . . . the entire panoply of species."

Despite the importance of natural hydrologic variation

in aquatic, wetland, and riparian ecosystems (Kusler & Kentula 1989; National Research Council 1992; Noss & Cooperrider 1994; Allan 1995), most ecosystem management and restoration efforts (for example, Hesse & Mestl 1993; Toth et al. 1993) have one or more shortcomings with respect to hydrology. Management decisions generally have focused on the known or perceived hydrologic requirements of only one, or at most a few, target aquatic species (Reiser et al. 1989), potentially neglecting the needs of other species and ecosystem processes and functions in general. For instance, the vast majority of instream flow prescriptions and water rights have been based solely upon the requirements of selected species of fish (Beecher 1990; Bishop et al. 1990; Kulik 1990; Zincone & Rulifson 1991). The range of flows needed to sustain aquatic-riparian ecosystems may be considerably greater than what would be prescribed for the aquatic system alone if the hydrologic requirements of riparian species also are considered (Hill et al. 1991). Other shortcomings include the failure to consider the influence of hydrologic processes on geomorphic changes, or on ecosystem functions such as material transport and cycling or food-web support, and the failure to consider the full range of temporal variability in hydrologic regimes.

Effective ecosystem management of aquatic, riparian, and wetland systems requires that existing hydrologic regimes be characterized using *biologically relevant* hydrologic parameters and that the degree to which human-altered regimes differ from natural or preferred conditions be related to the status and trends of the biota. Ecosystem management efforts should be considered experiments that test the need to maintain or restore natural characteristics of the hydrologic regime in order to sustain ecosystem integrity. Unfortunately, few limnology studies have closely examined hydrologic influences on ecosystem integrity, in part because commonly used statistical tools are poorly suited for characterizing hydrologic data into biologically relevant attributes. The lack of appropriate or robust statistical tools has in turn constrained knowledge about the effects of hydrologic alteration on ecosystem integrity. Without such knowledge, ecosystem managers will not be compelled to protect or restore natural characteristics of the hydrologic regime.

We present an approach (1) to statistically characterize the temporal variability in hydrologic regimes using biologically relevant statistical attributes, and (2) to quantify hydrologic alterations associated with pre-

sumed perturbations (such as dam operations, flow diversion, or intensive conversion of land uses in a watershed) by comparing the hydrologic regimes from pre-impact and post-impact time frames. We then illustrate the application of this method with a case study from the dam-altered Roanoke River in North Carolina (U.S.A). Our intent is to make available to ecosystem managers and researchers an easily utilized analytical tool for comprehensively summarizing complex hydrologic variation with biologically relevant attributes. It is not our intent to describe or predict biological responses to hydrologic alteration. Instead, we hope that this tool will facilitate investigations into the effects of hydrologic modifications on the biotic composition, structure, and function of aquatic, riparian, and wetland ecosystems.

## Methods

### Indicators of Hydrologic Alteration

Our general approach for hydrologic assessment is first to define a series of biologically relevant hydrologic attributes that characterize intra-annual variation in water conditions and then to use an analysis of the inter-annual variation in these attributes as the foundation for comparing hydrologic regimes before versus after a system has been altered by various human activities. Because the proposed method results in the computation of a

representative, multi-parameter suite of hydrologic characteristics—or *indicators*—for assessing hydrologic alteration, we refer to it as the Indicators of Hydrologic Alteration (IHA) method. The IHA method has four steps:

(1) Define the data series (e.g., stream gauge or well records) for pre- and post-impact periods in the ecosystem of interest.

(2) Calculate values of hydrologic attributes. We calculate values for each of 32 ecologically relevant hydrologic parameters (Table 1) for each year in each data series, i.e., one set of values for the pre-impact data series and one for the post-impact data series.

(3) Compute inter-annual statistics. We compute measures of central tendency and dispersion for the 32 parameters in each data series, based on the values calculated in step 2. This produces 64 inter-annual statistics for each data series (32 measures of central tendency and 32 measures of dispersion).

(4) Calculate values of the IHA. We compare the 64 inter-annual statistics between the pre- and post-impact data series, and we present each result as a percentage deviation of one time period (the post-impact condition) relative to the other (the pre-impact condition). The method can be used to compare the state of one system to itself over time (e.g., pre- versus post-impact as just described), or it can be used to compare the state of one system to another (e.g., an altered system to a reference

**Table 1.** Summary of hydrologic parameters used in the Indicators of Hydrologic Alteration and their characteristics.

| IHA statistics group | Regime characteristics | Hydrologic parameters |
|---|---|---|
| Group 1: Magnitude of monthy water conditions | Magnitude Timing | Mean value for each calendar month |
| Group 2: Magnitude and duration of annual extreme water conditons | Magnitude Duration | Annual minima 1-day means<br>Annual maxima 1-day means<br>Annual minima 3-day means<br>Annual maxima 3-day means<br>Annual minima 7-day means<br>Annual maxima 7-day means<br>Annual minima 30-day means<br>Annual maxima 30-day means<br>Annual minima 90-day means<br>Annual maxima 90-day means |
| Group 3: Timing of annual extreme water conditions | Timing | Julian date of each annual 1 day maximum<br>Julian date of each annual 1 day minimum |
| Group 4: Frequency and duration of high and low pulses | Magnitude Frequency Duration | No. of high pulses each year<br>No. of low pulses each year<br>Mean duration of high pulses within each year<br>Mean duration of low pulses within each year |
| Group 5: Rate and frequency of water condition changes | Frequency Rate of change | Means of all positive differences between consecutive daily means<br>Means of all negative differences between consecutive daily values<br>No. of rises<br>No. of falls |

system) or current conditions to simulated results based on models of future modification to a system.

The data we use in estimating all attribute values are daily mean water conditions (e.g., levels, heads, flow rates). The same computational strategies will work with any regular-interval hydrologic data, such as monthly means, but the sensitivity of the IHA method for detecting hydrologic alteration is increasingly compromised with time intervals longer than a day. Detection of certain types of hydrologic impacts, such as the rapid flow fluctuations associated with hydropower generation at dams, may require data from even shorter intervals (e.g., hourly).

## Hydrologic Attributes

Hydrologic conditions can vary in four dimensions within an ecosystem (three spatial dimensions and time). If the spatial domain is restricted to a specific point within a hydrologic system, however, (such as a measurement point in a river, a lake, or an aquifer), the hydrologic regime can be defined in terms of one temporal and one spatial dimension: changes in water conditions (e.g., levels, heads, rates) at a single location over time. Such temporal changes in water conditions are commonly portrayed as plots of water condition against time, or hydrographs (Fig. 1).

Our goal is to characterize the temporal variation of hydrologic conditions using attributes that are biologically relevant yet sensitive to human influences such as reservoir operations, ground water pumping, and agricultural diversions. Many attributes of hydrologic regimes can be used to characterize the "physical habitat templates" (Southwood 1977, 1988; Poff & Ward 1990; Townsend & Hildrew 1994) or "environmental filters" (Keddy 1992) that shape the biotic composition of aquatic, wetland, and riparian ecosystems. The IHA method is based on 32 biologically relevant hydrologic parameters divided into five major groups to statistically characterize intra-annual hydrologic variation (Table 1). These 32 parameters are based upon five fundamental characteristics of hydrologic regimes:

(1)    The *magnitude* of the water condition at any given time is a measure of the availability or suitability of habitat and defines such habitat attributes as wetted area or habitat volume, or the position of a water table relative to wetland or riparian plant rooting zones.

(2)    The *timing* of occurrence of particular water conditions can determine whether certain life-cycle requirements are met or can influence the degree of stress or mortality associated with extreme water conditions such as floods or droughts.

(3)    The *frequency* of occurrence of specific water conditions such as droughts or floods may be tied
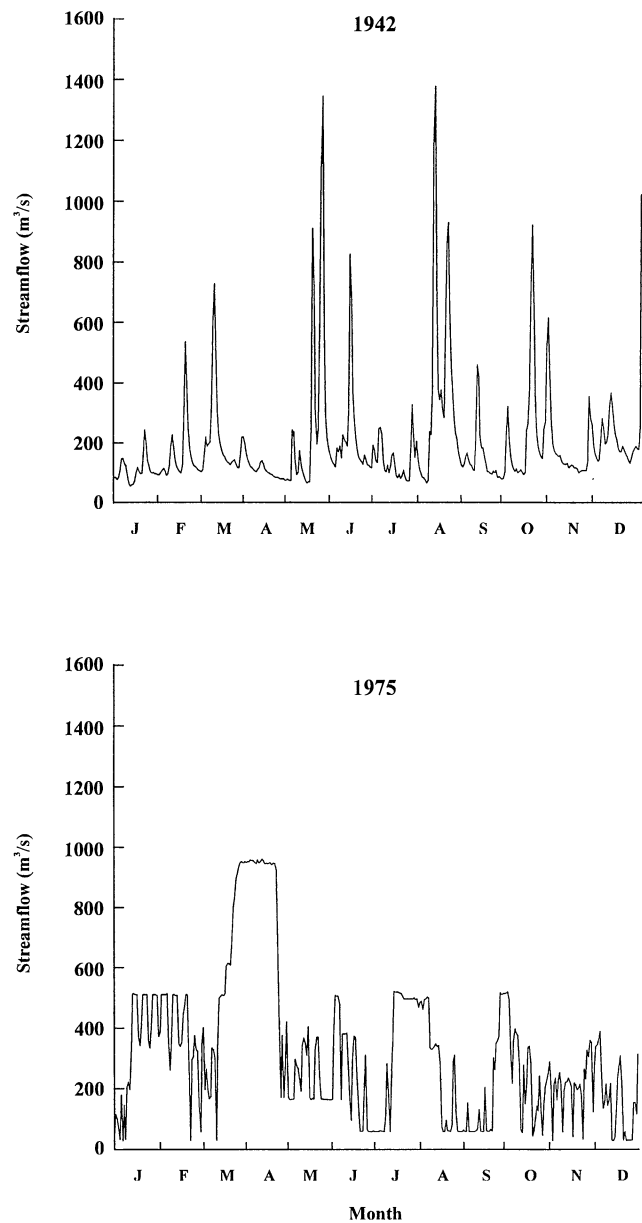


Figure 1. *Two hydrographs for the Roanoke River at Roanoke Rapids in North Carolina can be characterized by the five general features of a hydrologic regime: magnitude, frequency, duration, timing, and rate of change. These regime features can be altered by human influences such as dams, as illustrated by a comparison of the upper pre-dam hydrograph for 1942 with the lower post-dam hydrograph for 1975 (cms = cubic meters per second = 35.315 cubic feet per second).*

to reproduction or mortality events for various species, thereby influencing population dynamics.

(4)    The *duration* of time over which a specific water condition exists may determine whether a particular life-cycle phase can be completed or the degree

to which stressful effects such as inundation or desiccation can accumulate.

(5) The *rate of change* in water conditions may be tied to the stranding of certain organisms along the water's edge or in ponded depressions, or the ability of plant roots to maintain contact with phreatic water supplies.

The 32 IHA parameters provide a detailed representation of the hydrologic regime for the purpose of assessing hydrologic alteration. Most important, they entail hydrologic statistics commonly employed in limnology studies because of their great ecological relevance (Gustard 1984; Kozlowski 1984; Hughes & James 1989; Poff & Ward 1989). Also, because certain streamflow levels shape physical habitat conditions within river channels, we also identified 32 hydrologic characteristics that might aid in detection of physical habitat alteration in lotic systems. For example, changes in the central tendency of annual maxima might suggest changes in river morphology (Leopold 1994).

Sixteen of the hydrologic characteristics focus on the magnitude, duration, timing, and frequency of extreme events because of the pervasive influence of extreme forces in ecosystems (Gaines & Denny 1993) and geomorphology (Leopold 1994); the other 16 parameters measure the central tendency of either the magnitude or rate of change of water conditions. We describe the rationale underlying the five major grouping of hydrologic characteristics and the specific parameters included within each.

## 1. MAGNITUDE

This group includes 12 parameters, each of which measures the central tendency (mean) of the daily water conditions for a given month. The monthly mean of the daily water conditions describes "normal" daily conditions for the month, and thus provides a general measure of habitat availability or suitability. The similarity of monthly means within a year reflects conditions of relative hydrologic constancy, whereas inter-annual variation (e.g., coefficient of variation) in the mean water condition for a given month provides an expression of environmental contingency (Colwell 1974; Poff & Ward 1989). The terms *constancy* and *contingency* as used here refer to the degree to which monthly means vary from month to month (constancy) and the extent to which flows vary within any given month (contingency).

## 2. MAGNITUDE AND DURATION OF ANNUAL EXTREME CONDITIONS

The 10 parameters in this group measure the magnitude of extreme (minimum and maximum) annual water conditions of various duration, ranging from daily to seasonal. The durations we used follow natural or human-

imposed cycles and include the 1-day, 3-day, 7-day (weekly), 30-day (monthly), and 90-day (seasonal) extremes. For any given year, the 1-day maximum (or minimum) is represented by the highest (or lowest) single daily value occurring during the year; the multi-day maximum (or minimum) is represented by the highest (or lowest) multi-day average value occurring during the year. The mean magnitude of high and low water extremes of various duration provide measures of environmental stress and disturbance during the year; conversely, such extremes may be necessary precursors or triggers for the reproduction of certain species. The inter-annual variation (e.g., coefficient of variation) in the magnitude of these extremes provides another expression of contingency.

## 3. TIMING OF ANNUAL EXTREME CONDITIONS

Group 3 includes two parameters, one measuring the Julian date of the 1-day annual minimum water condition and the other measuring the Julian date of the 1-day maximum water condition. The timing of the highest and lowest water conditions within annual cycles provides another measure of environmental disturbance or stress by describing the seasonal nature of these stresses. Key life-cycle phases (e.g., reproduction) may be intimately linked to the timing of annual extremes; thus human-induced changes in timing may cause reproductive failure, stress, or mortality. The inter-annual variation in timing of extreme events reflects environmental contingency.

## 4. FREQUENCY AND DURATION OF HIGH AND LOW PULSES

The four parameters in group 4 include two that measure the number of annual occurrences during which the magnitude of the water condition exceeds an upper threshold or remains below a lower threshold, respectively, and two that measure the mean duration of such high and low pulses (Fig. 2). These measures of frequency and duration of high and low water conditions together portray the pulsing behavior of environmental variation within a year and provide measures of the shape of these environmental pulses. Hydrologic pulses are defined here as those periods within a year in which the daily mean water condition either rises above the 75th percentile (high pulse) or drops below the 25th percentile (low pulse) of all daily values for the pre-impact time period.

## 5. RATE AND FREQUENCY OF CHANGE IN CONDITIONS

The four parameters in group 5 measure the number and mean rate of both positive and negative changes in water conditions from one day to the next (Fig. 3). The rate and frequency of change in water conditions can be described in terms of the abruptness and number of in-
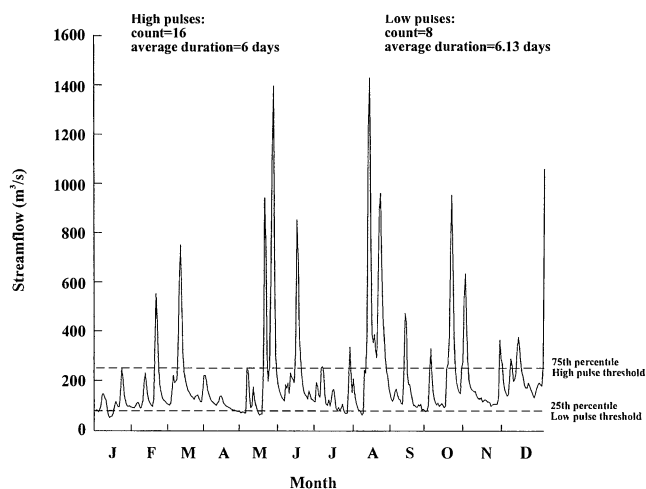
*Figure 2. The computations for IHA group 4 parameters are of frequency and duration of high and low pulses. High pulses are identified as those periods during which water levels rise above the 75th percentile of all pre-impact daily flows, which is equivalent to 258 cms for the Roanoke River. Low pulses represent drops in water levels below the 25th percentile, equivalent to 97 cms.*
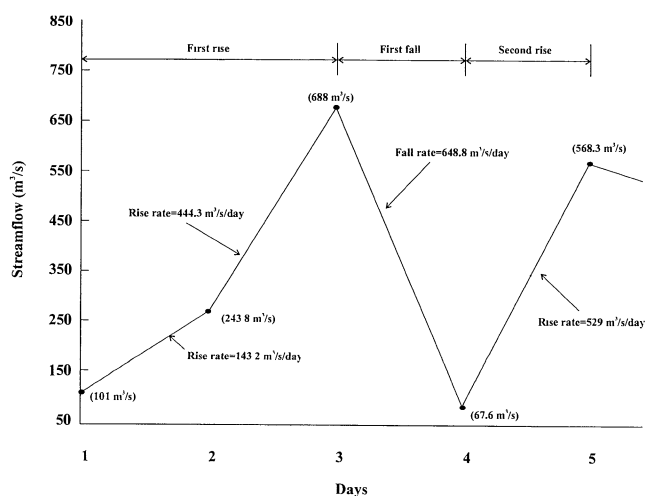


*Figure 3. The computations for IHA group 5 parameters are of rate and frequency of change in conditions, illustrated by means of a hypothetical hydrograph. Two hydrograph rises and one hydrograph fall are identified in the time period shown, along with their corresponding rates of rise and fall. A single rise or fall may last for multiple days and is terminated once the hydrograph begins to fall. Also, rise and fall rates are computed for each day within each year of record analyzed.*

tra-annual cycles of environmental variation and can provide a measure of the rate and frequency of intra-annual environmental change.

## Assessing Hydrologic Alteration

In assessing the impact of a perturbation on the hydrologic regime, we want to determine whether the state of the perturbed system differs significantly from what it would have been in the absence of the perturbation. In particular, we want to test whether the central tendency or degree of inter-annual variation of an attribute of interest has been altered by the perturbation (Stewart-Oaten et al. 1986). The assessment of impacts to natural systems often poses difficult statistical problems, however, because the perturbation of interest cannot be replicated or randomly assigned to experimental units (Hurlburt 1984; Stewart-Oaten et al. 1986; Carpenter 1989; Carpenter et al. 1989). The lack of replication does not hinder estimation of the magnitude of an effect but rather limits inferences regarding its causes. This issue has received considerable attention recently, and more sophisticated experimental designs that incorporate replication over time and sampling at "control" and "impact" sites have been suggested (Stewart-Oaten et al. 1986, 1992).

We are fully cognizant of the replication issue, and we have based the IHA method on the simple design of comparing hydrologic attributes of a single site before and after a putative perturbation. This method allows es-

timation of the magnitude of impacts but does not enable strong inferences regarding the cause. We take this simpler approach for two reasons. First, in many locations, no control site may be available. Second, causal inference, although desirable, may not always be a necessary prerequisite for prescribing management or restoration actions to mitigate for observed effects. But the IHA method is robust and can be easily adapted to more-sophisticated experimental designs.

To ensure consistency in the application of the IHA method, users should clearly identify the presumed cause of the impact(s) being evaluated—for example, the impact of an upstream reservoir or irrigation diversion on streamflow, or the effects of ground water pumping on wetland pond levels. The time period for which hydrologic records exist prior to the presumed perturbation can be defined as pre-impact, and the period of record since initiation of the presumed perturbation can be defined as post-impact. Once pre- and post-impact time periods have been defined, the hydrologic regimes from the two periods can be characterized and compared.

A standard statistical comparison of the 32 IHA parameters between two data series includes tests of the null hypothesis that the central tendency or dispersion of each has not changed. But this null hypothesis is generally far less interesting in impact assessments than ques-
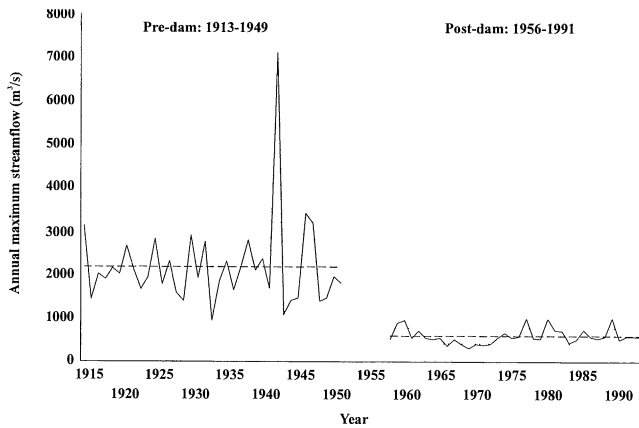
*Figure 4. A comparison of the annual series of annual maximum 1-day values (Group 2: magnitude and duration of annual extreme conditions) for the pre- and post-impact periods on the Roanoke River. Broken lines indicate values of the mean (dashes) and SD (dots) for each period.*
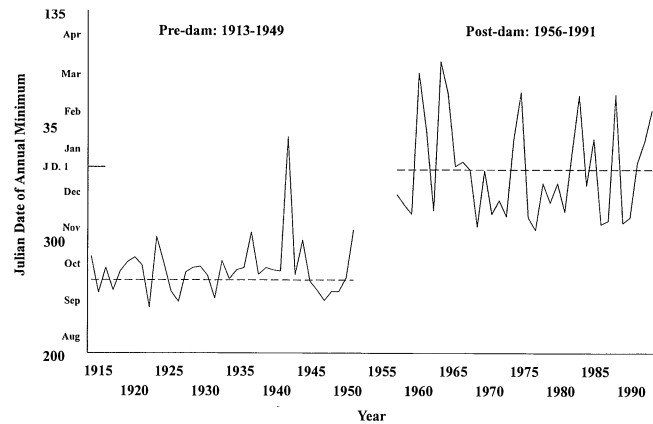


*Figure 6. A comparison of the annual series of values for the timing (Julian date) of annual minimum 1-day values (Group 3: timing of annual extreme conditions) for the pre- and post-impact periods on the Roanoke River. Dashed lines indicate values of the mean for each period.*

tions about the size of detectable changes and their potential biological importance. Accordingly, the results of the IHA method are most usefully presented in terms of the magnitude of the differences in central tendency (or dispersion) between the pre- and post-impact periods (Figs. 4–7), along with confidence limits for this difference, rather than as $p$ values for the null hypotheses that the central tendencies are the same. Hypothesis testing may be valuable for specific cases in which biologically relevant thresholds to hydrologic change can be identified. In these cases an equivalence test (McBride et al. 1993) can be used to test the null hypothesis that the ob-

served difference is greater than some user-identified biologically significant value.

When adequate hydrologic records are available for both the pre-impact and post-impact time periods, application of the IHA method will be relatively straightforward by means of the statistical procedures described. When pre- or post-impact records are nonexistent, include data gaps, or are inadequate in length, however, various data reconstruction or estimation procedures will be needed. Examples of such procedures include the techniques for hydrologic record extension de-
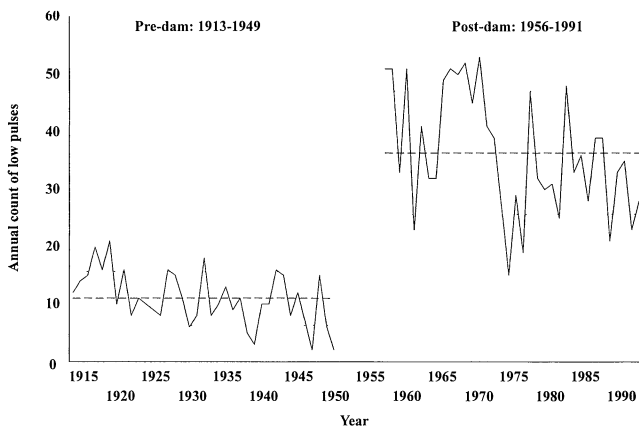


*Figure 5. A comparison of the annual series of annual low pulse counts (Group 4: frequency and duration of high and low pulses) for the pre- and post-impact periods on the Roanoke River. Broken lines indicate values of the mean (dashes) and SD (dots) for each period.*



*Figure 7. A comparison of the annual series of values for annual average rates of hydrograph rise (Group 5: rate and frequency of change in conditions) for the pre- and post-impact periods on the Roanoke River. Broken lines indicate values of the mean (dashes) and SD (dots) for each period.*

scribed by Searcy (1960) and Alley and Burns (1983). Hydrologic simulation modeling or water budgeting techniques can also be used to synthesize hydrologic records for comparison by means of the IHA method (Linsley et al. 1982).

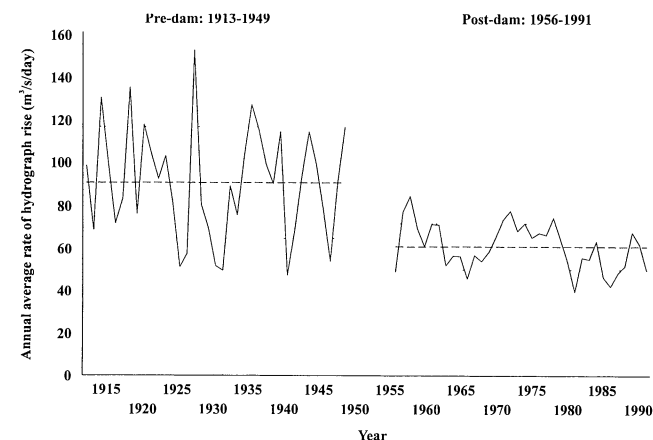Climatic differences between the pre- and post-impact time periods obviously have the potential to substantially influence the outcome of the IHA analysis. Various statistical techniques can be used to test for climatic differences in the hydrologic data to be compared. When the IHA analysis is based upon actual hydrologic measurements rather than estimates produced from models, a reference site or set of sites uninfluenced by the human alterations being examined can be used as climatic controls (Alley & Burns 1983). For example, a stream gauge may exist upstream of a reservoir that is thought to have affected a study site. Analyses can establish a statistical relationship between stream flows at the study site and at the upstream reference site using synchronous pre-dam data sets for the two sites. This relationship can then be used to estimate the stream flow conditions that would have occurred at the study site during the post-impact time period in the absence of the reservoir. The IHA method can then be used to compare the measured post-impact conditions with estimated unaffected conditions for the same time period. Alternatively, a time series of observed impact versus control differences that spans the time of perturbation at the impact site can be used to assess hydrologic impacts (Paller et al. 1992); this is the basis for the before-after-control-impact-pairs design suggested by Stewart-Oaten et al. (1986). In the absence of an appropriate control site, process-based hydrologic models that simulate climatic and runoff processes or other climate analysis techniques can be used to create model data sets for comparison by means of the IHA method (Maheshwari et al. 1995).

## Case Study Application

We selected the dam-altered Roanoke River in North Carolina to illustrate the application of the IHA method for assessing hydrologic alteration. Although we chose a surface water system for this case study, we emphasize the applicability of the method to analyses of ground water alterations as well.

In choosing appropriate estimators of the central tendency (e.g., mean, median) and dispersion (e.g., variance, coefficient of variation) of the hydrologic parameters, careful consideration needs to be given to the efficiency of the estimator and to the efficiency and assumptions of the statistical tests used to evaluate the difference between time periods. The mean is the most efficient estimator of central tendency when the underlying distribution is normal, and various $t$-like tests based on the mean are applicable even when assumptions of

the standard $t$ test (e.g., normal distribution, equal variances) are violated (Stewart-Oaten et al. 1992). We used the mean as an estimate of central tendency and the coefficient of variation ($CV$) as an estimate of dispersion. However, we programmed the IHA software to enable nonparametric analysis as well.

For each of the 32 hydrologic parameters the differences between the pre- and post-impact time periods in both the mean and coefficient of variation are presented, expressed as both a magnitude of difference and a deviation percentage (Table 2). These comparisons of means and coefficients of variation for each of the 32 parameters comprise the 64 different Indicators of Hydrologic Alteration. Approximate confidence limits are also estimated for the difference between means and $CV$, respectively (Table 2), using standard formulae that are approximately valid when distributions are not normal or changed (e.g., have unequal variances) between time periods (Snedecor & Cochran 1967; Stewart-Oaten et al. 1992).

Since 1913, The U.S. Geological Survey (USGS) has collected daily streamflow measurements at Roanoke Rapids on the Roanoke River. Flow values are recorded as cubic feet per second (cfs), but all results are converted here to cubic meters per second (cms). Dam impacts on the Roanoke River system began with the completion of Philpott Lake on the Smith River (in the upper watershed) in August 1950 and were followed by construction of Kerr Reservoir in 1950 for flood-control purposes. In 1955 Roanoke Rapids Lake was built downstream of Kerr Reservoir for "run-of-the-river" hydropower generation purposes. Another reservoir, Gaston Lake, was subsequently built between the locations of Roanoke Rapids Lake and Kerr Reservoir, but its influence on flow regimes in the lower Roanoke below Roanoke Rapids Lake are believed to be inconsequential. The pre-impact data set has therefore been defined as 1913–1949, and the post-impact data set covers 1956–1991. Typical pre- and post-dam annual hydrographs are presented in Fig. 1.

The IHA results for the Roanoke River are given in Table 2 and illustrated in Figs. 4–7. The relative differences between means ranged from −73% (annual 1-day maximum flow) to +232% (low pulse counts) for the individual attributes, whereas the average absolute difference for the five groups of hydrologic characteristics ranged from 15% (Group 1: monthly means) to 88% (Group 4: frequency and duration of pulses). For individual attributes the relative difference in $CV$ ranged from −60% (mean August flow) to +72% (mean April flow); the range for the five groups was 26% (Group 4: frequency and duration of pulses) to 41% (Group 3: timing of extreme events).

The results of the IHA analysis for the Roanoke River reflect the effects of Kerr Reservoir operations for the purposes of flood control and operations for generation

**Table 2.   Results of the Indicators of Hydrologic Alteration analysis for Roanoke River at Roanoke Rapids, North Carolina.**

| | Means | | | | Coefficients of variation | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | Streamflow[a] (m³/sec) | | | | | | | |
| IHA group | Pre-impact | Post-impact | Deviation[b] magnitude/% | Confidence limits (low–high) | Pre-impact | Post-impact | Deviation[b] magnitude/% | Confidence limits (low–high) |
| **Group 1: Monthly magnitude** | | | | | | | | |
| October | 162 | 166 | 4/3 | −58-66 | 0.90 | 0.70 | −0.17/−19 | −0.36-0.02 |
| November | 156 | 184 | 28/18 | −19-75 | 0.56 | 0.60 | 0.04/7 | −0.10-0.17 |
| December | 225 | 211 | −14/−6 | −71-43 | 0.62 | 0.48 | −0.14/−23 | −0.27--0.01 |
| January | 337 | 270 | −67/−20 | −149-1 | 0.64 | 0.44 | −0.21/−32 | −0.34--0.07 |
| February | 350 | 293 | −57/−16 | −119-7 | 0.40 | 0.42 | 0.02/5 | −0.08-0.12 |
| March | 361 | 303 | −58/−16 | −139-22 | 0.47 | 0.56 | 0.09/19 | −0.03-0.21 |
| April | 314 | 315 | 1/0 | −76-79 | 0.37 | 0.64 | 0.27/72 | 0.15-0.39 |
| May | 222 | 296 | 74/33 | 4-144 | 0.43 | 0.62 | 0.20/46 | 0.07-0.32 |
| June | 184 | 206 | 22/12 | −2-65 | 0.47 | 0.48 | 0.01/3 | −0.10-0.12 |
| July | 195 | 156 | −39/−20 | −93-14 | 0.68 | 0.62 | −0.05/−8 | −0.21-0.16 |
| August | 201 | 150 | −51/−26 | −118-15 | 0.97 | 0.39 | −0.58/−60 | −0.75--0.41 |
| September | 164 | 150 | −17/−10 | −71-37 | 0.90 | 0.49 | −0.41/−45 | −0.57--0.24 |
| Group averages[c] | | | 15% | | | | 28% | |
| **Group 2: Magnitude and duration of annual extremes** | | | | | | | | |
| 1-day minimum | 45 | 28 | −17/−37 | −23--11 | 0.39 | 0.20 | −0.20/−50 | −0.27--0.13 |
| 3-day minimum | 48 | 40 | −8/−16 | −15-0 | 0.39 | 0.28 | −0.11/−28 | −0.19--0.03 |
| 7-day minimum | 51 | 55 | 4/7 | −4-12 | 0.39 | 0.29 | −0.10/−24 | −0.17--0.01 |
| 30-day minimum | 68 | 81 | 13/19 | 1-24 | 0.34 | 0.31 | −0.03/−8 | −0.11-0.05 |
| 90-day minimum | 116 | 125 | 9/7 | −11-28 | 0.40 | 0.30 | −0.10/−25 | −0.18--0.02 |
| 1-day maximum | 2209 | 602 | −1607/−73 | −1958--1256 | 0.47 | 0.30 | −0.17/−36 | 0.26--0.08 |
| 3-day maximum | 1924 | 581 | −1343/−70 | −1650--1038 | 0.47 | 0.32 | −0.15/−32 | −0.25--0.06 |
| 7-day maximum | 1338 | 552 | −786/−59 | −1002--572 | 0.46 | 0.36 | 0.10/−22 | −0.20-0.00 |
| 30-day maximum | 633 | 477 | −156/−25 | −250--63 | 0.30 | 0.44 | 0.14/47 | 0.05-0.23 |
| 90-day maximum | 423 | 363 | −60/−14 | −121-79 | 0.25 | 0.42 | 0.17/70 | 0.09-0.25 |
| Group averages[c] | | | 21% | | | | 34% | |
| **Group 3: Timing of annual extremes** | | | | | | | | |
| Julian date of annual minimum | 264.0 | 360.7 | 96.7/37 | 75.7-117.6 | 0.17 | 0.12 | −0.05/−29 | −0.08--0.02 |
| Julian date of annual maximum | 71.9 | 137.8 | 65.9/92 | 17.7-114.1 | 0.72 | 0.70 | −0.78/−53 | −1.05--0.51 |
| Group averages[c] | | | 65% | | | | 41% | |
| **Group 4: Frequency and duration of high and low pulses** | | | | | | | | |
| Low pulse count | 11.0 | 36.4 | 25.5/232 | 21.4-29.4 | 0.43 | 0.29 | −0.13/−31 | −0.22--0.05 |
| High pulse count | 15.6 | 22.7 | 7.1/45 | 4.1-10.1 | 0.28 | 0.34 | 0.06/23 | −0.01-0.14 |
| Low pulse duration | 7.4 | 3.2 | −4.2/−57 | −5.5--3.0 | 0.48 | 0.36 | −0.12/−25 | −0.22--0.02 |
| High pulse duration | 6.0 | 4.9 | −1.1/−18 | −2.3-0.1 | 0.41 | 0.51 | 0.10/24 | −0.01-0.21 |
| Group averages[c] | | | 88% | | | | 26% | |
| **Group 5: Rate and frequency of change in conditions** | | | | | | | | |
| Fall rate | −55.1 | −59.6 | −4.5/8 | −11-2 | −0.27 | −0.21 | 0.06/−21 | 0.00-0.11 |
| Rise rate | 90.0 | 60.2 | −29.8/−33 | −39--20 | 0.29 | 0.18 | −0.11/−38 | −0.17--0.05 |
| Fall count | 67.7 | 90.9 | 23.2/34 | 19.8-26.6 | 0.11 | 0.88 | −0.03/−30 | −0.06--0.01 |
| Rise count | 60.9 | 91.6 | 30.7/50 | 27.0-34.4 | 0.14 | 0.07 | −0.07/−50 | −0.10--0.05 |
| Group averages[c] | | | 31% | | | | 35% | |

[a] Daily mean streamflows in cubic meters per second.
[b] The deviations represent the Indicators of Hydrologic Alteration.
[c] Group averages are computed as the mean of all deviations (in absolute values) within the group.

of hydroelectric power at Roanoke Rapids Lake. An obvious impact of flood control operations on the Roanoke is the virtual elimination of high-magnitude flooding. (Fig. 4). Floods in excess of 8500 cms (~ 30,000 cubic feet per second) occurred in only five of the post-dam years, whereas floods greater than this size occurred in

every pre-dam year. Multi-day maxima are likewise affected by the flood-control operations (Table 2).

The pulsing behavior of the Roanoke River has been severely affected because both high and especially low pulses (Fig. 5) now occur with substantially greater frequency. The average duration of pulses, on the other

hand, is much shorter in the post-dam period. This is a byproduct of hydropower generation, wherein water is stored in the reservoir until sufficient head is attained to generate power efficiently, at which time it is rapidly released through the dam turbines. The effect on the hydrologic regime is to create a greater frequency of high and low pulses of lesser duration (Group 4: frequency and duration of high and low pulses) and also to increase the number of hydrograph rises and falls (Group 5: rate and frequency of change in water conditions).

The magnitude and timing of the annual minima have changed, with a shift from higher fall season to lower mid-winter annual lows (Fig. 6). This probably results from attempts to capture winter flows for later spring and summer use in hydropower generation.

Surprisingly, the average hydrograph rise rate (Group 5: rate and frequency of change, Fig. 7) for the Roanoke is reduced from the pre-dam period. Typically, areas downstream of hydropower dams experience steeper hydrograph rises because of the rapid release of water from the reservoir during peaking power generation. The apparent reduction in rise rates on the Roanoke is probably due to the fact that flow releases seldom exceed 566 cms (20,000 cfs), which corresponds to turbine capacity limits. In the pre-dam period, flows commonly rose more than 1132 cms (40,000 cfs) in a single day during rainstorms.

Changes in the variability of the 32 IHA parameters are also evident (Table 2; Figs. 4-7). In general, variability has been reduced in summer and winter monthly means, in extremely low water conditions, in timing of the annual highs and lows, in high and low pulse durations, and in frequency and rate of hydrograph rises and falls. On the other hand, coefficients of variation increased for springtime monthly means and long duration (e.g., 30- and 90-day), high flow magnitudes.

Dam-related alterations to the Roanoke flow regime have been blamed for the drastic reduction of striped bass populations (Zincone & Rulifson 1991). Higher average streamflows in the spring months (May-June) have been associated with less successful rates of juvenile bass recruitment. Aquatic invertebrates inhabiting the littoral zone along the river's edge may be severely affected by the greater frequency of hydrograph pulses, rises, and falls. Rapidly reversing cycles of wetting and drying have been shown to decimate littoral-zone benthic fauna unable to migrate with the shifting river edge (Armitage 1984; Walker et al. 1992; Moog 1993). Such losses of benthic fauna may be substantially reducing the availability of prey for the Roanoke's fishes.

Altered flood patterns may lead to significant alterations in the composition and structure of the Roanoke's bottomland hardwood forest by changing the magnitude and duration of floods (Lea 1991; Richter 1993). This forest has been heralded as being the "highest quality and most extensive" bottomland hardwood forest on the

southeastern coastal plain (Lynch 1991). The different plant species and floodplain forest communities along the Roanoke are thought to be distributed along a gradient of inundation duration (or anoxic stress). With the elimination of high-magnitude flooding, higher floodplain surfaces are now seldom if ever inundated, enabling less flood tolerant species to become established on lower sites, and thus lowering overall vegetation diversity. Changes in the forest could also have serious implications for Neotropical migratory birds using this area (Zeller 1993).

## Using the IHA Method

During development of the IHA method, a longer list of statistical parameters was consolidated to minimize the number of computations and to reduce redundancy; at the same time we retained as much sensitivity to different forms of hydrologic alteration as possible. The 32 IHA parameters appear to be robust in their ability to quantitatively describe alterations peculiar to specific human influences such as flood control. We also considered aggregating the results across each of the five groups of hydrologic characteristics. Users must bear in mind, however, the risk of losing information when relative differences are averaged across parameters within IHA groups (Suter 1993). We strongly recommend that IHA results be presented in the full scorecard format as shown in Table 2 to retain information about the specific hydrologic alterations associated with the perturbation under investigation. Reporting the full suite of hydrologic parameters also enables investigators to explore relationships between individual parameters and biotic responses.

This caution about lumping hydrologic parameters into IHA groups and averaging results within groups should not inhibit exploration of the relationship between overall group averages and specific types of human influences such as reservoir operations, groundwater pumping, timber harvest, or urbanization. Such integrative analysis is urgently needed to enable ecosystem managers to better assess or anticipate the effects of certain land and water uses. The sensitivity and robustness of individual IHA parameters and IHA groups to a wide range of human influences in different ecoregional settings remains to be tested.

The U.S. Clean Water Act Amendments of 1972 (PL 92-500) called for the restoration and maintenance of the "chemical, physical, and biological integrity of the nation's waters." Increased use of analytical methods such as the IHA will demonstrate how far we have to go toward restoring the physical integrity of U.S. rivers, lakes, and aquifers. We anticipate that the IHA method will be used in conjunction with other ecosystem metrics that evaluate more directly the biological conditions and ecological degradation within an ecosystem, such as

the Index of Biotic Integrity (Karr 1991, 1993). Other authors (Karr 1991, 1993; Keddy et al. 1993; Minshall 1993) have emphasized the importance of using a multi-parameter suite of metrics to assess ecosystem integrity because it is unlikely that any one metric will be sufficiently sensitive to be useful under all circumstances.

As illustrated by our case study, the IHA method is extremely useful in drawing attention to aspects of a hydrologic regime altered by various types of human influences such as dams and ground water pumping. Elucidation of hydrologic alterations alone, however, says little about the nature or degree to which biologic patterns and processes may degrade in response to such alterations. The tough work of interpreting and documenting species- or community-specific responses to hydrologic changes remains. By revealing the direction and magnitude of hydrologic alterations, the IHA method will aid ecological researchers in formulating hypotheses about the hydrologic causes of various forms of ecosystem modification. For example, the IHA results for the Roanoke River direct our attention to assessing the effects of dam operations on fish populations, littoral-zone benthic fauna, and floodplain forest communities.

The IHA method should also prove useful in the design of ecological restoration programs. On the Roanoke River, for example, dam-altered flow regimes have been implicated in various forms of ecosystem degradation. Based on the IHA results (Table 2), restoration hypotheses should be directed at the expected biotic responses to increased frequencies of high-magnitude flooding, reductions in the frequency of high and low pulses, reductions in the frequency of hydrograph reversals between rising and falling river periods, and shifts in the annual minimum flows from winter back to the fall season. Programs to monitor the response to hydrologic restoration could follow two strategies: (1) continue to characterize the hydrologic regime using the IHA method, in order to look for expected decreases in the before and after deviations in IHA groups, and (2) directly monitor the status of the targeted biota. Both the hydrologic restoration strategy and the biomonitoring program could be continually refined as we learn about the system.

The utility of the IHA method for designing hydrologic restoration strategies or for assessing potential hydrologic effects associated with various water development proposals will be limited unless hydrologic simulation models can be used to create synthesized records of daily streamflow or water table fluctuations under future climate or development scenarios. If potential hydrologic conditions can be simulated using such models, these conditions could then be compared with existing conditions (actual hydrologic measurements or simulation of current conditions) by means of the IHA method. Management decisions could then be based upon the IHA's elucidation of hydrologic regime changes likely to be associated with alternative management scenarios.

## Software Availability and Acknowledgments

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