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A web-based software tool to estimate unregulated daily streamflow at ungauged rivers

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GMDD
5, 2503–2526, 2012

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S. A. Archfield et al.

Abstract

Streamflow information is critical for solving any number of hydrologic problems. Often times, streamflow information is needed at locations which are ungauged and, therefore, have no observations on which to base water management decisions. Furthermore, there has been increasing need for daily streamflow time series to manage rivers for both human and ecological functions. To facilitate negotiation between human and ecological demands for water, this paper presents the first publically-available, map-based, regional software tool to interactively estimate daily streamflow time series at any user-selected ungauged river location. The map interface allows users to locate and click on a river location, which then returns estimates of daily streamflow for the location selected. For the demonstration region in the northeast United States, daily streamflow was shown to be reliably estimated by the software tool, with efficiency values computed from observed and estimated streamflows ranging from 0.69 to 0.92. The software tool provides a general framework that can be applied to other regions for which daily streamflow estimates are needed.

1 Introduction

Streamflow information at ungauged rivers is needed for any number of hydrologic applications; this need is of such importance that an international research initiative known as Prediction in Ungaged Basins (PUB) has been underway for the past decade (Sivapalan et al., 2003). Concurrently, there has been increasing emphasis on the need for daily streamflow time series to understand the complex response of ecology to river regulation and to develop streamflow prescriptions to restore and protect aquatic habitat (Poff et al., 1997, 2010). Basin-wide water allocation decisions that meet both human and ecological demands for water require daily streamflow time series at river locations that have ecological constraints on water (locations where important or protected fish or ecological communities reside or rely on for life), human constraints on

GMDD
5, 2503–2526, 2012

water (locations on the river that are dammed or otherwise managed), or locations that have both constraints. Often times, these locations are unmonitored and no information is available to make informed decisions about water allocation.

Methods to estimate daily streamflow time series at ungauged locations can be broadly characterized under the topic of regionalization (Blöschl and Sivapalan, 1995), an approach which pools information about streamgauges in a region and transfers this information to an ungauged location. Generally there are two main categories of information that is pooled and transferred: (1) rainfall-runoff model parameters that are calibrated at gauged catchments and transferred in some way to an ungauged location (see Zhang and Chiew, 2009 for a review) and (2) gauged streamflows, or related streamflow properties, are directly transferred to ungauged locations. Examples of this type of regionalization approach include geostatistical methods such as top-kriging (Skøien and Blöschl, 2007) and more commonly used methods such as the drainage-area ratio method (as described in Archfield and Vogel, 2010), the MOVE method (Hirsch, 1979), and a non-linear spatial interpolation method, applied by Fennessey (1994), Hughes and Smakhtin (1996), Smakhtin (1999), Mohamoud (2008), Archfield et al. (2010), and Shu and Ourda (2012). For the software tool presented in this paper, a hybrid approach combining the drainage-area ratio and non-linear spatial interpolation methods is used to estimate daily streamflow time series.

When streamflow information is presented in an easy-to-use, freely-available software tool, this information can provide a scientific framework for water-allocation negotiation amongst stakeholders. Software tools to provide streamflow time series at ungauged locations have been previously published for predefined locations on a river; however few – if any – tools currently exist that provide daily streamflow time series at any stream location for which this information is needed. Smakhtin and Eriyagama (2008) and Holtschlag (2009) introduced software tools to provide monthly streamflows for ecological streamflow assessments at predefined river locations around the globe and in the Great Lakes region of the United States, respectively. Williamson et al. (2009) developed The Water Availability Tool for Environmental

GMDD
5, 2503–2526, 2012

Resources (WATER) to serve daily streamflow information at fixed stream locations in non-karst areas of Kentucky. These existing tools provide valuable streamflow information; yet, in most cases, at the monthly – not daily – time step and, in all cases, for only predefined locations on a river that may not be coincident with a river location of interest. The US Geological Survey StreamStats tool (Ries and others, 2008) does provide the utility to delineate a contributing area to a user-selected location on a river; however, only streamflow statistics – not streamflow time series – are provided for the ungauged location.

The software tool presented here is one of the first such tools to provide daily streamflow time series at ungauged locations in a regional framework for any user-desired location on a river. The software tool has a map-based user interface and leverages recently published methods to estimate daily streamflow at ungauged river locations. This paper first briefly describes the methods used by the software tool. The software tool is then presented and its functionality is described. Lastly the utility of the software tool to provide reliable estimates of daily streamflow is demonstrated for a large basin in the northeast United States.

2 Methods underlying the software tool

Streamflow is estimated in the software tool using information from an index streamgauge and catchment characteristics computed for the contributing area to the ungauged stream location of interest (Fig. 1). Catchment characteristics and the selected index streamgauge are first used to estimate a continuous, daily flow-duration curve (FDC) at the ungauged location (Fig. 1). The estimated FDC is then transformed to a time series of streamflow values by the index streamgauge (Fig. 1). The methods to estimate the FDC, select the index streamgauge, and transform the FDC to a time series of daily streamflow are explained in detail in the following sections.

GMDD
5, 2503–2526, 2012

2.1 Estimation of the flow-duration curve for the ungauged location

Estimation of the daily FDC at an ungauged location remains an outstanding challenge in hydrology. Castellarin et al. (2004) provides a review of several methods to estimate FDCs at ungauged locations and found that no particular method was consistently better than another. For this study, an empirical, piece-wise approach to estimate the FDC is used in the software tool (Fig. 2). This overall approach is similar to that used by Mohamoud (2008), Archfield et al. (2010), and Shu and Ourda (2012) in that the FDC is estimated by first developing regional regressions relating catchment characteristics to selected FDC quantiles and then interpolating between those quantiles to obtain a continuous FDC.

With the exception of streamflows having less than or equal to a 0.01 probability of being exceeded (streamflows with a probability of being exceeded more than 1 percent of the time), selected quantiles on the FDC are estimated from regional regression equations and a continuous FDC is log-linearly interpolated between these quantiles to obtain a continuous FDC (Fig. 2). Relations between streamflow quantiles at the 0.02, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.4, 0.5, 0.6, 0.7, 0.75, 0.8 and 0.85 exceedance probabilities were estimated by independently regressing each streamflow quantile against catchment characteristics (Fig. 2). Following the approach in Archfield et al. (2010), relations between streamflow quantiles at the 0.9, 0.95, 0.98, 0.99 and 0.999938 were estimated by regressing streamflows at these quantiles against one another and using these relations to recursively estimate streamflows (Fig. 2). Recursively estimating low streamflows, as was done in Archfield et al. (2010), exploits the strong structural relation between the streamflow quantiles (Fig. 2) and enforces the constraint that streamflows must decrease as the exceedance probability increases. Mohamoud (2008) and Archfield et al. (2010) observed that when regression is done against catchment characteristics, there is increased potential for the estimated quantiles to violate the constraint that streamflows must decrease as the exceedance probability increases because the uncertainty in the flow estimates is greatest at the lowest portion of the FDC.

GMDD
5, 2503–2526, 2012

Regressing quantiles against one another ensures that this constraint is not violated. This is an alternative approach to that used by Mohamoud (2008), who suggested discarding any estimated quantiles that violate the constraint. All regressions were fit using methods outlined in Archfield et al. (2010).

Archfield et al. (2010) showed that estimated streamflows determined by log-linear interpolation for exceedance probabilities of 0.01 or less do not match the shape of the FDC in this range and this interpolation method creates a bias in the estimated streamflows, which can substantially overestimate the peak streamflows. The shape of the FDC at the highest streamflows is so complex that, instead of using another interpolation method, streamflows from an index streamgauge are scaled to estimate the highest streamflows at the ungauged location. The assumption here is that the shape of the left tail of the FDC is better approximated by the streamflow quantiles at an index streamgauge than by a curve fit. Therefore, for streamflows having less than or equal to a 0.01 probability of being exceeded, streamflows are scaled by a drainage-area ratio approach (Eq. 1) in conjunction with the selected index streamgauge:

$$q_{p_u} = \frac{A_u}{A_g} q_{p_g} \qquad (1)$$

where q_{p_u} is the value of the streamflow quantile at the ungauged location for exceedance probability, p, A_u is the contributing drainage area to the ungauged location, A_g is the contributing drainage area to the index streamgauge, and q_{p_g} is the value of the streamflow quantile at the index streamgauge for exceedance probability, p.

2.2 Selection of the index streamgauge

As shown in Fig. 1, the index streamgauge is used for two purposes in the streamflow estimation approach: (1) to estimate streamflows that have less than a 1-percent chance of being exceeded, and (2) to transform the estimated FDC into a time series of streamflow at the ungauged location. The index streamgauge is selected by the

GMDD
5, 2503–2526, 2012

map-correlation method (Archfield and Vogel, 2010). The map-correlation method selects the index streamgauge estimated to have the highest cross-correlation between streamflow time series at the index streamgauge and the ungauged location. Archfield and Vogel (2010) showed that the selection of the index streamgauge using cross-correlation between streamflow time series outperformed the selection of the nearest index streamgauge when used with the drainage-area ratio method to estimate daily streamflow time series at ungauged locations. This finding supports the use of the map-correlation method for two reasons: (1) the drainage-area ratio approach is also used to estimate streamflows that have less than a 1-percent chance of being exceeded, and (2) because the streamflow time series is constructed by transferring the timing of the streamflows at an index streamgauge to the ungauged location, it follows that one would seek to select the index streamgauge that maximizes the cross-correlation between the streamflows at the ungauged location and the index streamgauge. Details of the map correlation method are described in Archfield and Vogel (2010).

2.3 Generation of streamflow time series

With an index streamgauge and estimated daily FDC at the ungauged location, a time series of daily streamflow for the simulation period is then constructed by use of the QPPQ transform method (Fennessey, 1994; Hughes and Smakhtin , 1996; Smakhtin, 1999; Mohamoud, 2008; Archfield et al. 2010; Shu and Ourda, 2012). The term QPPQ-transform method was coined by Fennessey (1994); however, this method has been by published Smakhtin (1999), Mohamoud (2008), and Archfield et al. (2010) under names including “non-linear spatial interpolation technique” (Hughes and Smakhtin, 1996; Smakhtin, 1999) and “reshuffling procedure” (Mohamoud, 2008). The method assumes that the exceedance probability associated with a streamflow on a given day at the index streamgauge also occurred on the same day as the ungauged location. For example, if the streamflow on 1 October 1974 was at the 0.9 exceedance probability at the index streamgauge, then it is assumed that the streamflow on that day at the ungauged location also was at the 0.9 exceedance probability. To implement the

GMDD
5, 2503–2526, 2012

QPPQ-transform method in the software tool, a FDC is constructed from the observed streamflows at the index streamgauge, and then the FDC and the daily flow time series are used together to construct a daily time series of exceedance probabilities for the streamgauge. The exceedance probability for each day at the streamgauge is then entered sequentially into the estimated FDC for the ungauged location to construct the daily streamflow time series there.

3 Software tool

All data underlying the software tool and methods are freely available across the United States and, therefore, the software tool can be considered a general framework to provide daily streamflow time series at ungauged locations in other regions. The software tool initially interfaces with the US Geological Survey StreamStats tool (Ries et al., 2008) to delineate a catchment area for any user-selected location on a river and to compute the catchment characteristics needed to estimate the FDC at the ungauged location (Fig. 1). The selection of the index streamgauge, the computation of the FDC and the estimate of the time series of daily streamflow is executed by a Microsoft Excel spreadsheet program with Visual Basic for Applications (VBA) coding language. The spreadsheet itself, which contains the VBA source code, can be used independently of the StreamStats interface and is, therefore, able to be customized to interface with other watershed delineation tools or with any study area for which the methods in Sect. 2 have been applied.

The StreamStats tool operates within a web browser, and is accessible at http://streamstats.usgs.gov. The StreamStats home page provides a general description of the application. A gray box on the left side of the page contains a series of links to pages that document how to use the application, define terminology, and so forth. The map navigation tools provided in the StreamStats user interface should be used to locate a point along the stream of interest. In addition to the stream network, users can view satellite imagery, topographic maps, and street maps to find the river location

GMDD
5, 2503–2526, 2012

of interest. With the map zoomed into a scale of at least 1:24,000, pressing on the *Watershed Delineation* button, and then on the map at location of interest will cause the catchment boundary for the selected location to be delineated and displayed on the map (Fig. 3A). Once the catchment is delineated, pressing on the *Basin Characteristics* button will result in the appearance of a new browser window that contains a table of the catchment characteristics for the selected location (Fig. 3B). StreamStats uses the processes described by *ESRI, Inc.* (2012) for catchment delineation and computation of catchment characteristics. StreamStats also provides a *Download* tool to export a shapefile of the contributing catchment (Fig. 5A) for use in other mapping applications.

The Microsoft Excel spreadsheet used to estimate daily streamflow for the stream location of interest contains five worksheets (Figs. 3C–F). The spreadsheet opens on the *MainMenu* worksheet, which provides additional instruction and support contact information (Fig. 3C). The user enters the catchment characteristics summarized by StreamStats into the *BasinCharacteristics* worksheet (Fig. 3D) and then presses the command button to compute the unregulated daily streamflows. The program then follows the process outlined in Fig. 1 and Sect. 2. The estimated streamflows are, in part, computed from regional regression equations that were developed using the catchment characteristics from the approach discussed in Sect. 2.1. Streamflows estimated for ungauged catchments having characteristics outside the range of values used to develop the regression equations are highly uncertain because these values were not used to fit the regression equations. Therefore, the software tool includes a message in the *BasinCharacteristics* worksheet (Fig. 3D) next to each characteristic that is outside the respective ranges of those characteristics used to solve the regression equations.

The *ReferenceGaugeSelection* worksheet (Fig. 3E) displays information about the ungauged catchment and index streamgauge that was selected from the method described in Sect. 2.2, including the percent difference between catchment characteristics at the ungauged and index streamgauge, the distance between the catchment characteristics at the ungauged location and index streamgauge, and the estimated cross-correlation resulting from the map-correlation method. Whereas the tool automatically selects the index streamgauge estimated to be most correlated with the ungauged location, the five index streamgauges estimated to be most correlated with the ungauged location are also reported (Fig. 3E). The tool also allows users to choose from any of the potential index streamgauges in the study (Fig. 3E). Users select a new index streamgauge from a pull-down list and then choose the update button (Fig. 3E). The *ContinuousFlowDuration* worksheet (Fig. 3F) displays the estimated continuous exceedance probabilities, and the *ContinuousDailyFlow* worksheet (Fig. 3G) displays the estimated daily time series for the ungauged site.

3.1 Demonstration area

The methods described in Sect. 2 were applied to the Connecticut River Basin (CRB), located in the northeast United States, and incorporated into a basin-specific tool termed the Connecticut River UnImpacted Streamflow Estimator (CRUISE) tool. The CRUISE tool is freely available for download at http://webdmamrl.er.usgs.gov/s1/sarch/ctrtool/index.html. The CRB is located in the northeast United States and covers an area of approximately 29 000 km^2 (Fig. 1). The region is characterized by a temperate climate with distinct seasons. Snowfall is common from December through March, with generally more snow falling in the northern portion of the CRB than in the south. The geology and hydrology of the study region are heavily affected by the growth and retreat of glaciers during the last ice age, which formed the present-day stream network and drainage patterns (Armstrong et al., 2008). The retreat of the glaciers filled the river valleys with outwash sands and gravel as well as fine- to coarse-grained lake deposits (Armstrong et al., 2008), and these sand and gravel deposits have been found to be important controls on the magnitude and timing of base flows in the southern portion of the study region (Ries and Friesz, 2000). The CRB has thousands of dams along the mainstem and tributary rivers that are used for hydropower, flood control, and water supply just as the CRB is home to a number of important fish species that rely on the river for all or part of their life cycle. These competing interests for water required daily streamflow time series at ungauged locations to understand how dam management can be optimized to meet both human and ecological needs for water.

Data from streamgauges located within the CRB and surrounding area are used in the CRUISE tool to estimate daily streamflow time series at ungauged locations (Table 1). The study streamgauges have at least 20 yr of daily streamflow record and have minimal regulation in the contributing catchment to the streamgauge (Armstrong et al., 2008; Falcone et al., 2010). Previous work in the southern portion of the study area by Archfield et al. (2010) showed that the contributing area to the streamgauge, percent of the contributing area with surficial sand and gravel deposits, and mean annual precipitation values for the contributing area are important variables in modeling streamflows at ungauged locations. For this reason, these characteristics were summarized for the study streamgauges and used in the streamflow estimation process. Contributing area to the study streamgauges ranges from 0.5 km^2 to 1845 km^2 with a median value of 200 km^2. Mean annual precipitation ranges from 101 cm per year to 157 cm per year with a median value of 122 cm per year. Percent of the contributing area with surficial sand and gravel ranges from 0 percent to 67 percent with a median value of 9.5 percent. Streamflow in the CRUISE tool is estimated for a 44-yr daily period spanning 1 October 1960 through 30 September 2004 using the methods described in Sect. 2. Estimated regression coefficients and variogram model parameters are shown in Tables 2–4, respectively.

3.2 Performance of estimated streamflows

To evaluate the utility of the underlying methods to estimate unregulated, daily streamflow at ungauged locations, a leave-one-out cross validation for 31 streamgauges (Fig. 4) was applied in conjunction with the methods described in Sect. 2. Goodness of fit between observed and estimated streamflows for the entire simulation period was evaluated using the Nash-Sutcliffe efficiency value (Nash and Sutcliffe, 1970), which was computed from both the observed and estimated streamflows as well as the natural logarithms of the observed and estimated streamflows (Fig. 4A). The natural logarithms

GMDD
5, 2503–2526, 2012

of the observed and estimated streamflows were taken to scale the daily streamflow values so that the high and low streamflow values were more equally weighted in the calculation of the efficiency metric. Efficiency values were mapped to determine if there was any spatial bias in the model performance (Fig. 4B). Selected hydrographs were also plotted to visualize the interpretation of the efficiency values (Figs. 4C–E).

The values in Fig. 4 show that the streamflows estimated by the CRUISE tool generally have good agreement with the observed streamflows at the 31 validation streamgauges. The minimum efficiency computed from the transformed daily streamflows is 0.69 and the maximum value is 0.92 (Fig. 4A), with an efficiency value equal to 1 indicting perfect agreement between the observed and estimated streamflows. The efficiency values for the untransformed observed and estimated streamflows range from 0.04 to 0.92 (Fig. 4A). This decrease in efficiency between the transformed and untransformed observed and estimate streamflows suggest that the fit between the observed and estimated streamflows from the CRUISE tool at high streamflow values is more of a challenge than the fit at the other streamflow values. Despite this, the CRUISE tool appears to result in high efficiency values across all validation sites (Fig. 4). Streamgauges in the northern portion of the basin have lower efficiency values than streamgauges in the middle and southern portions of the basin; however, it should be noted from the hydrographs in Fig. 4 that the CRUISE tool is able to represent the daily features of the hydrographs at the validation streamgauges even though the efficiency values are relatively lower in the northern portion of the study area. The efficiency values and hydrograph comparisons demonstrate that the CRUISE tool can provide a reasonable representation of natural streamflow time series at ungauged catchments in the basin.

4 Summary and conclusions

This paper presents one of the first software tools to provide daily streamflow time series for any user-selected river location in a region. The software tool is freely-available

GMDD
5, 2503–2526, 2012

and requires only an internet connection, a web browser program, and Microsoft Excel version 2000 or higher. Furthermore, the underlying data used to develop the tool and the source code are freely-available and adaptable to other regions of the United States. Daily streamflow is estimated by a four-part process: (1) delineation of the drainage area and computation of the basin characteristics for the ungauged location, (2) selection of an index streamgauge, (3) estimation of the daily flow-duration curve at the ungauged location, and (4) use of the index streamgauge to transfer the flow-duration curve to a time series of daily streamflow. The software tool, when applied to a river basin in the northeastern United States, provided reliable estimates of observed daily streamflows at 31 validation streamgauges across the basin. This software framework and underlying methods can be used to develop map-based, daily-streamflow estimates needed for water management decisions at ungauged stream locations for other regions.

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GMDD

5, 2503–2526, 2012

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GMDD
5, 2503–2526, 2012

A web-based software tool to estimate unregulated daily streamflow

S. A. Archfield et al.

Table 1. List of streamgauges used to estimate unregulated, daily streamflow at ungauged locations in the Connecticut River Basin.

Station Number	Station name	Period of record
01073000	Oyster River near Durham, NH	15 December 1934 – 31 December 2004
01082000	Contocook River at Peterborough, NH	7 July 1945 – 30 September 1977
01084500	Beard Brook near Hillsboro, NH	1 October 1945 – 30 September 1970
01085800	West Branch Warner River near Bradford, NH	22 May 1962 – 30 September 2004
01086000	Warner River at Davisville, NH	1 October 1939 – 30 September 1978
01089000	Soucook River near Concord, NH	1 October 1951 – 30 September 1987
01091000	South Branch Piscataquog River near Goffstown, NH	27 July 1940 – 30 September 1978
01093800	Stony Brook tributary near Temple, NH	1 May 1963 – 30 September 2004
01096000	Squannacook River near West Groton, MA	1 October 1949 – 31 December 2004
01097300	Nashoba Brook near Acton, MA	26 July 1963 – 31 December 2004
01105600	Old Swamp River near South Weymouth, MA	20 May 1966 – 24 July 2006
01105730	Indian Head River at Hanover, MA	8 July 1966 – 24 July 2006
01106000	Adamsville Brook at Adamsville, RI	1 October 1940 – 30 September 1978
01108000	Taunton River near Bridgewater, MA	1 October 1929 – 23 April 1976
01109000	Wading River near Norton, MA	1 June 1925 – 31 December 2004
01111300	Nipmuc River near Harrisville, RI	1 March 1964 – 30 September 1991
01111500	Branch Riverb at Forestdale, RI	24 January 1940 – 31 December 2004
01117500	Pawcatuck River at Wood River Junction, RI	7 December 1940 – 31 December 2004
01118000	Wood River Hope Valley, RI	12 March 1941 – 31 December 2004
01118300	Pendleton Hill Brook near Clarks Falls, CT	1 October 1958 – 31 December 2004
01118500	Pawtucket River at Westerly, RI	27 November 1940 – 31 December 2004
01120000	Hop Brook near Columbia, CT	1 October 1932 – 6 October 1971
01121000	Mount Hope River near Warrenville, CT	1 October 1940 – 31 December 2004
01123000	Little River near Hanover, CT	1 October 1951 – 31 December 2004
01127880	Big Brook Near Pittsburg Nh	1 December 1963 – 1 January 1984
01133000	East Branch Passumpsic River near East Haven, VT	1 October 1948 – 1 September 1979
01133500	Passumpsic River near St. Johnsbury, VT	1 May 1909 – 1 July 1919
01134500	Moose River at Victory, VT	1 January 1947 – 12 May 2010
01135000	Moose River at St. Johnsbury, VT	1 August 1928 – 1 September 1983
01137500	Ammonoosuc River at Bethlehem Junction, NH	1 August 1939 – 12 May 2010

GMDD
5, 2503–2526, 2012

Table 1. Continued

Station Number	Station name	Period of record
01139000	Wells River at Wells River, VT	1 August 1940 – 12 May 2010
01139800	East Orange Branch at East Orange, VT	1 June 1958 – 12 May 2010
01140000	South Branch Waits River near Bradford, VT	1 April 1940 – 1 September 1951
01141800	Mink Brook near Etna, NH	1 August 1962 – 1 September 1998
01142000	White River near Bethel, VT	1 June 1931 – 1 September 1955
01144000	White River at West Hartford, VT	1 October 1951 – 12 May 2010
01145000	Mascoma River at West Canaan, NH	1 July 1939 – 1 September 1978
01153500	Williams River near Rockingham, VT	1 June 1940 – 1 September 1984
01154000	Saxtons River at Saxtons River, VT	20 June 1940 – 30 September 1982
01155000	Cold River at Drewsville, NH	23 June 1940 – 30 September 1978
01161500	Tarbell Brook near Winchendon, MA	29 May 1916 – 6 September 1983
01162500	Priest Brook near Winchendeon, MA	1 October 1936 – 31 December 2004
01165500	Moss Brook at Wendell Depot, MA	1 June 1916 – 30 September 1982
01169000	North River at Shattuckville, MA	13 December 1939 – 31 December 2004
01169900	South River near Conway, MA	1 January 1967 – 31 December 2004
01171500	Mill River at Northampton, MA	18 November 1938 – 31 December 2004
01174000	Hop Brook near New Salem, MA	19 November 1947 – 30 September 1982
01174900	Cadwell Creek near Belchertown, MA	13 July 1961 – 30 September 1997
01175670	Sevenmile River near Spencer, MA	1 December 1960 – 31 December 2004
01176000	Quaboag River at West Brimfield, MA	19 August 1912 – 31 December 2004
01180000	Sykes Brook at Knightville, MA	20 June 1945 – 18 July 1974
01181000	West Branch Westfield at Huntington, MA	1 September 1935 – 31 December 2004
01187300	Hubbard River near West Hartland, CT	4 August 1959 – 31 December 2004
01187400	Valley Brook near West Hartland, CT	1 October 1940 – 30 September 1972
01188000	Burlington Brook near Burlington, CT	1 October 1931 – 31 December 2004
01193500	Salmon River near East Hampton, CT	1 October 1928 – 31 December 2004
01194500	East Branch Eightmile River near North Lyme, CT	1 October 1937 – 6 October 1981
01198000	Green River near Great Barrington, MA	1 October 1951 – 30 September 1971
01198500	Blackberry River at Canaan, CT	1 October 1949 – 20 October 1971
01199050	Salmon Creek at Lime Rock, CT	1 October 1961 – 31 December 2004
01200000	Ten Mile River, CT	1 October 1930 – 4 April 1988
01332000	North Branch Hoosic River at North Adams, MA	22 June 1931 – 30 September 1990
01333000	Green River at Williamstown, MA	20 September 1949 – 31 December 2004

GMDD
5, 2503–2526, 2012

A web-based software tool to estimate unregulated daily streamflow

S. A. Archfield et al.

Table 2. Number of streamgauges, goodness of fit values, explanatory variables, and estimated regression parameters for streamflows estimated from catchment characteristics. (%RMSE, Percent root-mean square error; **, characteristic not included in regression equation; †, Bias correction factor computed from Duan (1983); NSE, Nash-Sutcliffe efficiency value).

General regression information				Characteristics in the regression equation and coefficient value						
Exceedence probability	Number of stream-gauges used to develop regression equation	%RMSE	NSE	Constant term	Drainage area	Average annual precip-itation.	Percent of basin that is underlain by sand and gravel deposits	Y-location of the basin centroid	X-location of the basin centroid	Bias correla-tion factor†
0.02	51	1.49	0.99	−26.5758	0.9590	2.3262	**	1.4462	**	1.0103
0.05	51	0.62	1.00	−19.3148	0.9775	1.7521	**	1.0457	**	1.0023
0.1	51	0.73	0.99	−2.1224	0.9982	0.9106	**	**	**	1.0015
0.15	51	0.60	1.00	−2.9777	1.0050	1.0589	**	**	**	0.9972
0.2	51	0.86	0.99	−3.6935	1.0037	1.1920	**	**	**	0.9957
0.25	51	1.32	0.98	−4.6684	1.0110	1.3890	**	**	**	0.9950
0.3	51	1.86	0.98	−5.5394	1.0137	1.5688	**	**	**	0.9950
0.4	51	3.00	0.96	−6.7591	1.0206	1.8000	**	**	**	0.9960
0.5	51	3.86	0.95	−7.6803	1.0269	1.9577	**	**	**	0.9982
0.6	50	4.40	0.96	−8.3466	1.0184	2.0123	0.0804	**	**	1.0184
0.7	50	6.61	0.94	−8.4500	1.0480	1.9072	0.0949	**	**	1.0278
0.75	50	9.24	0.93	−8.7450	1.0655	1.9073	0.1040	**	**	1.0243
0.8	50	13.58	0.92	−9.1085	1.0951	1.9008	0.1251	**	**	1.0379
0.85	50	21.20	0.90	−9.3154	1.1239	1.8480	0.1515	**	**	1.0565

GMDD

5, 2503–2526, 2012

A web-based software tool to estimate unregulated daily streamflow

S. A. Archfield et al.

Table 3. Number of streamgauges, goodness of fit values, explanatory variables, and estimated regression parameters for streamflows estimated from other streamflow quantiles. (%RMSE, Percent root-mean square error; † , Bias correction factor computed from Duan (1983); NSE, Nash-Sutcliffe efficiency value).

	General regression information			Characteristics in the regression equation and coefficient value			
Exceedence probability	Number of streamgauges used to develop regression equation	%RMSE	NSE	Constant term	Coefficient on explanatory variable	Explanatory variable	Bias correlation factor†
0.9	50	32.36	0.89	−0.4112	1.0511	Streamflow at the 0.85 exceedence probability	1.0004
0.95	50	57.15	0.85	−0.4991	1.0607	Streamflow at the 0.9 exceedence probability	0.9986
0.98	50	67.36	0.79	−0.4695	1.0567	Streamflow at the 0.95 exceedence probability	1.0103
0.99	50	102.33	0.71	−0.3011	1.0467	Streamflow at the 0.98 exceedence probability	1.0000
0.999938	34	825.08	−1.30	−1.6658	1.2826	Streamflow at the 0.99 exceedence probaility	1.2011

Table 4. Variogram model parameters and root-mean-square error value resulting from a leave-one-out cross validation of the variogram models.

Station Number	Variance parameter	Range parameter	Root-mean-square error
01073000	0.0411	697945.4362	0.0399
01085800	0.0115	267272.8077	0.0388
01089000	0.0112	269793.6063	0.0462
01093800	0.0147	267272.7273	0.0416
01096000	0.0389	607472.9297	0.0469
01097300	0.0261	374218.0554	0.0488
01105600	0.0621	557922.7912	0.0488
01105730	0.0677	547625.3299	0.0447
01109000	0.0588	489036.3840	0.0487
01111300	0.0444	435141.4397	0.0470
01111500	0.0649	664951.4696	0.0452
01117500	0.0964	846131.5260	0.0548
01118000	0.0680	547336.8809	0.0456
01118300	0.0541	478962.6030	0.0421
01118500	0.1548	1255724.6703	0.0469
01121000	0.0440	467562.3777	0.0442
01123000	0.0487	476803.1943	0.0457
01127880	0.0475	451474.0307	0.0241
01134500	0.0585	593052.1148	0.0491
01135000	0.0828	885228.5293	0.0574
01137500	0.0421	469510.7730	0.0194
01139000	0.0354	483627.8140	0.0309
01139800	0.0224	369057.2000	0.0255
01141800	0.0116	267272.7273	0.0264
01144000	0.0155	302281.0433	0.0328
01153500	0.0135	267272.7081	0.0409
01154000	0.0129	213818.1818	0.0470
01161500	0.0187	337256.6753	0.0447
01162500	0.0176	291135.1932	0.0436
01165500	0.0291	445510.0450	0.0417
01169000	0.0190	317944.4643	0.0402
01169900	0.0245	398758.9250	0.0442
01171500	0.0310	393869.0688	0.0454
01174000	0.0249	330495.4703	0.0443
01174900	0.0321	412573.1453	0.0430
01175670	0.0366	486730.2368	0.0463
01176000	0.0357	526274.7021	0.0498
01181000	0.0333	502453.4839	0.0426
01187300	0.0566	846080.6046	0.0422
01188000	0.0313	454196.0564	0.0427
01193500	0.0412	435477.5668	0.0445
01199050	0.0212	368184.1116	0.0414
01200000	0.0401	538909.4325	0.0444
01332000	0.0114	175180.2029	0.0370
01333000	0.0148	267272.7273	0.0341

GMDD
5, 2503–2526, 2012

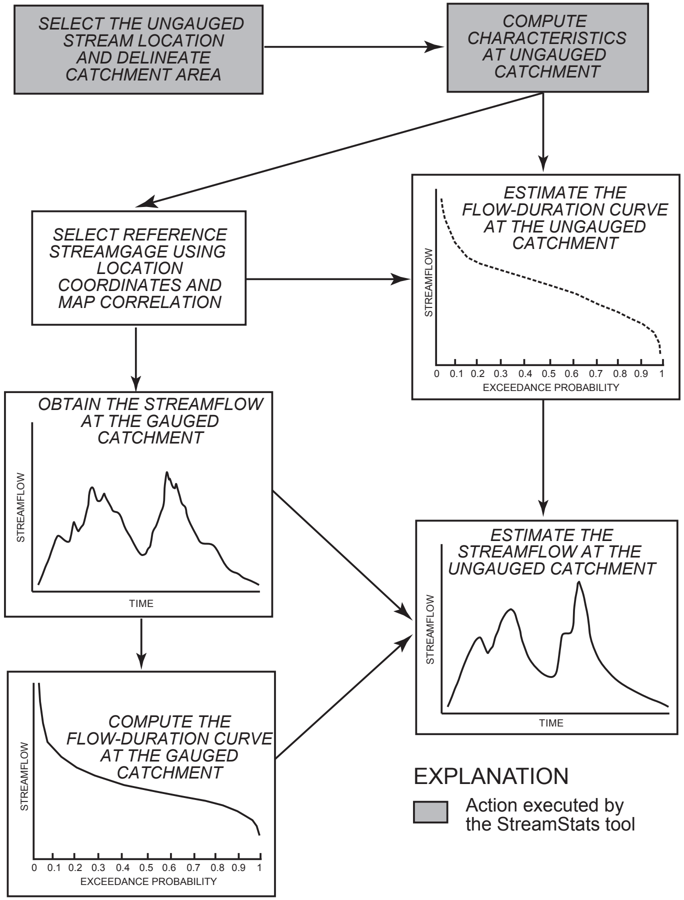

Fig. 1. Diagram of the process to estimate unregulated, daily streamflow at ungauged locations.

GMDD
5, 2503–2526, 2012

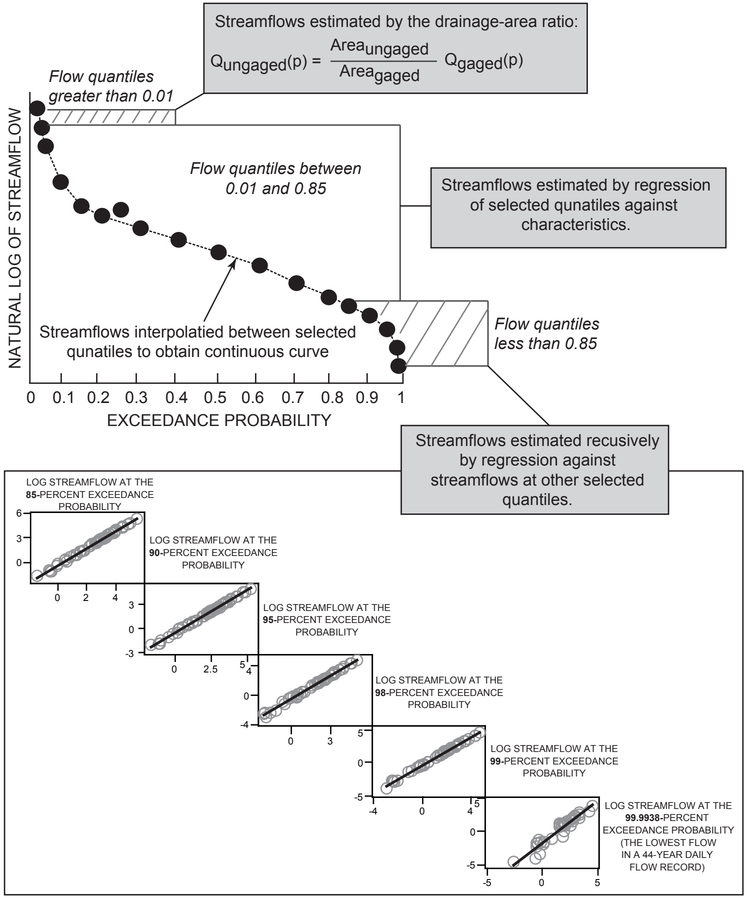

Fig. 2. Diagram showing the methods used to estimate a continuous, daily flow duration at an ungauged location.

GMDD
5, 2503–2526, 2012

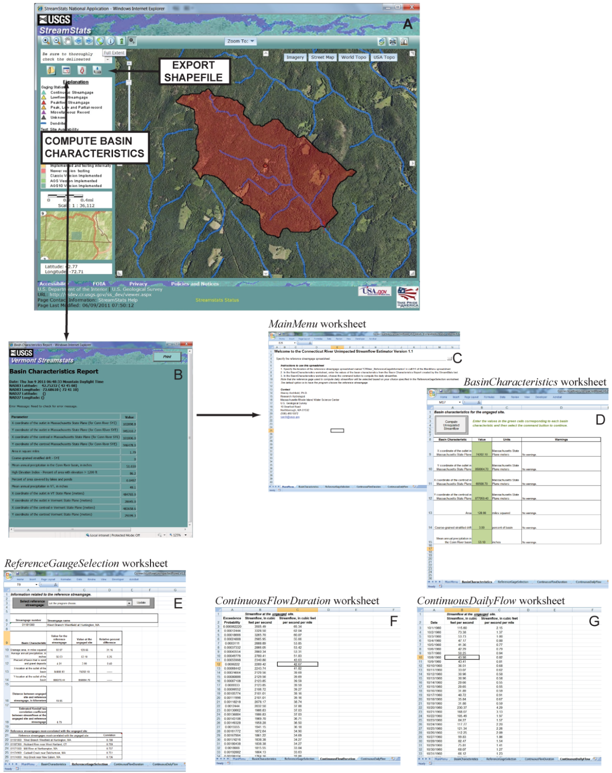

Fig. 3. Screen captures showing the decision-support tool used to estimate daily, unregulated time series. The program delineates a catchment for the ungauged location selected by the user **(A)** and summarizes the catchment characteristics **(B)**. The user then inputs these characteristics into a spreadsheet program **(C–E)** that generates the daily, period of record flow-duration curve **(F)** and the daily streamflow time series **(G)**.

GMDD
5, 2503–2526, 2012

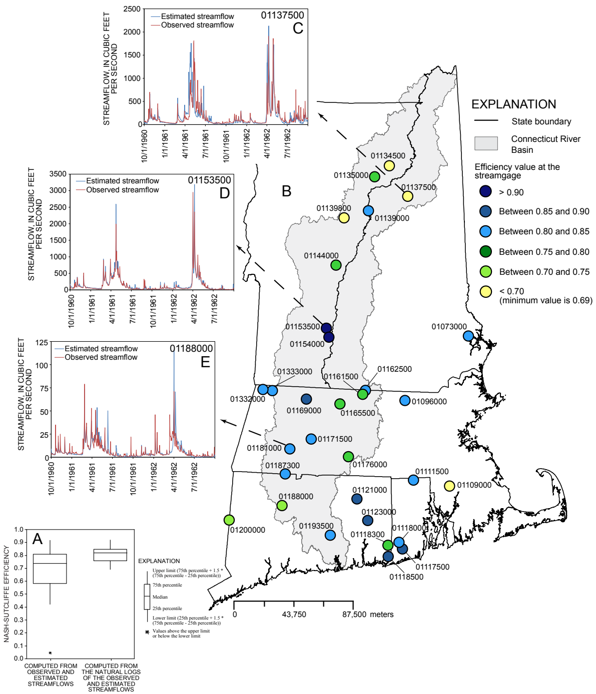

Fig. 4. Range of efficiency values computed between the observed and estimated streamflows at the 31 validation streamgauges **(A)**, spatial distribution of efficiency values resulting from log-transformed observed and estimated daily streamflow at 31 validation streamgauges **(B)** and selected hydrographs of observed and estimated streamflow for the period from 1 October 1960 through 30 September 1962 **(C–E)**.

GMDD
5, 2503–2526, 2012