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GEOTOOLS: A TOOLKIT FOR FLUVIAL SYSTEM ANALYSIS[1]

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ABSTRACT: Detailed mechanistic modeling of hydrogeomorphic processes in fluvial systems is extremely challenging, expensive, and of limited usefulness without explicit knowledge of prediction uncertainty. Accordingly, there is a need for parsimonious tools that support probabilistic scientific assessments of physical-biological linkages in streams and rivers. This paper introduces GeoTools, a suite of analysis tools for fluvial systems written in Visual Basic for Applications⁄Excel. Based on flow time series and basic geomorphic data, GeoTools automates computation of numerous hydrologic, hydraulic, and geomorphic descriptors including effective discharge, sediment transport and yield, temporal distributions of hydraulic parameters (e.g., shear stress and specific stream power), cumulative erosion potential, channel stability indices, and over 100 flow regime metrics. GeoTools accepts input flow records in standard USGS format and a variety of other formats and temporal densities. The package also serves as a post-processor for SWMM, and HSPF⁄BASINS model output. Three case studies illustrate specific applications of GeoTools: a channel restoration project, a stormwater management⁄hydromodification study, and an analysis of the effects of flow regulation below an impoundment dam.

(KEY TERMS: decision support systems; planning; environmental indicators; fluvial processes; urbanization; sediment transport; geomorphology; restoration.)

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INTRODUCTION

A growing emphasis on holistic management of fluvial systems has underscored the need for greater understanding of hydrogeomorphic-ecological linkages and risk-based tools that support management and decision-making (Jacobson *et al.*, 2001; National Research Council, 2001; Benda *et al.*, 2002; Montgomery and Bolton, 2003). Stream and river restoration expenditures are estimated to exceed US$1 billion annually in the United States, despite weak scientific underpinnings and the frequent lack of rigorous quantitative analysis in assessment and design (Bernhardt *et al.*, 2005; Palmer *et al.*, 2005; Wohl *et al.*, 2005). Detailed mechanistic modeling of hydrogeomorphic-ecological linkages in fluvial systems is extremely challenging, expensive, and of limited usefulness in management without explicit knowledge of prediction uncertainty (Wilcock *et al.*, 2003). Hence, there is a need for parsimonious tools that support scientific assessments based on

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probabilistic modeling (Shreve, 1975; Reckhow, 1999; Dunne *et al.*, 2001; Graf, 2001).

This article presents GeoTools, a new shareware package written in Visual Basic for Applications/Excel® that contains a suite of tools to streamline computation of many metrics and descriptors used in probabilistic modeling and assessment of hydrogeomorphic-ecological linkages in fluvial systems. GeoTools is designed to support management and research in many contexts including watershed analysis, fluvial audits (Thorne, 2002), stream restoration, management of land use change, urban stormwater and hydromodification issues, and flow regulation/reservoir operation. The following section provides a brief review of background concepts and previous work that guided the design and content of the GeoTools package.

BACKGROUND

Alluvial channels form in response to temporal sequences of flow and sediment supply. Interactions between flow regime and geomorphic processes control channel erosion and sedimentation, disturbance regime, and the structure, volume, and the availability of physical habitat when mediating biotic interactions (Jacobson *et al.*, 2001). Flow regime is often used as a surrogate for hydrologic-geomorphic interactions and may be characterized in terms of five key elements: magnitude, frequency, duration, timing, and rate of change (Poff *et al.*, 1997; Bunn and Arthington, 2002; Whiting, 2002). Scores of hydrologic metrics describing these aspects of flow regimes have been published over the last few decades (Olden and Poff, 2003). Although hydrologic metrics are not explicitly coupled with descriptions of geomorphic context, associations between hydrologic metrics and geomorphic and/or biotic responses in fluvial systems nonetheless have much practical utility in research and management. For example, researchers have demonstrated that ratios of post- to pre-development peak flow magnitudes can be used to discriminate between stable and unstable channel forms (Booth and Reinelt, 1993) and predict Benthic Index of Biotic Integrity scores (Booth *et al.*, 2004) in urbanizing watersheds of the Pacific Northwest. Hydrologic metrics have also been shown to be associated with the distribution of fishes at various spatial scales (Poff and Allan, 1995; Marchetti and Moyle, 2001; Roy *et al.*, 2005), riparian vegetation (Mahoney and Rood, 1998; Nilsson and Svedmark, 2002; Lytle and Merritt, 2004), and benthic macroinvertebrate indices (Rader and Belish, 1999; Kennen and Ayers, 2002; Holburn, 2005).

Because changes in physical habitat characteristics reflect the temporal sequence and combined action of water *and* sediment flows, interpretations of fluvial system behavior that do not include consideration of both hydrologic and sedimentation regimes are incomplete and may produce erroneous conclusions (Lane, 1955; Wilcock, 1997). For several decades, geomorphologists and engineers have recognized the value of coupling continuous flow series with sediment transport relationships to quantify the combined effects of flow and sediment regime using Magnitude-Frequency Analysis (MFA; Wolman and Miller, 1960). In this approach, the estimated geomorphic "effectiveness" (i.e., long-term sediment transport) of different flow levels is multiplied by the likelihood of occurrence (Pickup and Warner, 1976; Andrews, 1980). In practical applications of MFA, discharge values are typically arranged into a specified number of discrete classes, referred to henceforth as "bins." The number of observations in each bin represents a flow frequency relative to the total number of flows recorded. The product of the transport capacity of a representative flow from each bin and its flow frequency produces an estimate of how much sediment is transported by each bin. This procedure results in a series of discrete product values that form an effectiveness curve, with the effective discharge (Q_{eff}) being the flow corresponding to the maximum. The area under the effectiveness curve estimates the time-integrated sediment load transported through the channel. Effective discharge can also be estimated analytically by combining a theoretical statistical distribution of flows with a sediment transport relationship (Nash, 1994; Goodwin, 2004). However, Orndorff and Whiting (1999) and Soar and Thorne (2001) do not recommend such an approach, citing among other issues the bi- or polymodal empirical flow distributions sometimes encountered in practice.

Magnitude-Frequency Analysis is a fundamental tool for researchers and managers in several aspects of fluvial system assessment, despite ongoing debates regarding methodological details and definitions of effectiveness (Soar and Thorne, 2001). For example, effective discharge and MFA can be used to quantify channel maintenance flows (Andrews and Nankervis, 1995; Whiting, 2002; Schmidt and Potyondy, 2004), assess pre- *vs.* post-watershed disturbance conditions (MacRae and Rowney, 1992; Bledsoe, 2002a), evaluate flow regulation schemes (Van Steeter and Pitlick, 1998a,b; Richter and Richter, 2000), and support stream restoration design (Soar and Thorne, 2001; Shields *et al.*, 2003).

Human influences such as diversions and impoundment reservoirs can accelerate channel adjustment by changing flow patterns and sedimentation processes. By identifying the range of flows responsible for channel maintenance through MFA and other techniques, flow managers can develop management strategies that balance conservation of ecosystem functions and services related to physical habitat, riparian processes, flood conveyance, recreation and so on with consumptive demands. For example, Andrews and Nankervis (1995) reported that it was possible to largely maintain the long-term bedload transport characteristics of snowmelt-driven gravel-bed channels using 35% of the annual water volume.

Land use change, especially urbanization, has profound impacts on the runoff characteristics of land that it affects and consequently on the aquatic environments of the streams to which that runoff drains (Hollis, 1975; Konrad and Booth, in press). Stream instability resulting from land use change frequently leads to increased erosion potential, accelerated geomorphic activity, and to channel forms that are less heterogeneous and geomorphically complex (Booth and Jackson, 1997; Henshaw and Booth, 2000; Bledsoe and Watson, 2001a; Jacobson *et al.*, 2001). Several studies have reported channel enlargement and/or habitat simplification or homogenization in response to the increased erosive power of flow alterations in urbanizing watersheds (Hammer, 1972; Morisawa and LaFlure, 1979; Roberts, 1989; MacRae, 1997; Brown, 1999; Doll *et al.*, 2000; Pizzuto *et al.*, 2000). Reported changes in reach scale physical habitat include cross sections that are more rectangular and prismatic, straighter channels, reduced pool volume, reduced form roughness, and more runs with fewer pools and riffles (Bledsoe, 2002a).

A common strategy aimed at mitigating the effects of urbanization with regard to flooding and receiving water impacts is construction of retention basins that reduce peak discharges (Roesner *et al.*, 2001). An increasingly recognized shortcoming of this approach is the consequent magnification of erosive forces acting on erodible boundaries of receiving streams (McCuen and Moglen, 1988; MacRae, 1997). As peak flows are "shaved," the frequency and/or duration of moderate flow levels (e.g., one-half to three-fourths bankfull discharge) increases significantly, which can substantially increase cumulative sediment transport capacity, particularly in live bed streams. These effects, which are often combined with a long-term decrease in sediment supply, lead to incision and/or widening as channels adjust to the altered flow regimes (Booth, 1990). Researchers and practitioners have more recently argued that geomorphologically based design of stormwater controls based on MFA could protect stream systems from accelerated erosion because of hydromodification (MacRae, 1997; Roesner *et al.*, 2001; Bledsoe, 2002a,b; Palhegyi and Bicknell, 2004).

Magnitude-Frequency Analysis is also an important tool in channel restoration projects, especially in identifying a "dominant" discharge for design. While effective discharge computations are not a substitute for field reconnaissance, field assessment of bankfull indicators only provides current (pre-restoration and probably non-equilibrium) information about the channel state and involves a high degree of subjectivity (Williams, 1978; Wilcock, 1997). Moreover, calculating a specific return period event (e.g., 1.5-year flood) as a surrogate for dominant discharge does not incorporate reach-specific characteristics such as floodplain connectivity or boundary materials. Calculating Q_{eff} provides designers with additional information that may be particularly useful in disturbed systems where field indicators of an equilibrium form are lacking. Moreover, stream restoration projects may be more rigorously assessed in terms of the congruency of time-integrated sediment transport capacity among restoration reaches with different morphologies by evaluating single event designs with MFA. Soar and Thorne (2001) define a capacity-supply ratio (CSR) based on MFA to address the issue that contiguous but different channel forms frequently encountered in stream restoration design (e.g., supply reach *vs.* design reach) may maintain sediment and water continuity at a specific design discharge, but not across the full range of geomorphically relevant flow events. By using MFA to examine the CSR based on time-integrated sediment transport capacity, the stability of restoration projects spanning different channel forms may be rapidly evaluated across the entire post-restoration flow regime.

Finally, metrics that act as surrogates for hydrogeomorphic processes by combining information on both flow and geomorphic context have proven useful in a variety of other applications. Several researchers have linked thresholds of specific stream power or shear stress with channel stability (Brookes, 1988; Booth, 1990; Bledsoe and Watson, 2001a). Simple metrics that include measures of both flow energy and boundary erodibility have been linked to channel planform prediction (van den Berg, 1995; Bledsoe and Watson, 2001b). Shear stress based metrics have also been used in simple statistical models to predict scour/fill depths and the prevalence of unstable bed patches in gravel bed rivers (Haschenburger, 1999; Bigelow, 2005), as well as benthic macroinvertebrate community composition in streams with different disturbance regimes (Townsend *et al.*, 1997; Townsend and Riley, 1999; Brandt, 2000).

THE GEOTOOLS SUITE OF TOOLS

Tools that automate computation of hydrologic and geomorphic metrics from several common sources of input data enable scientists, engineers, and environmental managers efficiently develop models for assessment and decision-making. Accordingly, there is a growing body of license-free fluvial analysis software. Comprehensive packages, such as those produced by the US Army Corps of Engineers Hydrologic Engineering Center (e.g., HEC-RAS, HEC-6) can provide detailed 1-D modeling of large and complex fluvial systems. Such tools are widely used in industry and research, but also require a relatively high level of expertise and significant amounts of input data and parameterization. The Australian Commonwealth Scientific and Industrial Research Organization maintains the Catchment Modeling Toolkit (CMT), a user-friendly package of modeling tools for hydrologic and fluvial systems analysis. CMT users choose only the tools necessary for the specific analyses desired. The independence of the modular programs in the CMT provides a structure that allows for ongoing and efficient distribution of new functionality as it is developed.

The GeoTools package presented in this paper has a modular design similar to the CMT, but provides analysis features not yet available from existing fluvial software packages. Specifically, this package combines functions for effective discharge calculations, sediment transport analyses, characterizing bed disturbance regimes, and over 100 hydrologic metrics in a flexible spreadsheet-based format. Earlier versions took advantage of the rapid application development power inherent in Microsoft Excel to provide a user friendly tool that supports the preliminary assessment of fluvial processes and mitigation of hydromodification impacts in urbanizing watersheds. The package has been subsequently expanded to facilitate many other types of analyses commonly encountered in managing fluvial systems. Based on input channel geometry and continuous flow series data, the modular suite of programs in GeoTools provides users with outputs including: (1) temporal distributions of hydraulic parameters including shear stress, specific stream power and potential mobility of various particle sizes; (2) effective discharge and sediment yield based on a wide range of user-defined analysis options; (3) comparisons of changes in hydraulics, effective discharge sediment transport and yield as a result of altered flow regimes; (4) metrics related to channel form and potential biotic responses; (5) statistics on scour depth and numbers of flow events exceeding a critical shear stress criterion; and (6) over 100 hydrologic metrics.

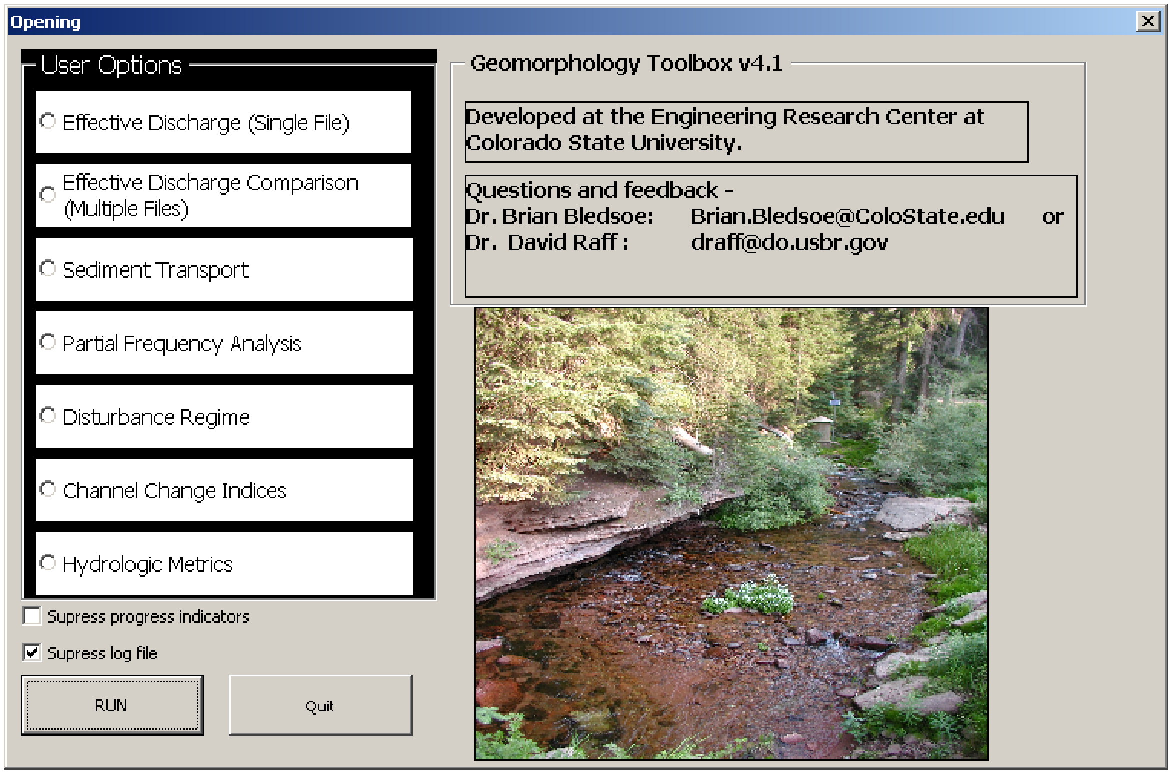
GeoTools is available for immediate download at http://www.engr.colostate.edu/~bbledsoe/GeoTool/. GeoTools has been tested in various stages to a reasonable level. Results from the various modules have been verified with hand calculations, output from independent software programs, and examples from peer-reviewed publications [e.g., Julien (1995); Yang (1995); Soar and Thorne (2001)]. The following section describes key features of the model but is not intended to be a comprehensive orientation. However, a user's manual detailing operational instructions and steps necessary to ensure proper functioning on most PC computers running Microsoft's Excel is bundled with the application. GeoTools has undergone basic beta testing on a range of different computer types and configurations. Compatibility problems will be further addressed in future versions.

FUNCTIONAL MODULES

GeoTools (Figure 1) has six modules that are available from the main menu: (1) an effective discharge calculator that can operate on one file or compare effects across multiple files; (2) a partial duration frequency analysis tool for producing flood frequencies of short return periods; (3) a stand alone sediment transport calculator that makes available several common transport equations; (4) a disturbance regime module for providing bed mobility statistics based on a flow record; (5) an option for calculating a list of metrics related to geomorphic processes and channel form; and (6) a module for generating over 100 hydrologic metrics that have been previously reported by Richter *et al.* (1996), Olden and Poff (2003), and Konrad *et al.* (2005). The modules will accept flow records in seven different file formats including common U.S. Geological Survey (USGS) records, U.S. Environmental Protection Agency's (USEPA) Storm Water Management Model (SWMM) and Hydrological Simulation Program – Fortran (HSPF) as well as user-defined input formats. The following is a summary discussion of selected important features of the GeoTools modules.

Effective Discharge

GeoTools has been designed with a great deal of flexibility to accommodate a range of user specifications. The effective discharge functionality is particularly robust in this regard (Figure 2). The user is also given full control over the binning process in computing Q_{eff}. Bins can be distributed either arith-



☐ Supress progress indicators

☑ Supress log file

Geomorphology Toolbox v4.1

Developed at the Engineering Research Center at Colorado State University.

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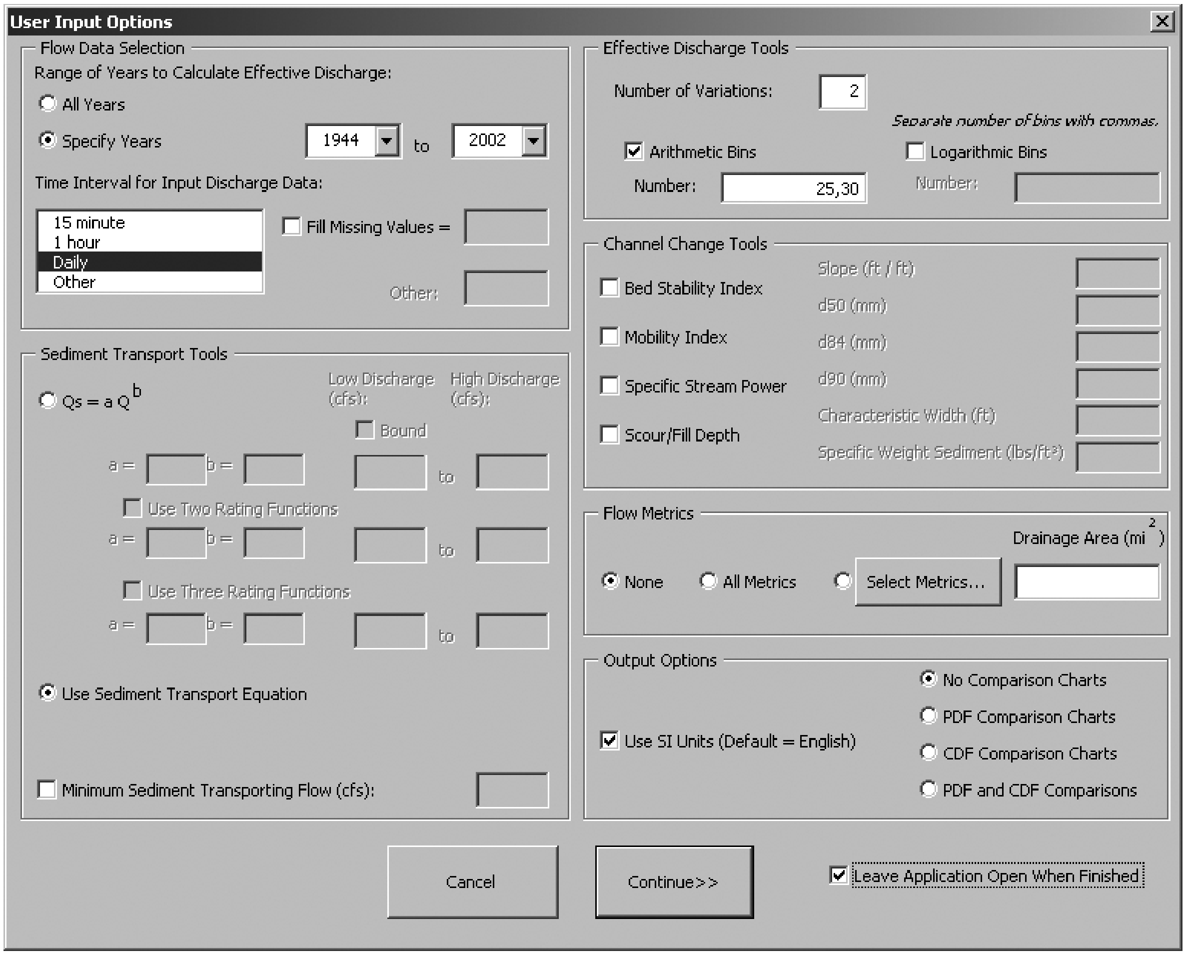
FIGURE 1. GeoTools Main Menu.

metically or logarithmically. The representative discharge value for each bin is the mean value (arithmetic or geometric depending on bin type) of the bounds of the range of flows contained in the bin. The total number of bins determines this range and therefore the value of the discharge assigned to each. In general, the number and type of bins substantially affects resulting estimates of effective discharge and great care should be taken when making these choices (Soar and Thorne, 2001). GeoTools allows the user to specify 20 simultaneous bin scenarios, providing an efficient method of examining the sensitivity of the Q_{eff} estimate to alternative methodological approaches.

Hydraulic parameterization is accomplished with user-defined at-a-station hydraulic geometry relationships, including multi-stage hydraulic geometry power functions. This functionality allows the user to account for the observed thresholds in morphology, particularly overbank conditions. GeoTools outputs both cumulative distribution functions (CDFs) and probability distribution functions (PDFs) comparing discharge, sediment transport, shear stress and stream power for all input flow files. Two general options are provided for estimating sediment transport: rating curve or transport equation. GeoTools has several common equations built in representing a spectrum of uses, with more to be implemented in future releases. The currently available equations are Brownlie (1981) Total Load, Bagnold (1966) Total Load, Meyer-Peter and Müller (1948), Yang (1996) Sand d_{50} Total Load and Wilcock and Kenworthy (2002) two-phase bedload transport relationship. When a transport equation is utilized, the user is prompted for the appropriate channel properties information, such as slope, grain size and width. If the user wishes, a critical discharge may be entered such that all flows below which will be assigned a sediment discharge of zero. This feature is useful in eliminating the effects of low flows that may not be well represented by the selected equation.

A second option for estimating transport is to specify a sediment rating curve. GeoTools accepts up to three staged rating curves for flows of increasing magnitude. The same critical discharge functionality is available with this option, reducing the error commonly associated with such curves at low discharges. By specifying the range of flows under which each relationship is valid, the calculations can more accurately reflect supply limited or other observed transport behavior. GeoTools includes an option to exclude flows below a user-specified threshold.



User Input Options

Flow Data Selection

Range of Years to Calculate Effective Discharge:

○ All Years

● Specify Years 1944 to 2002

Time Interval for Input Discharge Data:

15 minute
1 hour
Daily
Other

☐ Fill Missing Values =

Other:

Sediment Transport Tools

○ $Qs = a Q^b$

Low Discharge (cfs): High Discharge (cfs):

☐ Bound

a = b = to

☐ Use Two Rating Functions

a = b = to

☐ Use Three Rating Functions

a = b = to

● Use Sediment Transport Equation

☐ Minimum Sediment Transporting Flow (cfs):

Effective Discharge Tools

Number of Variations: 2

Separate number of bins with commas.

☑ Arithmetic Bins

Number: 25,30

☐ Logarithmic Bins

Number:

Channel Change Tools

☐ Bed Stability Index
☐ Mobility Index
☐ Specific Stream Power
☐ Scour/Fill Depth

Slope (ft / ft)
d50 (mm)
d84 (mm)
d90 (mm)
Characteristic Width (ft)
Specific Weight Sediment (lbs/ft³)

Flow Metrics

● None ○ All Metrics ○ Select Metrics...

Drainage Area (mi^2)

Output Options

☑ Use SI Units (Default = English)

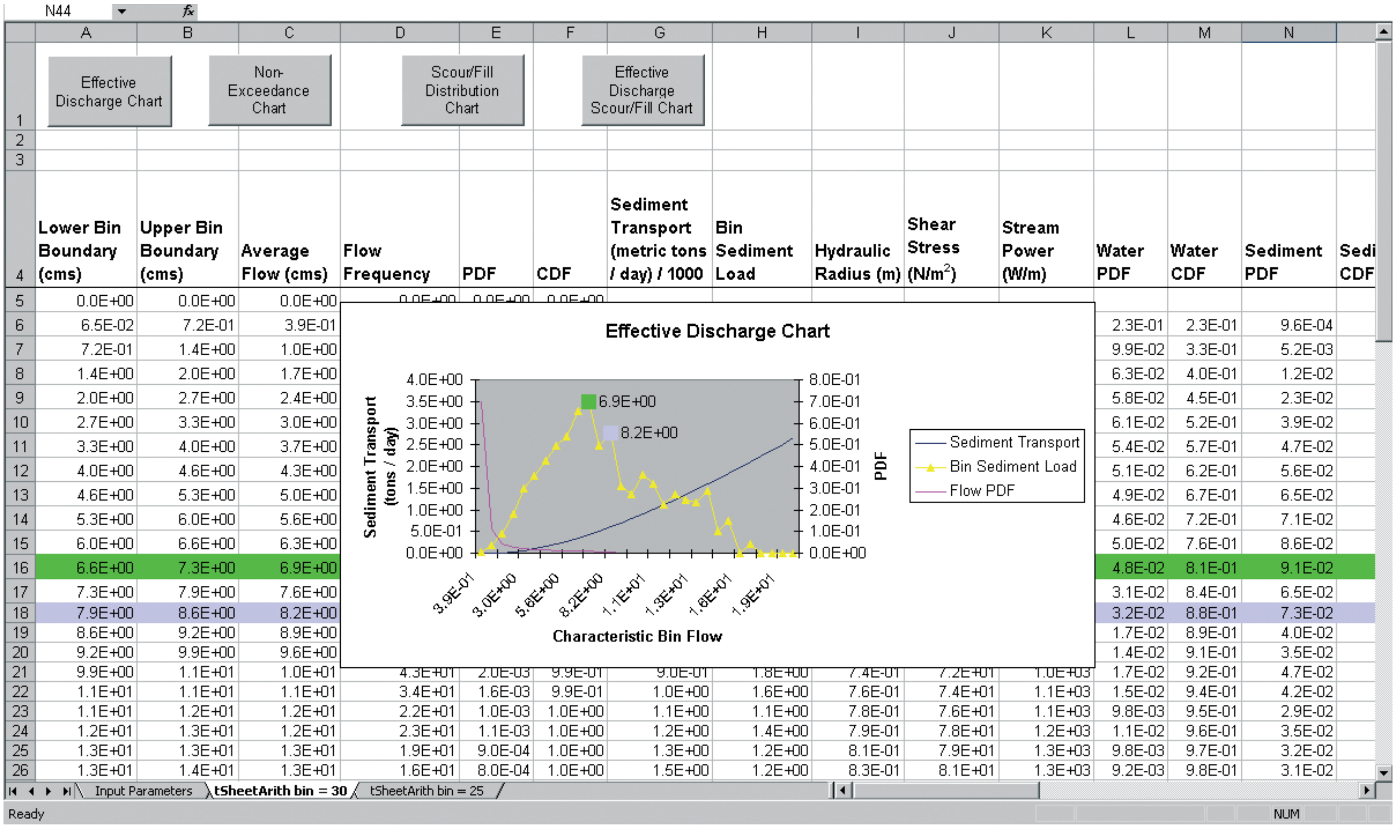
● No Comparison Charts
○ PDF Comparison Charts
○ CDF Comparison Charts
○ PDF and CDF Comparisons

☑ Leave Application Open When Finished

FIGURE 2. Effective Discharge Inputs Form.

Additional features have been designed to increase the usability of the modules. The user can identify whether the entire flow record or a subset period will be analyzed, eliminating the need to parse the individual flow records. GeoTools can accept a default baseflow to be used to fill incomplete data records, reducing the need to inspect large data files before use and increasing the accuracy of probability and cumulative distribution functions. The single file effective discharge tool output worksheet is laid out to maximize the readability of results. All bin information is displayed with respect to timing and magnitude of shear stress, sediment and flow characteristics, as well as a graphical representation of the effectiveness curve (Figure 3). The file contains a single tab for each bin variation run as well as a summary of the input parameters for reference. The tool highlights the flow corresponding to the primary peak of the effective work function as well as the secondary peak.

GeoTools has two modes for producing effective discharge information: single and comparison file modes. Single File mode is employed if the user would like to analyze a single flow record. The output includes effective discharge calculations, a distribution of shear stress and stream power (total and specific) and a series of flow regime statistics described below. Channel maintenance flows can be studied with the CDFs for water, sediment and time (Emmett, 1999). With the graphical display created by GeoTools, users can easily see what ranges of flow and fractions of water volume move different proportions of the long-term sediment load and the proportion of time such flows occur. The user may also choose to calculate disturbance regime statistics describing bed stability and scour as described below. Comparison mode permits direct comparison of these same factors among multiple flow files, or different time periods of the same file. The program and calculations are the same as a single-flow record, but users can specify additional output not available when using Single File mode. GeoTools will generate comparison sheets for probability and cumulative distribution functions for water, sediment, stream power, and shear stress distributions if the user chooses these options. There



4	Lower Bin Boundary (cms)	Upper Bin Boundary (cms)	Average Flow (cms)	Flow Frequency	PDF	CDF	Sediment Transport (metric tons / day) / 1000	Bin Sediment Load	Hydraulic Radius (m)	Shear Stress (N/m^2)	Stream Power (W/m)	Water PDF	Water CDF	Sediment PDF	Sedi CDF
5	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00									
6	6.5E-02	7.2E-01	3.9E-01									2.3E-01	2.3E-01	9.6E-04	
7	7.2E-01	1.4E+00	1.0E+00									9.9E-02	3.3E-01	5.2E-03	
8	1.4E+00	2.0E+00	1.7E+00									6.3E-02	4.0E-01	1.2E-02	
9	2.0E+00	2.7E+00	2.4E+00									5.8E-02	4.5E-01	2.3E-02	
10	2.7E+00	3.3E+00	3.0E+00									6.1E-02	5.2E-01	3.9E-02	
11	3.3E+00	4.0E+00	3.7E+00									5.4E-02	5.7E-01	4.7E-02	
12	4.0E+00	4.6E+00	4.3E+00									5.1E-02	6.2E-01	5.6E-02	
13	4.6E+00	5.3E+00	5.0E+00									4.9E-02	6.7E-01	6.5E-02	
14	5.3E+00	6.0E+00	5.6E+00									4.6E-02	7.2E-01	7.1E-02	
15	6.0E+00	6.6E+00	6.3E+00									5.0E-02	7.6E-01	8.6E-02	
16	6.6E+00	7.3E+00	6.9E+00									4.8E-02	8.1E-01	9.1E-02	
17	7.3E+00	7.9E+00	7.6E+00									3.1E-02	8.4E-01	6.5E-02	
18	7.9E+00	8.6E+00	8.2E+00									3.2E-02	8.8E-01	7.3E-02	
19	8.6E+00	9.2E+00	8.9E+00									1.7E-02	8.9E-01	4.0E-02	
20	9.2E+00	9.9E+00	9.6E+00									1.4E-02	9.1E-01	3.5E-02	
21	9.9E+00	1.1E+01	1.0E+01	4.3E+01	2.0E-03	9.9E-01	9.0E-01	1.8E+00	7.4E-01	7.2E+01	1.0E+03	1.7E-02	9.2E-01	4.7E-02	
22	1.1E+01	1.1E+01	1.1E+01	3.4E+01	1.6E-03	9.9E-01	1.0E+00	1.6E+00	7.6E-01	7.4E+01	1.1E+03	1.5E-02	9.4E-01	4.2E-02	
23	1.1E+01	1.2E+01	1.2E+01	2.2E+01	1.0E-03	1.0E+00	1.1E+00	1.1E+00	7.8E-01	7.6E+01	1.1E+03	9.8E-03	9.5E-01	2.9E-02	
24	1.2E+01	1.3E+01	1.2E+01	2.3E+01	1.1E-03	1.0E+00	1.2E+00	1.4E+00	7.9E-01	7.8E+01	1.2E+03	1.1E-02	9.6E-01	3.5E-02	
25	1.3E+01	1.3E+01	1.3E+01	1.9E+01	9.0E-04	1.0E+00	1.3E+00	1.2E+00	8.1E-01	7.9E+01	1.3E+03	9.8E-03	9.7E-01	3.2E-02	
26	1.3E+01	1.4E+01	1.3E+01	1.6E+01	8.0E-04	1.0E+00	1.5E+00	1.2E+00	8.3E-01	8.1E+01	1.3E+03	9.2E-03	9.8E-01	3.1E-02	

FIGURE 3. Effective Discharge Output File.

is also a summary sheet that compares flow characteristics for each time series used.

Partial Duration Frequency Analysis

The common empirical distribution function method of using annual peak flows for calculating flood recurrence intervals cannot be reliably used for frequent events (< 10-year return period) (Langbein, 1949). Theoretically, the partial duration frequency analysis method provides a better estimate of events of recurrence intervals less than 10 years than do the exceedance/non-exceedance probabilities associated with the annual maximum series (Stedinger *et al.*, 1993). To calculate the partial duration frequency, GeoTools allows the user to specify a minimal discharge threshold below which flows are not considered floods, as well as a minimum inter-event duration period between discrete events exceeding the threshold. Specifying an inter-event duration prevents multiple peaks in the same event from being considered as distinct events. Output results are presented in both tabular and graphical forms reporting flow rates and the number of exceedances per year.

Sediment Transport

The sediment transport module provides stand-alone versions of the five sediment relationships available in the effective discharge module. Each stand-alone sediment transport function has a separate and unique interface for inputting the necessary geomorphic and sedimentary characteristics. Results are reported as both concentrations and loads.

Disturbance Regime

GeoTools calculates bed mobility metrics based on an input flow record and user specified sediment and channel characteristics. The output summary provides the flow discharge necessary for incipient motion of the bed material, the number of discrete times and total time the incipient motion criterion is exceeded and the average length of time exceeded for each event. This module also computes scour depth statistics based on an exponential scour and fill model developed by Haschenburger (1999) and tested by Bigelow (2005).

Channel Change Tools

Several metrics related to flow energy and channel stability may be rapidly computed from a flow series and basic hydraulic information in GeoTools. These descriptors include: specific stream power (Bagnold, 1966; Brookes, 1988; Rhoads, 1995):

$$\omega = \frac{\gamma QS}{w} \tag{1}$$

where γ is the specific weight of water, Q is the dominant discharge, S is the slope, and w is the width. The mobility index (Chang, 1988; Bledsoe and Watson, 2001b) is defined as

$$S\sqrt{\frac{Q}{d_{50}}} \tag{2}$$

where d_{50} is the median bed material size of the surface layer; and the bed stability indicator of Olsen *et al.* (1997) is defined as

$$\frac{\tau_{\mathrm{i}}}{\tau_{\mathrm{c_i}}} \tag{3}$$

where τ_{i} is the bankfull shear stress, $\tau_{\mathrm{c_i}}$ is the critical shear stress for motion of d_{84} or other particle size; and time-integrated erosion potential (MacRae, 1991; Bledsoe, 2002a) is defined as

$$E_{\mathrm{P}} = \frac{\sum q_{\mathrm{spost}}\Delta t}{\sum q_{\mathrm{spre}}\Delta t} \tag{4}$$

where q_{s} represents the sediment transport capacity, and t is the time.

The time-integrated erosion potential index when combined with effective discharge/sediment yield analysis is especially useful in examining the effects of all geomorphically important events as opposed to a single estimated flood event (MacRae and Rowney, 1992; MacRae, 1997).

Hydrologic Metrics

The hydrologic metric module incorporates over 100 statistics that characterize the magnitude, frequency, duration, timing, and rate of input flow series. These statistics include several metrics recommended by Olden and Poff (2003), mean annual discharge, 1.5 and 2-year recurrence intervals, discharge exceedance times, a subset of the Indicators of Hydrologic Alteration (Richter *et al.*, 1996), flashiness indices (Sanborn and Bledsoe, 2006), and metrics sensitive to urbanization and disturbance regimes in urban streams (Konrad and Booth, 2002; Konrad *et al.*, 2005). A complete listing of all metrics is provided in the GeoTools user manual.

CASE STUDIES

The following sections illustrate specific applications of GeoTools using three focused case studies: a channel restoration project, a stormwater management/hydromodification study, and an analysis of the effects of flow regulation below an impoundment dam. The case studies were selected to concisely suggest the breadth of potential GeoTools applications and necessarily highlight only a narrow subset of GeoTools full capabilities.

Eagle River – Effective Discharge Analysis Under Altered Conditions

A stream and wetland restoration project design is currently under development for approximately five miles of the Eagle River near Pando, Colorado. The Eagle River was channelized and centered in the Eagle Park valley in 1942 during construction of a military base. Today, the river is incised throughout much of the segment, leaving the channel hydrologically disconnected from the floodplain with generally poor and homogeneous instream habitat. The restoration plan involves reestablishing a meandering channel and reconnecting it to floodplain wetlands. Because upstream diversions and land-use changes have permanently altered the hydrology of the watershed, reproducing the exact historic channel morphology is inappropriate. Furthermore, a USGS report (Webb *et al.*, 2004) indicates that the early 20th Century was an extremely wet period in the Colorado River Basin. Therefore, a new study must be performed to design a stable channel that has is likely to attain dynamic equilibrium under the current climate and flow regime.

The most proximate and representative USGS gage is located four miles downstream of the restoration site near Red Cliff, Colorado. The gage record has daily mean flows from 1911-25, and 1944 to present. A standard field survey conducted in 2004 indicated that the Eagle River upstream of the gage has a local average slope of 0.009 m/m, an at-a-station hydraulic geometry relationship for hydraulic radius (R) of $R = 0.28Q^{0.38}$ where R and Q are in meters and cubic meters per second, respectively, and a median bed particle size of 69 mm (Bledsoe *et al.*, 2005). These data were input to GeoTools and the flow record was divided into two periods for comparative purposes; flows before 1925 were considered the pre-alteration condition, and flows recorded after 1944 when the bulk of diversions were in place represent current conditions. The Wilcock and Kenworthy (2002) bedload relationship was selected to estimate sediment transport.

A generalized comparison of the pre- and post-development effective discharge results is shown in Figure 4. The effectiveness function represents the product of the transport capacity and the probability distribution function. The curves show a general decrease in the effective discharge cumulative sediment transport of the channel from its historical state.

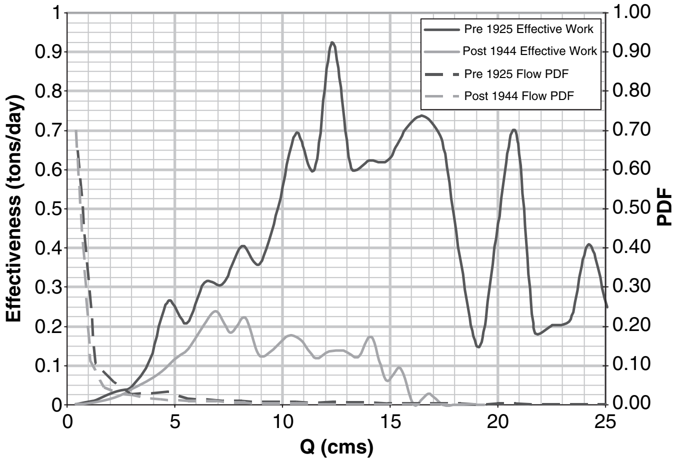


FIGURE 4. Eagle River Pre- and Post-development Effectiveness.

To further evaluate potential design discharges, ranges of input values were entered to test the sensitivity of the results. The site survey was not designed to accurately quantify the sand fraction, a key parameter in the Wilcock-Kenworthy transport relationship. A range of five bin variations (20,25,30,35 and 40 arithmetic bins), three sand sizes (0.5, 1, and 2 mm) and three sand fractions (0%, 5%, and 10%) were rapidly examined with GeoTools. The goal was to test the sensitivity of the resultant Q_{eff} values to the combination of inputs; a subset of these 45 scenarios is presented in Figure 5. The Q_{eff} estimates ranged between 6.5 and 6.9 cms. As can be seen from the chart, for each bin variation, the estimated Q_{eff} was the same regardless of the sand fraction; Q_{eff} only varied as the bin number varied. This implies an insensitivity to the sand parameters. A similar process can be performed with little effort to assess sensitivity to slope, hydraulic radius/discharge and median bed particle size inputs. If sensitivity to particular parameters is revealed, the designer can efficiently focus time and resources on those aspects of the design.

GeoTools facilitates comparisons between computed values of Q_{eff} and design discharge estimates based on other techniques. For example, the flood discharge with a recurrence interval of 1.5 years ($Q_{1.5}$) is sometimes used as a surrogate for bankfull discharge (Emmett and Wolman, 2001; but see Williams, 1987), and is output in all results from GeoTools effective discharge module. GeoTools calculated a $Q_{1.5}$ of 5.9 cms for the post alteration period. Ultimately, both discharge estimates were adjusted for the upstream restoration site using drainage area scaling and will be considered in developing the final design.

Geomorphic Channel Response to Urbanization – Statistical Comparison

GeoTools streamlines comparison of pre- and post-land use change scenarios by simultaneously calculating numerous hydrologic and geomorphic descriptors for long term flow series associated with disparate watershed conditions. After specifying a baseline or pre-alteration flow series, users can add up to four other files representing future scenarios. GeoTools will then present both CDFs and PDFs comparing discharge, sediment transport, shear stress and specific stream power for all of the input flow series. Several standard hydrologic metrics (e.g., 1.5 and 2 year events based on the input time step, mean annual discharge, coefficient of variation for annual maximums) are also calculated and automatically presented in tabular form. This information enhances the ability of planners to evaluate potential geomorphic and biotic responses to different flow management scenarios. To illustrate these features of GeoTools, suburban development of a 22 ha area near Fort Collins, Colorado, was modeled using the Storm Water Management Model (SWMM) (Rohrer *et al.*, 2004) to represent four different stormwater management scenarios and analyzed with GeoTools. The first scenario establishes a baseline and is a minimally developed area of pastureland with 9.6% imperviousness. In the other three scenarios, 45% of the pastureland is converted to medium-density residential land use, which results in 19% total impervious land cover. In the second scenario, the medium-density residential area is drained without any stormwater controls. The third scenario includes stormwater controls that limit the 100-year post-development flow peak to the 2-year pre-development peak, an "over controlled" scheme. The final scenario combines controls that result in no post-development changes in the 100-year and 2-year peaks with an extended detention Best Management Practice (BMP) for water

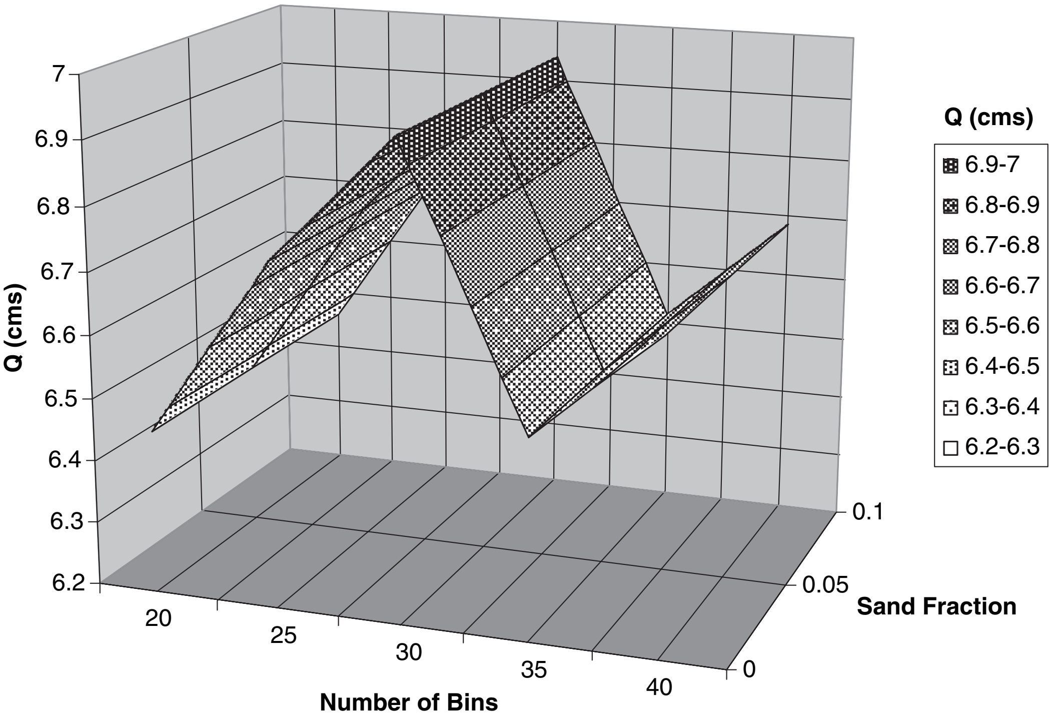


FIGURE 5. Analysis Showing Sensitivity of Q_{eff} to Sand Fraction and Number of Bins for Eagle River.

quality. Fifty years of measured precipitation data were used in SWMM to conduct continuous simulations of discharge through the sand bed outlet channel for each scenario at 15-min intervals. SWMM output formats differ from USGS gage records and in the modeled case resulted in files that were 167 MB each. GeoTools contains conversion programs that post-process SWMM and HSPF files directly without extraneous preparation by the user, providing a seamless transition between applications. In this case, the four resulting SWMM flow records were post-processed and analyzed in the GeoTools effective discharge comparison module using the Yang (1996) total load equation.

A sensitivity analysis, similar to the one described in the previous section, was conducted to determine the most appropriate bin type and number. The advantages and disadvantages of both arithmetically and logarithmically distributed bins have been well described (Thorne *et al.*, 1998; Soar and Thorne, 2001). One issue associated with arithmetic bins is that the first bin containing baseflows is often the most effective for sand bed channels where appreciable sediment transport is occurring at even the lowest flows. After running GeoTools with a range of arithmetic bins it was noted that resulting values of Q_{eff} were in the first (lowest discharge) bin. A second run with differing numbers of logarithmic bins was performed and produced Q_{eff} values that did not vary greatly and a bin number of 25 was chosen as a representative case. A summary of relevant results of running the four scenarios through GeoTools is presented in Table 1.

One statistic in particular that has demonstrated potential as an indicator of channel stability is the erosion potential index (E_{p}) (MacRae and Rowney, 1992; Bledsoe, 2002a). The E_{p} is the ratio of the time-integrated sediment transport capacity of the altered flow regime over the transport of a baseline case. The SWMM modeling results suggest that the cumulative sediment transport capacity of the stream is magnified 46 to 125 percent across the three stormwater management scenarios. Although both mitigation strategies are likely to result in instability, the scenario with 100 and 2-year peak shaving coupled with an extended detention BMP most closely matches the pre-development condition over the full range of erosive flows.

GeoTools facilitates computation of metrics that represent the cumulative erosive energy of flows relative to the resistance of various boundary materials. Such metrics can be used in risk-based modeling to develop criteria for protecting stream stability in urbanizing watersheds. For example, E_{p} values were computed and analyzed for several streams across a gradient of urbanization in study of streams near San Jose, CA (Palhegyi and Bicknell, 2004). Data from this study and E_{p} values were used to develop regionally calibrated logistic regression models of

TABLE 1. SWMM Flow Regime Statistics (25 log bins).

	Scenarios			
	Baseline	**Uncontrolled**	**Over Controlled**	**Peak Shaving + BMP**
$Q_{\text{mean annual}}$ (cms)	0.00302	0.00319	0.00317	0.00317
$Q_{\text{effective}}$ (cms)	0.0190	0.0285	0.0345	0.00877
$Q_{1.5}$ (cms)	0.0612	0.1210	0.0629	0.0530
Q_2 (cms)	0.075	0.1485	0.0756	0.0677
$Q_{1.5}/Q_{\text{ma}}$	20.25	38.00	19.82	16.72
$Q_{1.5}/Q_{\text{e}}$	3.22	4.25	1.82	6.05
Q_2/Q_{ma}	24.84	46.57	23.82	21.35
Q_2/Q_{e}	3.94	5.20	2.19	7.72
Mean discharge exceedance time	0.2860	0.0979	0.0781	0.111
CV annual maximums	1.52	1.34	1.30	1.55
Sediment transport (tons/year)	6.75	15.23	10.94	9.84
Erosion potential index	n/a	2.26	1.62	1.46

channel stability (Menard, 1995; Bledsoe and Watson, 2001b) which successfully discriminate between stable (risk of channel instability equal to zero) and unstable (risk of channel instability equal to one) channels using a single predictor variable (Figure 6). For example, if the E_p for a channel scenario is 3, there is 50% likelihood that the channel will become unstable. These results suggest that the type of output information provided by GeoTools can be linked in a probabilistic sense to the future geomorphic response of streams in urbanizing watersheds.

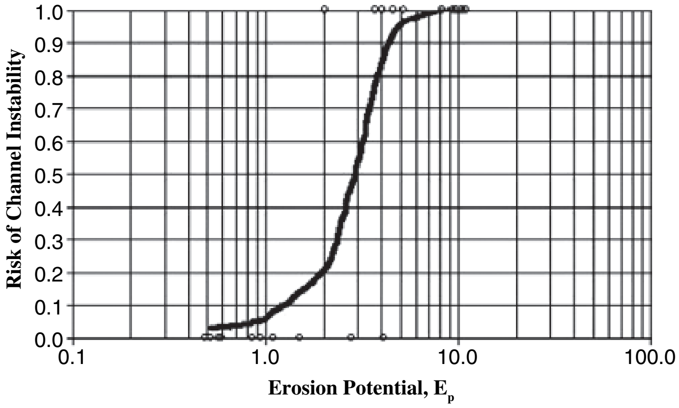


FIGURE 6. Logistic Regression Curve Relating E_p to Risk of Channel Instability (after Palhegyi and Bicknell, 2004).

Flow Regulation and Biotic Response Below Dams

A substantial literature exists on the influence of flow regulation on channel geomorphology (Hammer, 1972; Booth, 1990; Brown, 1999; Brandt, 2000; Whiting, 2002) and instream biota (Statzner and Higler, 1986; Poff and Allan, 1995; Power *et al.*, 1996; Rader and Belish, 1999; Nelson, 2004; Whiting, 2002). In general, studies of flow alteration would benefit from more rigorous quantitative analyses correlating hydrologic changes to geomorphic and biologic responses (Lignon *et al.*, 1995). It is with the goal of promoting this kind of analysis that the hydrologic metrics module was developed in GeoTools. Over 100 metrics are available to the user, representing discharge magnitude, frequency, timing and duration of both high and low flows and rates of change between flow levels. As an example of how such statistical analysis can enhance understanding of biotic responses to flow regulation, the following case study of a biological survey conducted below a dam is presented.

Cle Elum Dam drains 520 km^2 of south central Washington State and is part of the larger Bureau of Reclamation Yakima River Project. The reservoir stores water for release during the summer months, providing irrigation for 23,000 ha of fertile land. USGS gage 12479000 is located at the base of the dam and has 75-year record of daily mean flows. The period 1903-30 represents the pre-alteration flow regime of the Cle Elum River before construction on the permanent dam was begun. The period 1934-78 typifies the below dam flow regime after it became regulated. Operation of the dam has created a shift from a period of spring flooding to one of high summer flows designed to meet irrigation needs.

GeoTools produced an averaged hydrograph of the two periods in the flow record (Figure 7). From this it can be seen that the natural period of approximately 4 months of high flows (April-July) has been replaced with a later period of 5 months in duration (May-September). A subset of calculated flow metrics are reported in Table 2 and represent hydrologic characteristics that have changed most markedly since the construction of the dam. An increase in the amount of time the channel is exposed to higher flows is represented in the metric T_{Qmean} (Konrad and Booth, in press). T_{Qmean} is the

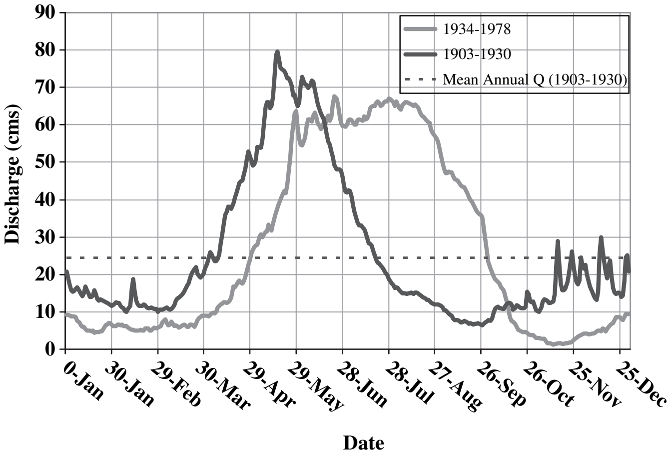


FIGURE 7. Average Daily Discharge Below Cle Elum Dam.

amount of time (represented as a fraction of the flow record) that daily flows are above a mean daily discharge for the entire record. GeoTools results also indicate that for the pre-construction period, the mean daily discharge was 24.3 cms. Of the 9,862 total days, this discharge was exceeded 3,085 times for a T_{Qmean} of 0.31. For the post-construction record of the 16,071 recorded days, 6,768 were above the mean discharge, $T_{\mathrm{Qmean}} = 0.42$. This represents an increase of approximately 1 month per year of exposure to relatively high flows. The next four metrics in Table 2 deal with discharge levels at or below bankfull levels, which, in the absence of surveyed data, is approximated by $Q_{1.5}$. In addition to introducing days where the recorded discharge is zero, the operation of the dam keeps discharges at specific levels longer than given unregulated conditions. In particular, the number of days of discharge at 50% of the computed $Q_{1.5}$ has increased threefold.

Although effective discharge comparisons were precluded by a lack of pre- and post-alteration bed material data, the hydrologic metrics provided by GeoTools allow managers to quantify the effects of the dam on the flow regime and hydraulic habitat of Cle Elum River. Hydrologic metrics can also be used in drawing inferences about the effects of flow regulation on biotic communities below dams. For example, in a study examining aquatic invertebrate taxa richness in this region, Nelson (2004) concluded that the timing and duration of exposure to high flows resulted in significantly lower mean richness levels below Cle Elum dam when compared to unaltered reference reaches. The statistics provided by GeoTools make it possible to further develop this type of analysis by rapidly quantifying the flow characteristics and developing associations between sites across a gradient of flow alteration and observed biotic responses.

SUMMARY AND CONCLUSIONS

The GeoTools package facilitates rapid computation and comparison of the following attributes of multiple continuous flow series:

(1) Over 100 hydrologic metrics describing the magnitude, frequency, duration, timing, and rate of change characteristics of input flow series;
(2) Temporal distributions of shear stress, specific stream power, sediment transport capacity, and mobility of various particle sizes;
(3) Effective discharge/sediment yield estimates with extensive user control on the analysis process and comparison of multiple flow series; and
(4) Channel stability metrics.

GeoTools accepts a wide variety of input formats and serves as a post-processor for HSPF and SWMM. GeoTools provides end users with a suite of tools to compare the erosive potential of long-term hydrologic data from model simulations, provide metrics for predicting channel changes that might result from different land use management scenarios, and to improve interpretation of biomonitoring information through better quantification of stream disturbance regimes. A timely feature of the package for stormwater management is the rapid computation of *time-integrated* erosion potential and sediment transport across a range of flows and time periods associated with varying hydromodification

TABLE 2. Cle Elum Flow Metrics.

Flow Metric	**Pre-construction**	**Post-construction**
T_{Qmean}	0.31	0.42
Average number of days with zero discharge	0.0	8.3
Average number of days at bankfull	3.5	5.5
Average number of days at 75% bankfull	12.0	26.8
Average number of days at 50% bankfull	33.3	91.4
Flashiness index	0.11	0.065

mitigation schemes. Through application of this and other indices, predictive scientific assessments (Reckhow, 1999), and risk-based models of the potential impacts of land use change on aquatic ecosystems may be developed. Decision-based models of stream stability and ecological integrity that include flow regime and hydrogeomorphic metrics may be supplemented with variables describing the condition of channel banks and riparian zones, geologic or wood influences on channel adjustability, floodplain connectivity, and development style, and other factors contributing to channel resilience.

GeoTools has been designed to provide a wide range of useful information from a parsimonious set of inputs. With the ability to control the specifics of MFA methods, such as bin type and number, users are able to fully explore the sensitivity of outputs to both inputs and computational method options. GeoTools uses a straightforward graphical user interface and the Excel® platform, making it available to the widest possible audience. All of this has been designed to bypass the need for individual investigators to produce custom, "homegrown" data analysis tools.

Risk-based models based on metrics from GeoTools will undoubtedly require regional calibration, but nonetheless have the potential to improve prediction and interpretation of geomorphic and biotic responses to decisions on stormwater controls, dam operation, watershed restoration, and water quality management. Users will be better positioned to identify streams most susceptible to land-use changes and to identify better strategies for stewardship of aquatic ecosystems in rapidly changing watersheds.

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