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AUTOMATED WEB GIS BASED HYDROGRAPH ANALYSIS TOOL, WHAT[1]

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ABSTRACT: The separation of the base flow component from a varying streamflow hydrograph is called "hydrograph analysis." In this study, two digital filter based separation modules, the BFLOW and Eckhardt filters, were incorporated into the Web based Hydrograph Analysis Tool (WHAT) system. A statistical component was also developed to provide fundamental information for flow frequency analysis and time series analysis. The Web Geographic Information System (GIS) version of the WHAT system accesses and uses U.S. Geological Survey (USGS) daily streamflow data from the USGS web server. The results from the Eckhardt filter method were compared with the results from the BFLOW filter method that was previously validated, since measured base flow data were not available for this study. Following validation, the two digital filter methods in the WHAT system were run for 50 Indiana gaging stations. The Nash-Sutcliffe coefficient values comparing the results of the two digital filter methods were over 0.91 for all 50 gaging stations, suggesting the filtered base flow using the Eckhardt filter method will typically match measured base flow. Manual separation of base flow from streamflow can lead to inconsistency in the results, while the WHAT system provides consistent results in less than a minute. Although base flow separation algorithms in the WHAT system cannot consider reservoir release and snowmelt that can affect stream hydrographs, the Web based WHAT system provides an efficient tool for hydrologic model calibration and validation. The base flow information from the WHAT system can also play an important role for sustainable ground water and surface water exploitation, including irrigation and industrial uses, and estimation of pollutant loading from both base flow and direct runoff. Thus, best management practices can be appropriately applied to reduce and intercept pollutant leaching if base flow contributes significant amounts of pollutants to the stream. This Web GIS based system also demonstrates how remote, distributed resources can be shared through the Internet using Web programming.

(KEY TERMS: hydrograph analysis; base flow separation; digital filter; rivers/streams; WHAT; Web GIS.)

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INTRODUCTION

Many hydrologic and water quality computer models have been developed and tested over the years that are useful for effective watershed management (Young *et al.,* 1987; Srinivasan and Arnold, 1994; Lim and Engel, 2003). For accurate estimation of water quality parameters using these models, the hydrologic component should typically be validated first, because hydrology is the driving force of sediment, nutrient, and pesticide movement. For validation of hydrology components of models, direct runoff and base flow components of the streamflow hydrograph typically need to be separated, because direct runoff and base flow are usually simulated separately in computer models (Srinivasan and Arnold, 1994).

The process of separating the base flow component from the varying streamflow hydrograph is called "hydrograph analysis." The shape of the hydrograph varies depending on physical and meteorological conditions in a watershed (Bendient and Huber, 2002), thereby complicating hydrograph analysis. The first step of a typical hydrograph analysis is to identify the starting and ending points of direct runoff. Direct

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runoff starts when the flow begins to increase, while the ending point can be identified when a plot of log flow rate against time becomes a straight line (Chapman, 1999). There are several graphical methods to define base flow between these starting and ending points (Chow *et al.,* 1988). However, these methods are not very efficient when separating base flow for long time periods. Also, these subjective techniques can result in inconsistent results, even with the same flow data.

One widely used base flow separation application is the U.S. Geological Survey (USGS) program called 'HYSEP' (Sloto and Crouse, 1996). HYSEP is a public domain computer program with three separation methods: fixed interval, sliding interval, and local minimum method. However, the HYSEP program is not user friendly and requires a great deal of user intervention to prepare input data and run the program. In addition to the HYSEP separation method, digital filtering methods have recently become commonplace in hydrograph separation (Lyne and Hollick, 1979; Chapman, 1987; Nathan and McMahon, 1990; Arnold *et al.,* 1995; Arnold and Allen, 1999; Eckhardt, 2005). The digital filter method was originally used in signal analysis and processing (Lyne and Hollick, 1979). Filtered base flow values using a digital filter were compared with measured results, and the R^2 value was 0.83 (Arnold and Allen, 1999).

Although these separation methods in HYSEP and digital filters discussed earlier have proven useful for hydrograph analysis, users must install these programs on their computers or implement them in spreadsheet programs, and they must also prepare input data manually. This can be a time consuming job if one has to repeat these jobs for many streams for long periods of time. Thus, a Web based hydrograph separation model, the iSep system (Lim, 2004), was developed for automated hydrograph analysis. The iSep system results were compared with HYSEP base flow results. The iSep system always overestimated the base flow compared with HYSEP (S. Muthukrishnan, K.J. Lim, J. Harbor, and B.A. Engel, 2003, unpublished manuscript), because iSep does not consider the duration of direct runoff in separating base flow (Figure 1). Thus, there is a need for better base flow separation algorithms in iSep than the local minimum method that does not consider flow duration.

In addition to base flow separation, many people use the USGS streamflow data to obtain flow statistics for frequency analysis and time series analysis. However, statistics are not provided by the iSep system. Histograms and quantile quantile (QQ) plots are typical ways to check the distribution of raw and log-transformed flow data and the normality of the raw and log transformed flow data. The addition of a statistics component to iSep would provide users with very fundamental information for flow frequency analysis and time series analysis.

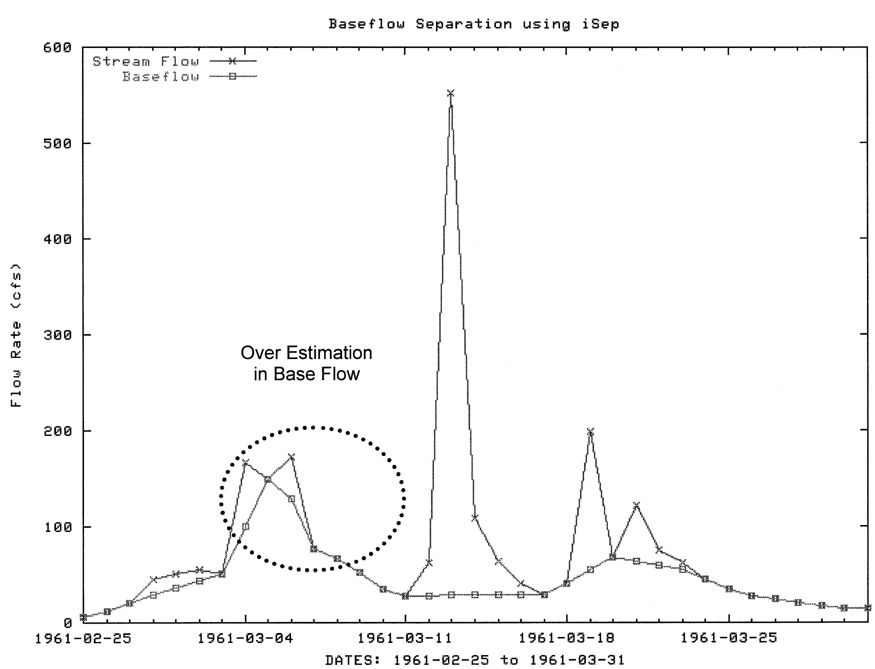

Figure 1. Hydrograph Separation Using Flow Minimum Method in iSep System for Little Eagle Creek, Speedway, Indiana.

The USGS collects stream level, streamflow, reservoir and lake level, surface water quality, and rainfall data for more than 850,000 gaging stations in the United States (USGS, 2004). The data are collected by automatic recorders and manual measurements at field installations across the nation. These data are provided from the USGS National Water Information System (USGS, 2005) website. The daily streamflow data can be accessed from the database by state, hydrologic region, latitude-longitude, site name, site number, agency code, drainage area, number of observations, and period of record. Although the USGS website provides many options to query its databases, it is a text based, rather than graphically based, interface. Since the gaging stations are distributed spatially, it would be ideal to provide a graphical interface to help users choose gaging stations of interest using a map interface and run base flow separation modules.

The objectives of this study are to develop a Web GIS based hydrograph analysis tool that uses digital filter based base flow separation modules (Arnold and Allen, 1999; Eckhardt, 2004) and statistical components, and to compare the Eckhardt (2005) digital filter method base flow with the Arnold and Allen (1999) digital filter base flow. The Arnold and Allen (1999) digital filter method was previously compared with measured base flow data and was therefore selected to evaluate the Eckhardt filter results.

WHY SEPARATE BASE FLOW FROM STREAMFLOW?

For more than 100 years, base flow recession has been investigated by hydrologists and hydrogeologists to examine aquifer characteristics (Dewandel *et al.,* 2003). It has been well known that base flow contributes much of the streamflow. Thus, quantification of shallow ground water aquifers is important for sustainable ground water and surface water exploitation for irrigation and industrial purposes, and estimation of contamination impacts in downstream areas of wastewater discharge. Dewandel *et al.* (2003) estimated the aquifer thickness from stream recession analysis using the Maillet and Boussinesq formula. Wittenberg and Sivapalan (1999) estimated recharge to the shallow ground water aquifer from a base flow separation method considering evapotranspiration of deep rooted trees. These results can be used for sustainable ground water development in a basin, not to exceed the recharge rate to the ground water aquifer.

Doležal and Kvítek (2004) separated direct runoff, interflow, and base flow components from streamflow to estimate nitrate contribution from each component to the total stream nitrate loads for a watershed where a highly permeable recharge zone is located on flat tops of hills. A digital filter method suggested by Chapman and Maxwell (1996) and a simple conceptual model, called GROUND (Kulhavy *et al.,* 2001), were used to separate base flow and direct runoff, respectively. From the measured total streamflow, these two components were subtracted to obtain the interflow component. The nitrate concentration for each component, direct runoff, interflow, and base flow, was estimated using simplified nonlinear optimization. It was found that the interflow and base flow are the primary contributors of nitrate to the stream. Although the results obtained were not validated, the hydrograph separation methods with stream nitrate concentration data can be used to estimate the role of different runoff components in water quality generation in the stream.

Schilling and Zhang (2004) examined long term streamflow with nitrate concentration data to quantify nitrate losses in base flow and streamflow at the Raccoon River watershed in Iowa. Hydrograph separation combined with a load estimation program was used to estimate base flow nitrate loading. It was found that approximately two-thirds of the annual nitrate loads are contributed by the base flow in the Raccoon River watershed. The results indicated that proper best management practices, such as establishment of deep rooted riparian buffers, needed to be placed to reduce and intercept the nitrate being leached (Schilling and Zhang, 2004).

DIGITAL FILTER METHODS FOR BASE FLOW SEPARATION

The digital filter method has been used in signal analysis and processing to separate high frequency signal from low frequency signal (Lyne and Hollick, 1979). This method has been used in base flow separation because high frequency waves can be associated with the direct runoff, and low frequency waves can be associated with the base flow (Eckhardt, 2005). Thus, filtering direct runoff from base flow is similar to signal analysis and processing (Eckhardt, 2005). Equation (1) shows the digital filter used for base flow separation (Lyne and Hollick, 1979; Nathan and McMahon, 1990; Arnold and Allen, 1999; Arnold *et al.,* 2000).

$$q_t = \alpha \times q_{t-1} + \frac{(1+\alpha)}{2} \times \left(Q_t - Q_{t-1}\right) \tag{1}$$

where, q_t is the filtered direct runoff at the t time step (m^3/s); q_{t-1} is the filtered direct runoff at the t-1 time step (m^3/s); α is the filter parameter; Q_t is the total streamflow at the t time step (m^3/s); and Q_{t-1} is the total streamflow at the t-1 time step (m^3/s).

The digital filter method has no physical meaning, but it removes the subjective aspect from manual separation, and it is fast, consistent, and reproducible (Arnold *et al.,* 1995). However, it is recommended that experienced hydrologists evaluate the quality of the results from the digital filter methods subjectively. Arnold *et al.* (1995) compared digital filter results with manual separation results. Annual filtered base flow results were within 11 percent of base flow estimated from manual separation (Arnold *et al.,* 1995). Arnold and Allen (1999) compared digital filter results with the measured base flow for six watersheds. The R^2 value was 0.83 with a slope of 1.07 for monthly comparisons. The software developed based on the digital filter shown in Equation (1) is available from the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS, 1999). Although the digital filter method provided a good match between filtered base flow and measured base flow values, Chapman (1991) pointed out that the digital filter method estimates constant streamflow and base flow when the direct runoff has ceased. Thus, Chapman (1991) developed a new algorithm as shown in Equation (2a). Chapman and Maxwell (1996) proposed a simplified equation as shown in Equation (2b), which provides similar results to Equation (2a).

$$b_t = \frac{3\alpha - 1}{3 - \alpha} \times b_{t-1} + \frac{1-\alpha}{3-\alpha} \times \left(Q_t + Q_{t-1}\right) \quad (2a)$$

$$b_t = \frac{\alpha}{2 - \alpha} \times b_{t-1} + \frac{1-\alpha}{2-\alpha} \times Q_t \quad (2b)$$

where b_t is the filtered base flow at the t time step; b_{t-1} is the filtered base flow at the t-1 time step; α is the filter parameter, Q_t is the total streamflow at the t time step (m^3/s); and Q_{t-1} is the total streamflow at the t-1 time step (m^3/s).

Eckhardt (2005) proposed the general form of a digital filter considering a digital filter parameter and BFI_{max} (maximum value of long term ratio of base flow to total streamflow) (Equation 3).

$$b_t = \frac{\left(1 - BFI_{\max}\right) \times \alpha + b_{t-1} + \left(1-\alpha\right) \times BFI_{\max} \times Q_t}{1 - \alpha \times BFI_{\max}} \quad (3)$$

where b_t is the filtered base flow at the t time step; b_{t-1} is the filtered base flow at the t-1 time step; BFI_{max} is the maximum value of long term ratio of base flow to total streamflow; α is the filter parameter; and Q_t is the total streamflow at the t time step.

BFI_{max} is a new variable introduced in the digital filter method by Eckhardt (2005). To reduce the subjective influence of using BFI_{max} on base flow separation, representative BFI_{max} values were estimated for different hydrological and hydrogeological situations by comparing the base flow from conventional separation methods with those of the Eckhardt digital filter method (Eckhardt, 2005). Eckhardt (2005) proposed the use of BFI_{max} values of 0.80 for perennial streams with porous aquifers, 0.50 for ephemeral streams with porous aquifers, and 0.25 for perennial streams with hard rock aquifers. These values were obtained through Eckhardt's (2005) application and validation of his filtering approach on watersheds in Pennsylvania, Maryland, Illinois, and Germany.

DEVELOPMENT OF WEB BASED HYDROGRAPH ANALYSIS TOOL

The Web based Hydrograph Analysis Tool (WHAT) system (Lim and Engel, 2004) was developed by incorporating digital filter methods (Equations 1 and 3) (Lyne and Hollick, 1979; Nathan and McMahon, 1990; Arnold and Allen, 1999; Eckhardt, 2005) for base flow separation with the iSep system (S. Muthukrishnan, K.J. Lim, J. Harbor, and B.A. Engel, 2003, unpublished manuscript). Thus, three base flow separation modules, the local minimum method and two digital filter methods, are available in the WHAT system. To distinguish between the digital filter methods, each digital filter method is given a different name in this paper. The digital filter method by Lyne and Hollick (1979) is called the "BFLOW filter," because BFLOW software (USDA-ARS, 1999) was developed based on this digital filter method, and the digital filter method proposed by Eckhardt (2005) will be called the "Eckhardt filter.".

To utilize either the BFLOW filter or the Eckhardt filter for base flow separation, users must provide parameters: a filter parameter for the BFLOW filter method, and a filter parameter and BFImax value for the Eckhardt filter method. Nathan and McMahon (1990) found that the filter parameter of 0.925 gave realistic results when compared to manual separation results. Eckhardt (2005) found that the filter parameter is not very sensitive to the filtered results (Equation 3), while the BFI_{max} value greatly influences the results (Eckhardt, 2005). Thus, representative BFI_{max} values for different hydrological and hydrogeological conditions are provided in the WHAT system. To help users run the WHAT system using either of these digital filter methods, the default values of the digital filter parameter and the BFI_{max} value are used in the WHAT system. However, if these values are available for a local area, users can modify these values easily in the interface.

To explore whether the digital filter methods incorporated into the WHAT system perform better than the local minimum method in the iSep system, which does not consider the duration of flow, base flow was computed using the BFLOW and Eckhardt filter methods in the WHAT system as shown in Figure 2. The WHAT system was run for the same gaging station and time period shown in Figure 1. The base flow values obtained using the digital filter methods do not overestimate base flow when multiple high peaks occur in a short time period as shown in Figure 2, compared with base flow separated using a local minimum method that typically overestimates base flow (Figure 1).

Figure 3 shows the WHAT interface. The WHAT system checks for data breaks in USGS streamflow data, because USGS daily streamflow data are not continuous for some gaging stations. For manual and other base flow separation techniques, it is the user's responsibility to check for data gaps when raw flow data are downloaded from the USGS web server. The WHAT system provides a series of flow datasets as shown in Figure 3(c). Once the base flow is separated from the streamflow, daily, monthly, and yearly direct runoff and base flow output values are provided in tabular format as well as a graphical hydrograph (Figure 3d and 3e). Some users may want to use local flow data measured at non-USGS gaging stations to separate base flow from streamflow. Thus, a web interface was developed to allow users to enter the flow data or upload flow data to the WHAT server. This capability provides an efficient tool for international and other users with local datasets.

The WHAT system provides a map interface for the USGS daily streamflow database as shown in Figure 3. This map interface, developed using a customized Web GIS application, can complement the text based USGS streamflow database. In the current version of the WHAT Web GIS system, spatial data for Indiana, Illinois, Ohio, Michigan, Minnesota, and Wisconsin are provided. However, this can be easily scaled nationwide. Figure 4 shows how the Web GIS version of the WHAT system works to automatically separate base flow from streamflow using the USGS daily streamflow database at the USGS web server. The Web GIS application sends a uniform resource locator (URL) request with gaging station information to the USGS web server to query long term daily streamflow data for a selected gaging station. Then, the WHAT system retrieves USGS daily stream flow for that gaging station and reformats it for base flow separation. Depending on the separation method selected, the WHAT system performs base flow separation and prepares the tabular data and hydrograph automatically. With the WHAT system, base flow separation can be completed in less than a minute. The WHAT system is a very efficient tool when users must separate base flow for many gaging stations and long term periods.

In addition to base flow separation, many people use the USGS streamflow data to obtain flow statistics for frequency analysis and time series analysis. Thus, a flow statistics component was developed as shown in Figure 5. Histograms showing the distribution of the raw and log transformed flow data are drawn with the normal distribution curve on it. A QQ plot is also generated to check the normality of the raw or log transformed flow data. These capabilities provide users with the fundamental information for flow frequency analysis and time series analysis. The base flow separation or hydrograph analysis is frequently used to calibrate and validate the direct runoff and base flow components in the hydrologic model by comparing the simulated values with the measured values. As a measure of the "goodness of the fit," the coefficient of determinant (R^2) and the Nash-Sutcliffe coefficient (Nash and Sutcliffe, 1970) are often used. Thus, the Web based interface was developed to compute these two coefficients easily and quickly. Also, an X-Y graph showing the relationship between the two datasets, such as the model simulated direct runoff and measured direct runoff, is generated.

COMPARISON OF FILTERED BASE FLOW USING DIGITAL FILTER METHODS

Arnold and Allen (1999) compared the base flow results using the BFLOW filter with results from manual separation and measured base flow data. The R^2 value was 0.83, with a slope of 1.07. However, the filtered base flow using the Eckhardt filter was not compared with measured base flow data, but was compared with results from conventional separation methods (Eckhardt, 2005). Thus, the filtered base flow using the Eckhardt filter was compared with results from the BFLOW filter.

For the comparison of filtered base flow using the BFLOW and Eckhardt filter methods, 50 of 275 gaging stations in Indiana were randomly selected using the Web GIS version of the WHAT system. The drainage areas for these gaging stations ranged from 33 km^2 to 313,933 km^2. The filtered daily base flow data from the Eckhardt filter method were compared

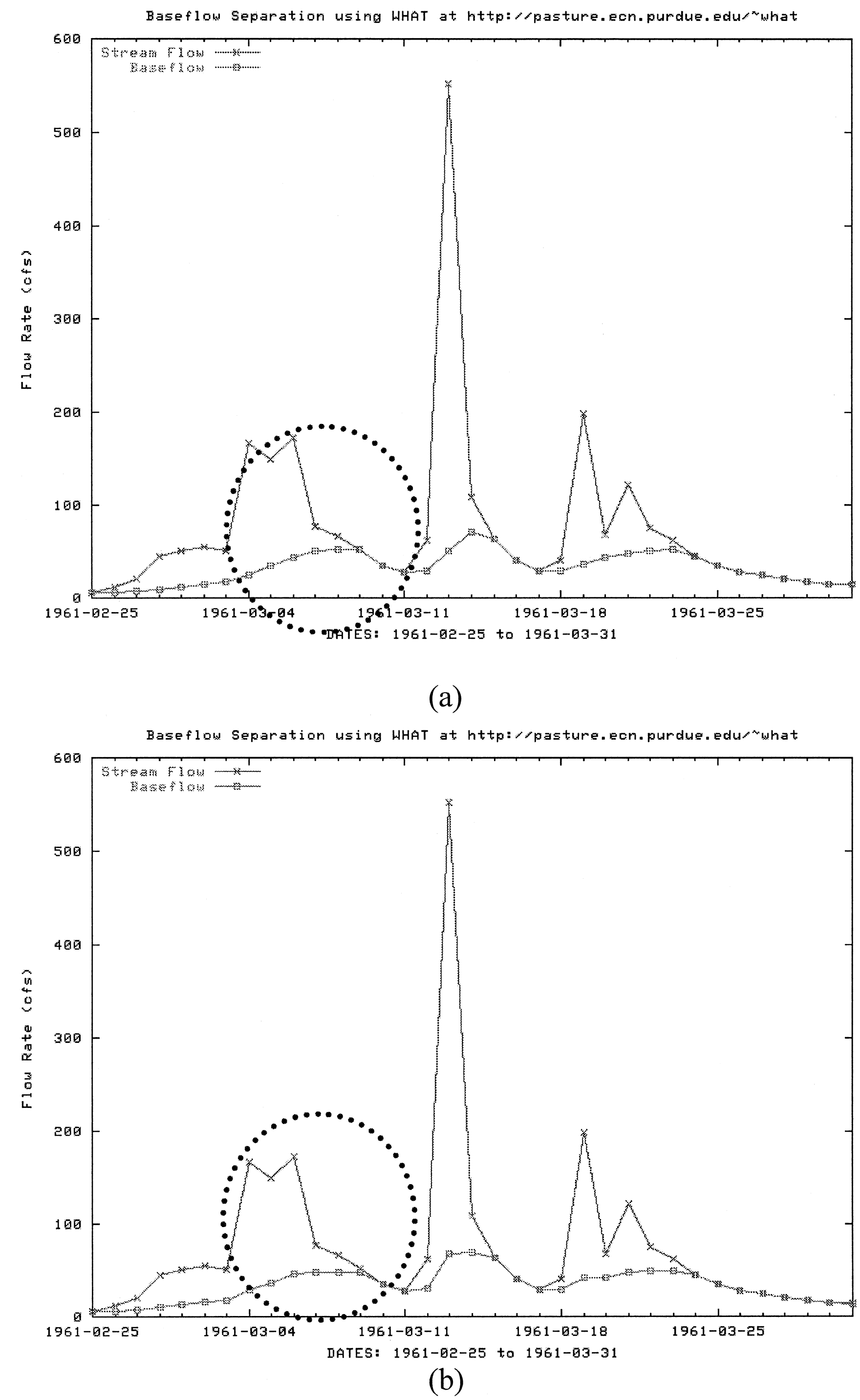

Figure 2. Hydrograph Separation for USGS Gaging Station 03353600 Using the (a) BFLOW Filter and (b) the Eckhardt Filter for the Same Gaging Station and Period Shown in Figure 1.

with those from the BFLOW filter method, and the Nash-Sutcliffe coefficient and R^2 were computed using the WHAT system component to describe the "goodness of fit." Figure 6 shows the filtered base flow using the Eckhardt filter and the BFLOW filter for USGS Gaging Station 3341500 in Indiana. The Nash-Sutcliffe coefficient and the R^2 values are both 0.99. The Nash-Sutcliffe coefficient values were computed for 50 gaging stations, and the results are shown in Figure 7. For all 50 gaging stations, Nash-Sutcliffe coefficient values were over 0.91 and the R^2 values were over 0.98. This indicates the filtered base flow

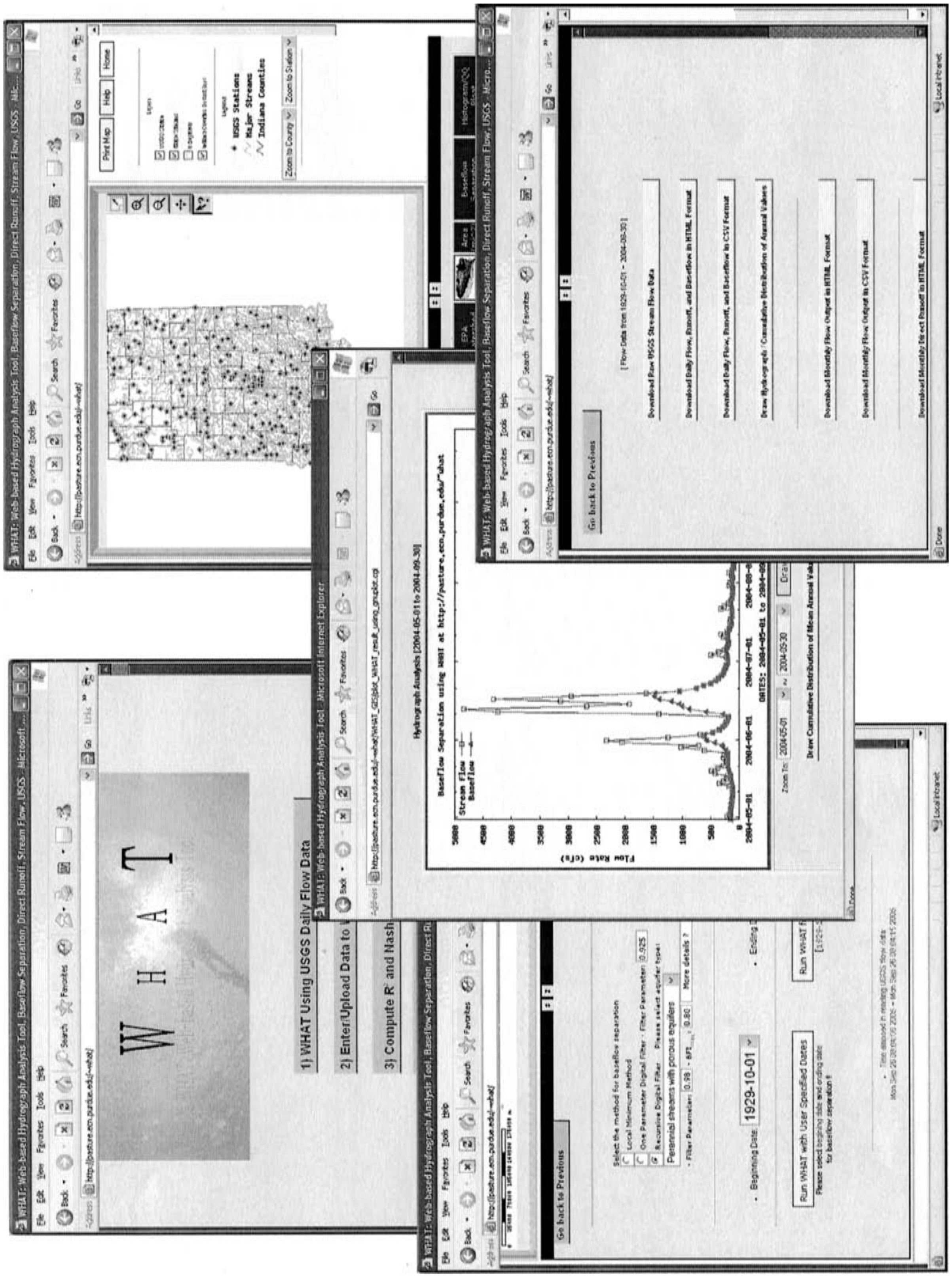

Figure 3. WHAT Web GIS Interface. (a) WHAT Web Interface, (b) Web GIS Interface, (c) Data Break Checking in USGS Daily Streamflow Data, (d) Daily, Monthly, Yearly Streamflow, Direct Runoff, and Base Flow Output in Tabular and Spreadsheet Format, and (e) Hydrograph for User Specified Time Period.

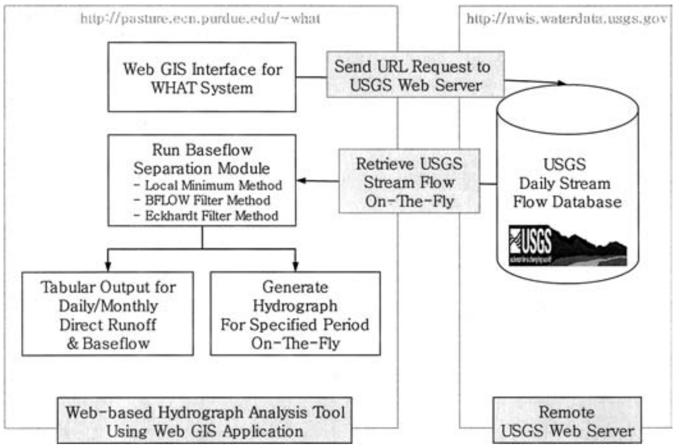

Figure 4. Overview of the WHAT Web GIS System for Base Flow Separation Using USGS Daily Streamflow.

using the Eckhardt filter should typically match base flow from manual separation and measured base flow.

CONCLUSIONS

Two digital filter methods, the BFLOW filter and the Eckhardt filter methods, were incorporated into the WHAT system because of limitations in the local minimum method of base flow separation from streamflow in the iSep system. A statistical component was also developed to compute histogram and QQ plots for gaging station data, which provides fundamental information for flow frequency analysis and time series analysis. The WHAT system accesses and uses USGS daily streamflow data from the USGS web server for base flow separation. Thus, the WHAT system can be readily used for base flow separation for any USGS gaging station in the U.S. For users with

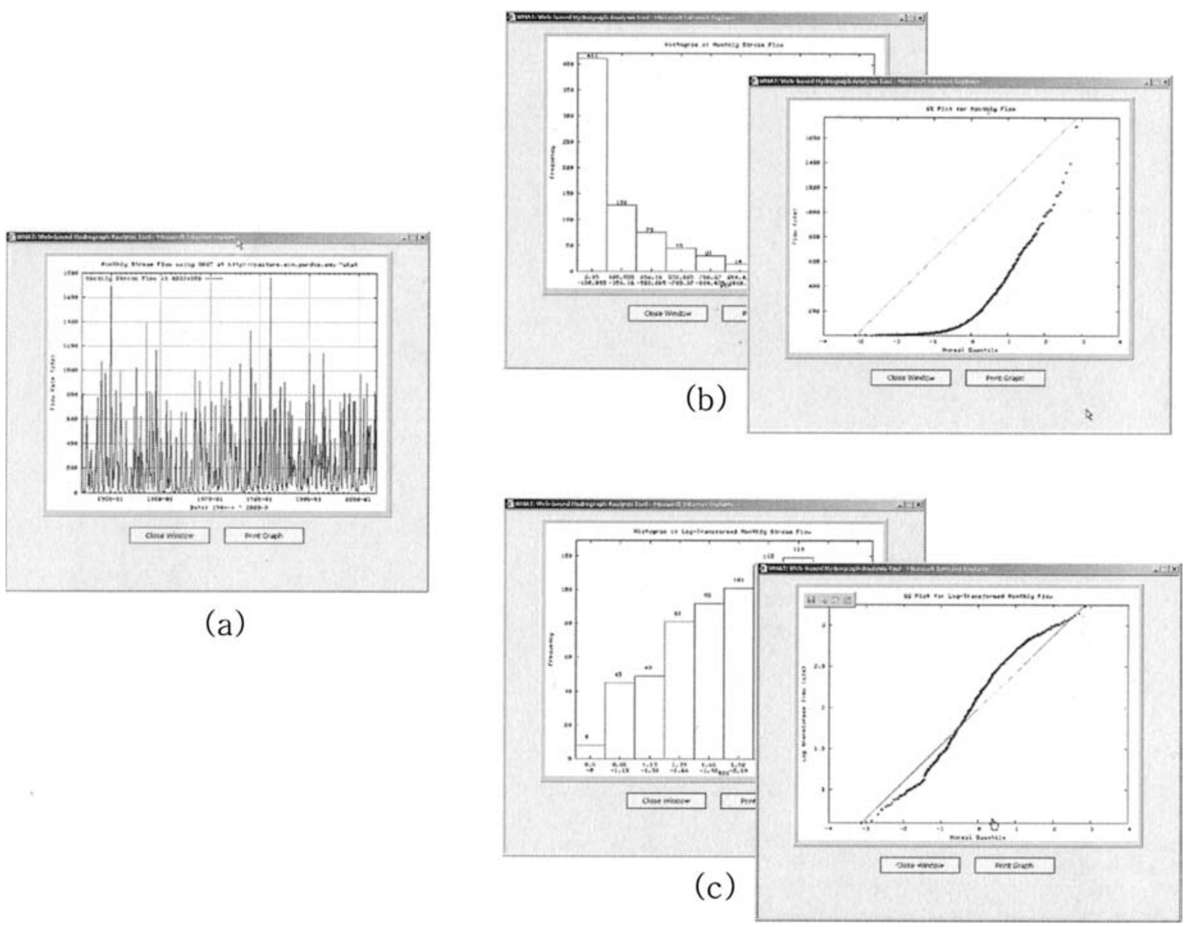

Figure 5. Statistical Component Results of the WHAT System: (a) Monthly Streamflow Hydrograph, (b) Histogram and QQ Plot of Raw Monthly Streamflow Data, and (c) Histogram and QQ Plot of Log Transformed Streamflow Data.

local datasets, users can enter or upload flow data to the WHAT server for base flow separation.

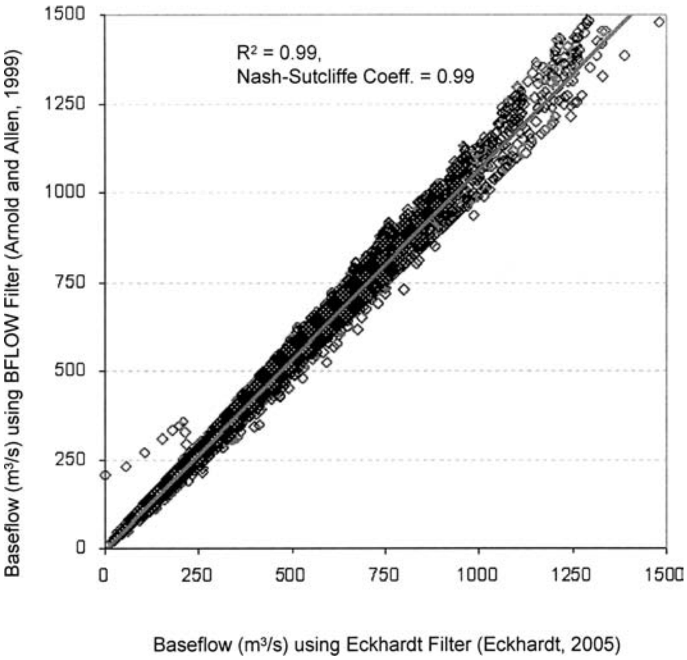

Figure 6. Comparison of Filtered Base Flow Using Eckhardt Filter and Filtered Base Flow Using the BFLOW Filter for USGS Gaging Station 03341500 in Indiana.

The filtered base flow data using the Eckhardt filter method were compared with the results using the BFLOW filter method for 50 gaging stations in Indiana, because the BFLOW results had previously been compared with manually separated and measured base flow data and showed a good match (R^2 value of 0.83). The Nash-Sutcliffe coefficient and the R^2 values for this comparison were over 0.9 for all gaging stations, which indicates the filtered base flow using the Eckhardt filter method will typically match measured base flow. Compared with the manual separation of base flow from streamflow, which can lead to inconsistencies in the results, the WHAT system provides consistent results in less than a minute. Although the base flow separation algorithms in the WHAT system cannot consider external factors, such as reservoir releases and snowmelt that can affect stream hydrographs, the Web GIS based WHAT system can be efficiently used for hydrologic model calibration and validation.

This approach demonstrates how remotely located resources can be shared through the Internet using Web programming. As the USGS updates its database, the WHAT system can retrieve the latest data through the URL request to the USGS server. The USGS provides the daily stream flow in Extensible Markup Language (XML) format, so efforts are underway to parse the streamflow data in XML format directly with XML programming. This will eliminate the time to retrieve data from the remote server and save it to the WHAT server. Also, an advantage of using the Web GIS version of the WHAT system is that it provides a graphical interface that complements the text based USGS daily streamflow query and retrieval website.

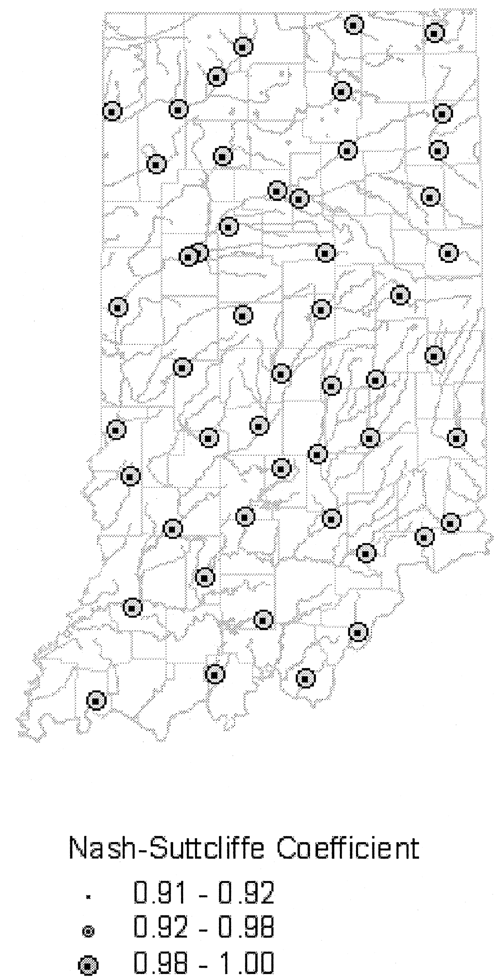

Figure 7. Comparisons of Filtered Base Flow Using BFLOW and Eckhardt Filter Method for 50 Indiana Gaging Stations.

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