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Regional estimation of base flow for the conterminous United States by hydrologic landscape regions

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Summary Information on base flow availability and/or contributions is needed to develop water quantity and water quality management strategies. Base flow availability varies over space and time in a region due to climate, topography, landscape, and geological characteristics. In this study, base flow index (BFI) (base flow/total stream flow) was estimated from daily streamflow records using a recursive digital filter method and interpolated to produce a raster grid map for the conterminous United States. When compared for validation, BFI estimated by recursive digital filter method showed good agreement overall with the USGS smoothed minima BFI method. Estimated base flow index and volume were analyzed, with Hydrological Landscape Regions (HLRs) developed for the United States to identify the mean hydrologic flow response within HLR. They were also used to determine relationships with hydro-geologic descriptive variables and used for defining the HLRs based on Pearson's correlation table and a stepwise multiple regression. These descriptive variables used in defining the HLRs include relief, effective rainfall, potential evapotranspiration and percentage of sand. The regression results indicated that relief and percentage of sand were highly correlated to base flow index, and the amount of base flow volume can be related to gradient and the amount of effective rainfall. The regression results also suggested that the descriptive variables used in constructing the HLR can be used to define mean values of shallow ground water flow within the regions. Further testing is needed to ascertain if such relationships could be used to define flow within an HLR.

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Introduction

A new concept — based on a regional framework — is needed to assess water quality and quantity at continental scales (Wolock, 2003a). Regional frameworks such as ''Ecoregions'' (Omernik and Bailey, 1997) and ''hydrologic landscape regions'' (HLR) (Wolock et al., 2004) have gained importance among government and other agencies. These agencies are interested in addressing water quality and quantity issues across local, state, and federal boundaries with a regional framework in a holistic perspective (Simon et al., 2004). A regional framework considers aggregation of spatial patterns of hydrological, geological, biotic and abiotic characteristics, and any other factors considered being useful to broaden the approach for management of resources. Several studies focused on the regionalization concept. Regionalization of streamflow characteristics is based on the premise that catchments with similar geology, topography, climate, vegetation, and soils would have similar streamflow responses (Smakhtin, 2001; Winter, 2001; Wolock, 2003a). The concept of hydrological landscape regions (HLRs) is based on the idea that a single, simple physical feature of the land, termed a fundamental hydrologic landscape unit, controls the hydrologic response of an area (Winter, 2001; Wolock et al., 2004). While HLR and similar concepts appear sound, they have neither been tested against regional hydrologic variables, nor for integrity of the delineated regions especially at 'continental scale'. Wolock et al. (2004) and Winter's (2001) hypothesis is that the watershed areas can be separated with reference to physical attributes and these can be correlated to ground water flow. This hypothesis has been attempted by several studies. Lacey and Grayson (1998) have attempted to relate the base flow to catchment properties in southern part of Australia. Neff et al. (2005) used base flow separation coupled with surficial geology classes and percentage of surface water to predict base flow at ungaged sites within the Great Lakes basin using regression models. Their model predicted the observed base flow at individual gages up to 89 and 94% of the time. These studies indicate the usefulness of regional base flow separation for prediction of general ground water contribution to streams in ungaged areas. In the present study, the authors have related landscape regions and the hydro-geologic variables within them to base flow at 'continental scale' in the United States.

Base flow is an important component of the ground water system. It is the component of streamflow that is attributed to ground water discharge and other delayed sources such as snow melt into streams. Reay et al. (1992) found that neglecting base flow (shallow ground water discharge) as a nutrient source to streams leads to misinterpretation of data and mismanagement. Knowledge on base flow availability is important in: development of water management strategies, especially for drought conditions; establishment of relationships between aquatic organisms and their environment; estimation of small to medium water supplies; and management of salinity, water quality, and algal blooms. In addition, base flow maintains flow for navigation, water supply, hydroelectric power and recreational uses in reservoirs (McMahon and Mein, 1986). Stuckey (2006) infers that studies estimating base flow contributions to streams are useful for watershed planners to determine water availability, water use allocations, assimilative capacity of streams and aquatic habitat needs.

Base flow displays spatial and temporal variability due to climate, land use, soils, frequency and amount of recharge, vegetation, topography, and geology (Stuckey, 2006; Delin et al., 2007). At the continental scale, Heath (1984) divided the United States into ground water regions based on rock units; however, he neither addressed topography nor climate. Vogel and Kroll (1992) statistically categorized regions and assessed many geomorphic variables, but did not incorporate findings into definable landscape regions.

This study substantiates the relationship between base flow and hydrologic landscape regions. As the variability of base flow is key to the understanding of the ground water system, and hydrologic landscape regions have defined the spatial variations in hydrologic characteristics, this study will test their degree of interrelationship and thus their potential as a tool in water resources management. The specific objectives of the study were to:

(1) estimate base flow index using the recursive digital filter method for the conterminous United States;
(2) analyze the hydrologic response (base flow and surface runoff) of hydrologic landscape regions of the United States using the estimated base flow index and base flow volume, and
(3) determine the relationship between the base flow index or base flow volume and the hydro-geological characteristics (descriptive variables) of the hydrologic landscape regions.

The first part (''Methodology'' section) of the methodology describes the estimation of the base flow index and the volume for the conterminous United States and the second part (''Base flow analyses with relevance to hydrological landscape regions'' section) describes how the hydrologic landscape regions are related to base flow index and base flow volume in the conterminous United States. Results and inferences made from both of these parts are discussed in ''Results and discussion'' section.

Methodology

Estimation of base flow index for the conterminous United States

In general, base flow is estimated through hydrograph analysis by separating streamflow into surface runoff and base flow. The separation is often estimated by using standard analytical methodologies or tracer techniques or a mass balance approach (Pinder and Jones, 1968; McCuen, 1989). Several analytical methods have been developed to separate base flow from streamflow. Neff et al. (2005), Scanlon et al. (2006) and Nolan et al. (2007) reviewed the relative merits of several base flow separation methods including recursive digital filter methods. Although, most of these methods are based on physical reasoning, exact separation of the streamflow hydrograph into surface flow and ground water flow is difficult and time consuming, especially, if

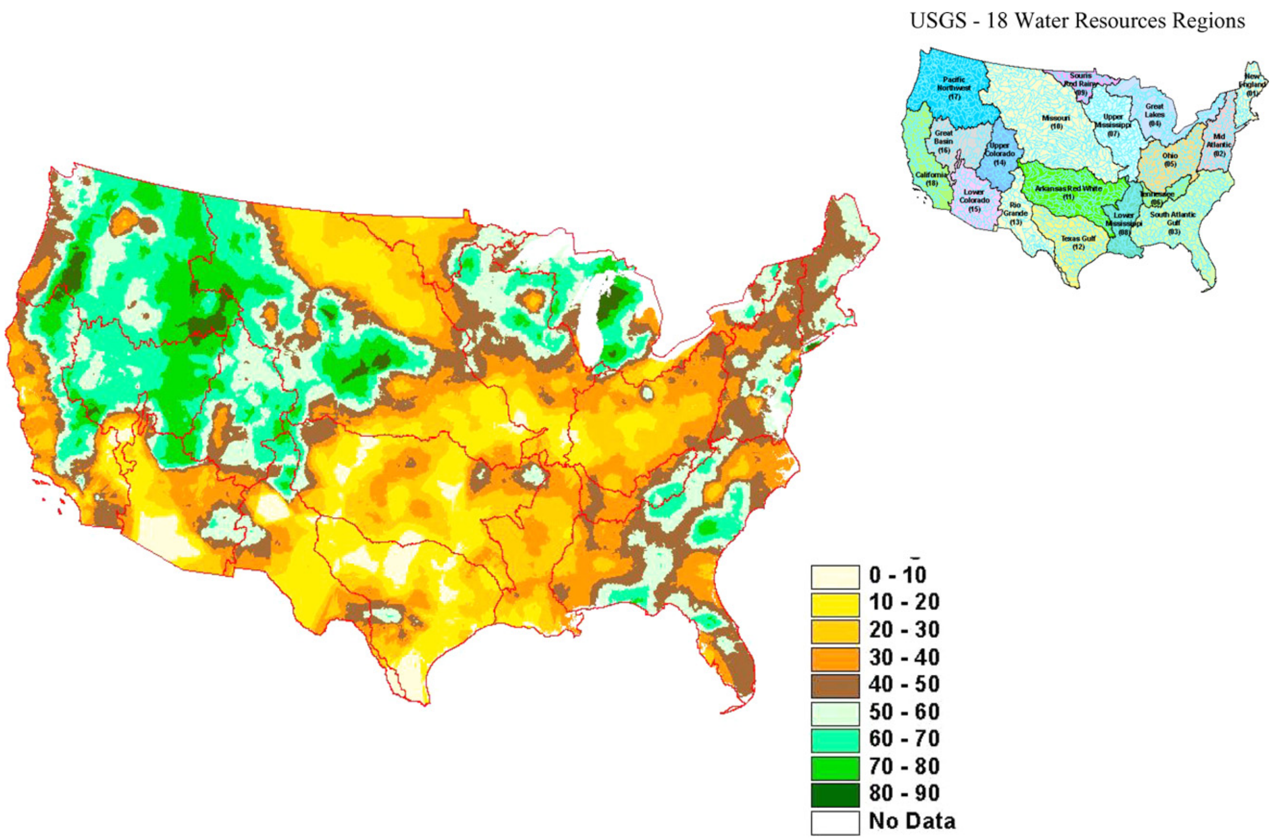

Figure 1 USGS grid map of the base flow index (in %) for the conterminous United States developed from USGS BFI method.

there is a need to deal with regional scale studies. In addition, while such separation methods are valuable in indicating regional trends in the base flow and surface flow, they require long term continuous streamflow data without missing values.

Base flow filters are of two types; the United Kingdom (UK) smoothed minima method (Institute of Hydrology, 1980; Wahl and Wahl, 1988) and the recursive digital filter method (Nathan and McMahon, 1990). The smoothed minima method is described below, followed by a discussion of recursive digital filter method which is used in this paper (Nathan and McMahon, 1990; Arnold et al., 1995).

Smoothed minima method or USGS BFI method

The US Geological Survey (USGS) has developed a base flow index raster data set for the conterminous United States using base flow index (BFI) program (Wahl and Wahl, 1988, 1995; Wolock, 2003a). The BFI program implements a deterministic procedure proposed in 1980 by the Institute of Hydrology in the United Kingdom. The method combines a smoothed minima approach with a recession slope test. The BFI program uses a set of procedures in which the water year is divided into *N*-day period (number of days, say 5 days or less) and the minimum flow during each *N*-day period (say, 5 day period) is identified. Each fixed period minimum is then compared to adjacent minima to determine turning points on the base flow hydrograph. Straight lines drawn between turning points on a semi-logarithmic paper define the base flow component of the stream hydrograph; the area beneath the hydrograph is the estimate of the base flow volume for the period (Wahl and Wahl, 1995). The ratio of this volume to the total streamflow volume for the period is defined as the base flow index.

Wolock (2003a,b) estimated the BFI values for the conterminous United States using streamflow records of 8249 selected stream gages. These values were used to prepare the grid map for the conterminous United States (Fig. 1) using inverse distance weighting interpolation method. The grid was constructed to assess the base flow at ungaged streams. The authors found that drainage area explained 67% of the BFI variance.

Recursive digital filter technique

The digital filter method used by Nathan and McMahon (1990) was originally used in signal analysis and processing (Lyne and Hollick, 1979). Filtering surface runoff (high frequency signals) from base flow (low flow signals) is similar to the filtering of high frequency signals in signal processing. The equation of the filter program is

$$q_t = \beta q_{t-1} + (1+\beta)/2 * (Q_t - Q_{t-1}) \quad (1)$$

where q_t is the filtered surface runoff at time step t, Q_t is the original streamflow and β is the filter parameter. Base flow b_t is calculated using the equation

$$b_t = Q_t - q_t \quad (2)$$

In this technique, the filter can be passed over the streamflow data three times (forward, backward, and forward). Passing the filter through the streamflow data multiple times systematically lowers the percentage of base flow.

In general, each pass will result in less base flow as a percentage of total flow. This option gives the user some flexibility in adjusting the separation more accurately to approximate site conditions. Arnold et al. (1995) have provided a detailed description of this technique and compared the digital filter results with results from manual separation techniques and with the PART model (Rutledge, 1993; Rutledge and Daniel, 1994) for 11 watersheds in Pennsylvania, Maryland, Georgia, and Virginia (White and Slotto, 1990). Annual base flow estimated from the filter method was on an average within 11% of base flow estimated by manual techniques and the PART model. Another study by Mau and Winter (1997) found that the filter method agreed reasonably well with the graphical partitioning method. Neff et al. (2005) used six hydrograph separation methods to estimate the base flow in the Great Lakes region of the United States. The six methods were: the PART method (Rutledge, 1993; Rutledge and Daniel, 1994), digital filter method (Arnold and Allen, 1999), three different methods of HYSEP (Sloto and Crouse, 1996), and UK Institute of Hydrology (UKIH)'s modified smoothed minima method (Piggott et al., 2005). These authors concluded that the recursive digital filter method gave the same range of separation but averaged the lowest total base flow index of the six methods. As mentioned earlier, the base flow index value varies depending on the number of passes. It was not stated how many passes of the filter were used in the filter method in their study so direct comparison of the methods is difficult. However, the UKIH method is similar to the USGS BFI method and the reported minimum BFI values were closer to the filter method. When UKIH and digital filter methods were compared, the maximum BFI values estimated were within 5% and the average was within 6% (Neff et al., 2005). Based on the studies conducted in southern Australia, Nathan and McMahon (1990) have indicated that the recursive filter method is found to be stable, reproducible, and objective method of continuous base flow separation when compared to smoothed mimina method. Stable estimates are helpful in characterizing the catchment conditions. Hence, recursive digital filter method was used in this study.

Selection of gaging stations for recursive digital filter method

In the current study, nearly 8600 USGS stream gage locations distributed across the conterminous United States were selected to estimate the base flow index using the recursive digital filter method. Gages were selected with drainage areas of 50–1000 km^2 to minimize the effects of flow routing, and limit the influence of reservoir releases, and each selected gage had a minimum of 10 years of daily streamflow observations. The digital filter method (Arnold et al., 1995) was used to estimate the base flow index (expressed in percentage) from daily streamflow records for the selected gages during low ET months. These base flow index values were used to develop a smooth grid map of the base flow index values using inverse distance weighting spatial interpolation method (Fig. 2).

It is important to interpolate point data to get a continuous grid surface that could be overlayed on smaller watersheds in the contiguous US for regional scale analysis of base flow index. The base flow index used for interpolation is estimated during low ET forcing (i.e., during nonsummer months) from selected stream gauging stations that have contributing drainage areas in the range 50–2000 sq. km, and unaffected by dams and reservoirs. It is assumed that the base flow index at any particular gage

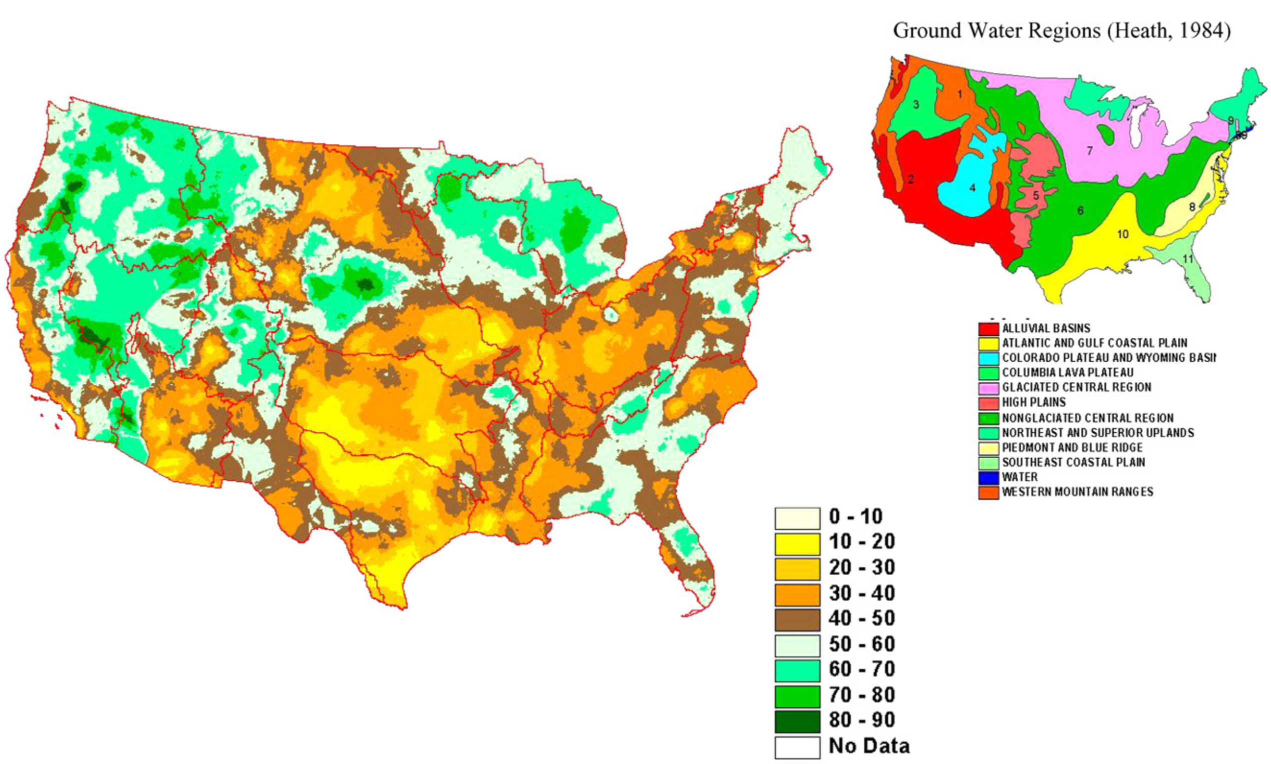

Figure 2 Grid map of the base flow index (in %) for the conterminous United States developed from digital filter method.

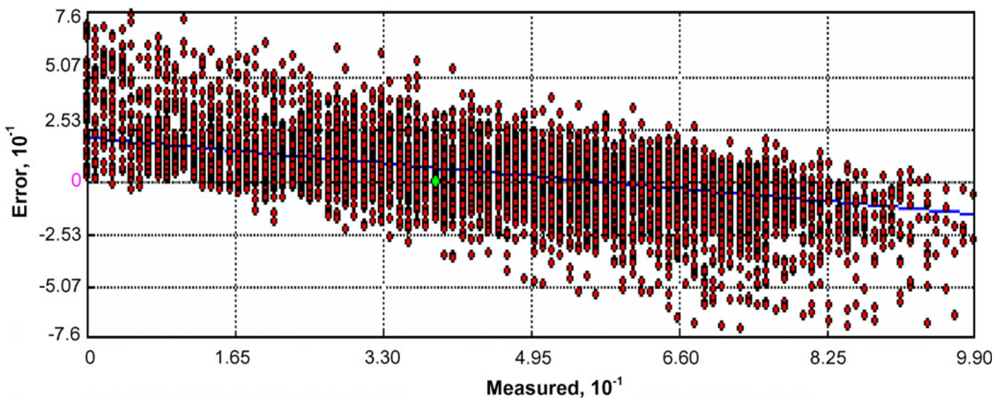

Figure 3 Error (predicted (interpolated) − actual base flow index values) against the measured base flow index at the gages selected for digital filter method.

occurs within the contributing drainage area. The base flow index is a volumetric ratio between base flow and total flow volume, limiting the direct influence of drainage area. At the same time, it is realized that the interpolation results may introduce errors or uncertainty. The potential error that could be introduced due to interpolation was quantified (Fig. 3). It could be observed from Fig. 3 that most of the error (interpolated − measured base flow index expressed in fraction) were within 25%. Further analysis indicated that in 90% of the gages studied, the differences between actual and measured base flow index values were within 25%. This is considered to be reasonable at a continental scale and proceeded further with the interpolation. A grid resolution of 1000 m and the inverse distance weighting interpolation method were used in the present study to be consistent with the USGS approach and direction comparison is possible. The standard error between the actual and interpolated base flow index values were estimated using the Kriging method as well and this analysis indicated that error could vary from 12% to 22% depending on the region of the US.

Comparison of base flow index estimated by digital filter method with base flow index estimated by USGS for the conterminous United States

The base flow index estimated using the digital filter method (Fig. 2) was compared with the base flow index estimates made by the USGS (Fig. 1) for validation. Base flow index estimated by both methods were summarized by the USGS delineated 8-digit Hydrologic Unit Catalogs (HUCs) and the residuals (difference in percentage of base flow) between the two methods (Fig. 4) were compared. Findings of the comparison are discussed in the ''Results and discussion'' section of this paper.

Estimation of base flow volume for the conterminous United States

In this study, the base flow volume (Fig. 5) was estimated using the base flow index values estimated from the filter method for the conterminous United States. Total flow volumes were estimated by interpolation of total flow contours for the conterminous United States prepared by Gebert et al. (1987) using measured streamflow data from 5951 USGS gaging stations across the country unaffected by reservoirs, diversions, or return flow. Base flow volume was then estimated by multiplying total flow volume map with digital filter base flow index map. For the total flow interpolation, a study by Rochelle et al. (1989) on the uncertainty analysis of total flow estimates from the flow contour map has shown that uncertainty could be about 15% due to interpolation. Interpolation was also used by Gebert et al. (1987), when they developed a spatially complete flow map of the US. Rochelle et al. (1989) have also concluded that interpolation from a total flow contour map provides adequate estimates for un-gauged systems and recommended using total flow contour maps for environmental issues at regional scale.

The stream flow records of the gages used for estimating the base flow index grid map varied in period depending on the availability of gage data, mostly pre 1989. The base flow volume map was prepared using the total flow contours that used 30 years of stream flow records (1951—1980) (Gebert et al., 1987). Although the two data sets used were not exactly of the same period, both of these data sets had significant temporal overlap. A temporal period of about 30 years is considered an adequate period for long term averages (as used by the meteorology community), and the base flow volumes shown in the study were also long term averages. The average annual total flow value is a good indicator to get representation of the hydrology and it was used for obtaining the base flow volume map for the entire US. Moreover, these contours are interpolated and used widely by several authors for regional scale studies (Wolock and McCabe, 1999). It is the only source of obtaining flow information for the entire US. Hence, the current approach used in this study is considered better as using original data may create gaps and increases uncertainty.

Base flow analyses with relevance to hydrological landscape regions

This section describes how the base flow index and base flow volume can be related to the hydrologic landscape regions in order to fulfill objectives 2 and 3.

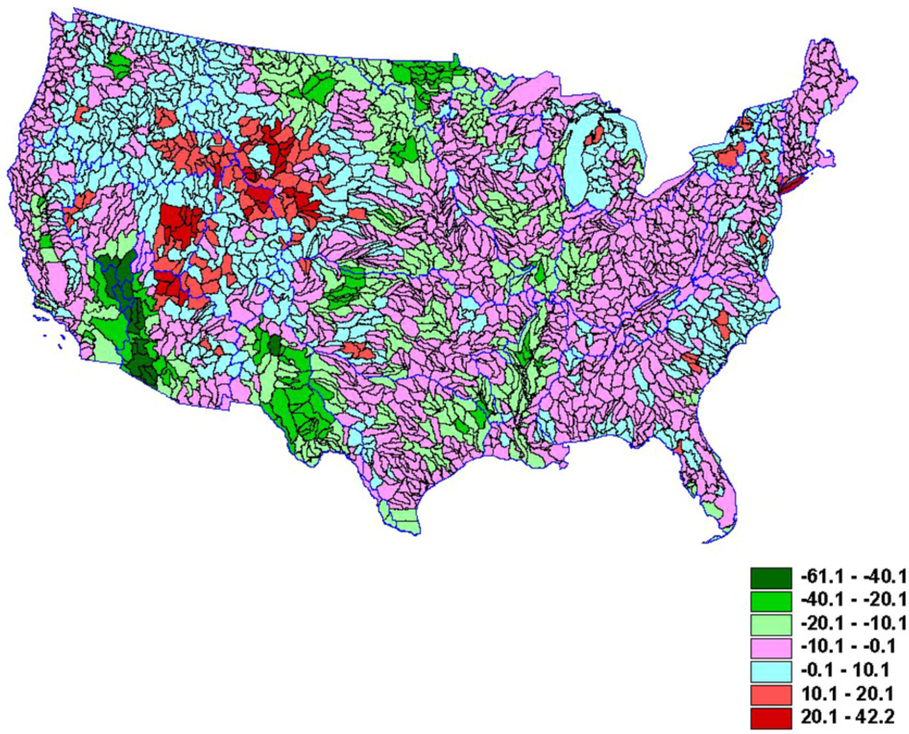

Figure 4 Residuals (in %) of base flow index at 8-digit HUCs between the USGS base flow index and recursive digital filter methods.

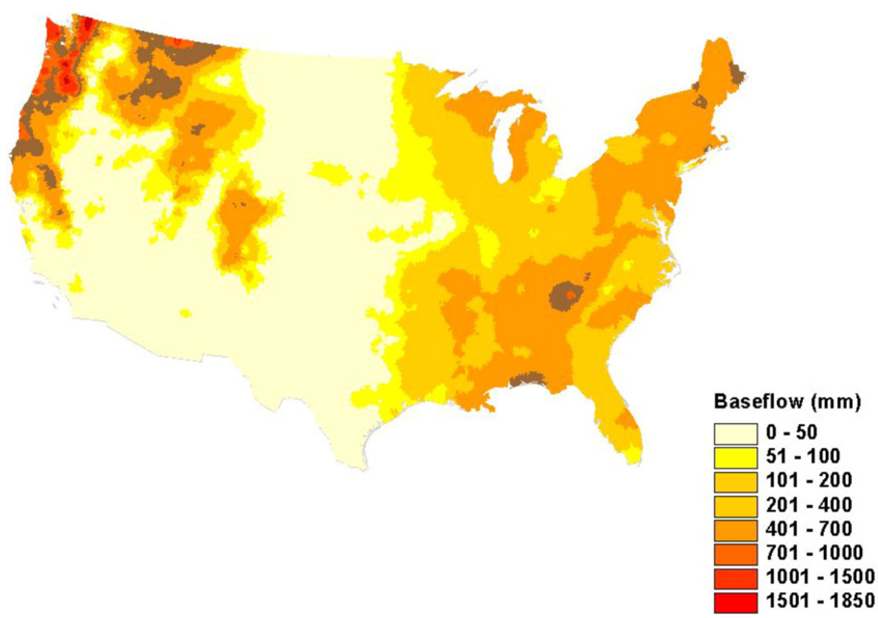

Figure 5 Base flow volume estimated for the hydrologic landscape regions from filter base flow index and USGS total flow.

Hydrological landscape regions

In the present study, the concept of hydrologic landscape regions developed by Wolock et al. (2004) is used for analysis. According to Wolock et al. (2004), the hydrologic system of a fundamental hydrologic landscape unit consists of: (a) the movement of surface water, which is controlled by the slopes and permeability of the landscape; (b) the movement of ground water, which is controlled by the hydraulic characteristics of the geologic framework; and (c) atmosphere-water exchange, which is controlled by climate (Fig. 6). All hydrologic units are variations of fundamental hydrologic landscape units that can be used to define general landscape types. Also, the movement of water over the surface and through the subsurface of generalized landscapes is controlled by common physical principles regardless of the geographic location of the landscapes. The authors suggest that for example, in a landscape with low

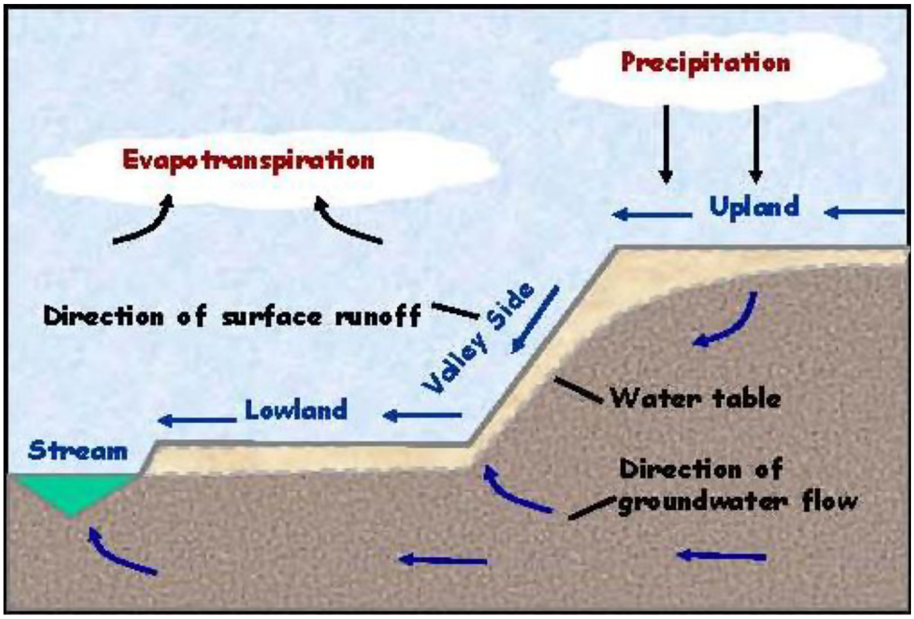

Figure 6 Fundamental hydrologic landscape unit concept (after Winter, 2001; Wolock et al., 2004; Courtesy: Liu, University of Arizona).

permeable soils, surface runoff will be extensive and recharge to ground water will be limited.

Wolock et al. (2004) delineated hydrologic landscape regions in the United States using GIS techniques combined with statistical tools such as principal component and cluster analysis to land surface form, permeability of the soil and bedrock, and climate variables that describe the physical and climate setting of an area. These authors considered

(a) terrain characteristics such as relief, total percentage of flatland in the watershed, the percentage of flatland located in upland and lowland areas of the watershed for describing land-surface form;
(b) soil permeability (percentage of sand) and bedrock permeability for describing geological texture, and
(c) mean annual precipitation minus potential evapotranspiration (PET) to describe climate characteristics.

Using these characteristics, the authors delineated 43,931 small (approximately 200 sq. km) watersheds in the United States. These small watersheds were then grouped into 20 non-contiguous regions based on similarities in

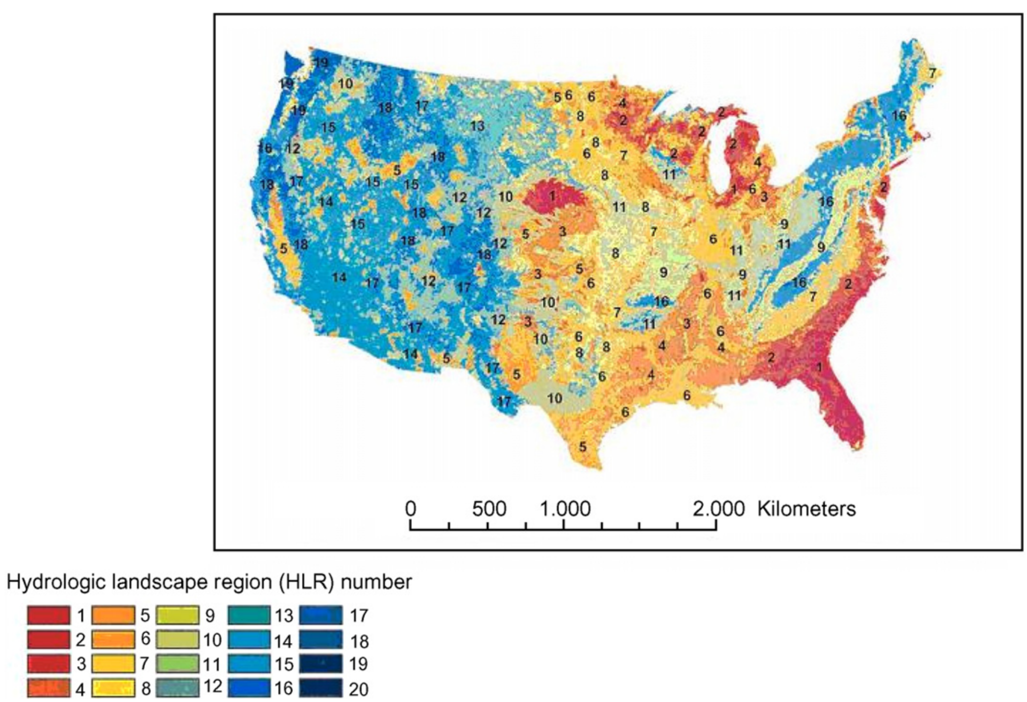

Figure 7 Hydrologic landscape regions of the United States (after Wolock et al., 2004).

Table 1 Revised hydrologic response of hydrologic landscape regions (HLRs) based on base flow index values

HLR	Description of hydrologic landscape region	Response to surface flow[a]	Response to ground water flow[a]	Overland flow % total (percentile)	Shallow ground water % total (percentile)	Total flow (mm)
1	Subhumid plains with permeable soils and bedrock		X	44(23.3)	56(78.8)	307
2	Humid plains with permeable soils and bedrock		X	43.1(20.0)	56.9(80)	379.3
3	Subhumid plains with impermeable soils and permeable bedrock	X		56.5(67.9)	43.5(31.9)	280.3
4	Humid plains with permeable soils and bedrock		X	56.3(67.3)	43.7(32.7)	376.1
5	Arid plains with permeable soils and bedrock		X	58.3(74.4)	41.7(25.5)	95.7
6	Subhumid plains with impermeable soils and bedrock	X		62.9(90.9)	37.1(9)	264.7
7	Humid plains with permeable soils and impermeable bedrock		X	52.5(53.7)	47.5(46.3)	416.0
8	Semiarid plains impermeable soils and bedrock	X		64.1(95.2)	35.9(4.7)	151.2
9	Humid plateaus with impermeable soils and bedrock	X		56.3(67.3)	43.7(32.7)	508.8
10	Arid plateaus with impermeable soils and permeable bedrock	X		54.4(60.5)	45.6(39.5)	92.2
11	Humid plateaus with impermeable soils and bedrock	X		61.1(84.5)	38.9(15.4)	411.7
12	Semiarid plateaus with permeable soils and impermeable bedrock		X	51.8(51.2)	48.2(48.8)	225.4
13	Semiarid plateaus with impermeable soils and bedrock	X		58.9(76.6)	41.1(23.3)	158.7
14	Arid playas with permeable soils and bedrock		X	43.2(20.4)	56.8(79.7)	99.2
15	Semiarid mountains with Impermeable soils and permeable bedrock	X		41.1(12.9)	58.9(87.2)	235.3
16	Humid mountains with permeable soils and impermeable bedrock		X	52.3(52.9)	47.7(47)	673.9
17	Semiarid mountains with impermeable soils and bedrock	X		49.2(41.9)	50.8(58.1)	227.3
18	Semiarid mountains with permeable soils and impermeable bedrock		X	43.1(20.0)	56.9(80.1)	468.6
19	Very humid mountains with permeable soils and impermeable bedrock		X	42.9(19.3)	57.1(80.7)	1586.7
20	Very humid mountains with permeable soils and impermeable bedrock		X	37.7(1)	62.3(99.4)	744.4

[a] Cell with X shows the hydrologic response for HLR from Wolock et al. (2004).

land-surface form, geologic texture, and climate characteristics (Fig. 7). An important aspect of HLRs is that the same region can occur in different parts of the United States.

Wolock et al. (2004) also used particular combinations of land-surface form, geologic texture, and climate characteristics to develop hypotheses on how the hydrologic system might function for a given hydrologic landscape. They developed a qualitative description to summarize the mean hydrologic landscape characteristics for each HLR as shown in Table 1 and column 1.

Hydrologic response of the hydrologic landscape regions based on base flow index values

The total flow and base flow for each HLR were estimated by overlying total flow volume map and base flow volume map (as described in ''Estimation of base flow volume for the conterminous United States'' section) individually with HLR map of the United States. Mean annual percentage of base flow and surface flow for each HLR were calculated using the total flow volume and base flow estimated for each HLR (Table 1). This information was used to analyze the hydrologic response (mean hydrologic characteristics such as predominance of base flow or surface flow) in each HLR. Statistical analysis of the base flow index and base flow volume for the HLRs were also performed (Table 3).

Relationship of base flow index and base flow volume with hydro-geological variables used for defining the HLR

Wolock et al.'s (2004) hypothesis is that a watershed area can be separated based on physical attributes which can be correlated to ground water flow. However, it has not been tested against regional hydrologic variables, especially at a 'continental scale'. In this study, the mean base flow index and the base flow volume estimated for the HLRs were used to determine the relationship with the descriptive hydro-geologic variables, that were used to delineate the HLRs, using Pearson's correlation and stepwise regression analyses. The descriptive variables used include relief, percentage of flatland in upland and lowland, soil permeability in terms of percentage of sand and bedrock permeability, and potential evapotranspiration and precipitation.

Results and discussion

Comparison of digital filter base flow index with USGS base flow index

Figs. 1 and 2 show the base flow index estimated by the USGS BFI method and digital filter method, respectively. The filter BFI values satisfactorily matched with the USGS BFI method estimates in most of the USGS delineated water resources regions[1] (shown as part of Fig. 1) of the United States except for some minor variations in certain parts of Colorado rocky mountains, southwest irrigation belt and southwest Florida.

When compared by the ground water regions[2] classified by Heath (1984) (shown as part of Fig. 2), both methods showed high base flow index values in the northwestern United States including Columbia Lava Plateau, Northern Colorado Plateau, Rocky Mountains, and Northern Nonglaciated Central Region, and Northern High Plains. High base flow index values were also seen in the Great Lakes Region and in portions of the Appalachian Piedmont and Blue Ridge Region. The mid-continent including Nonglaciated Central Region, Glaciated Central region, Alluvial Basins of the Western United States, and Atlantic and Gulf Coastal Plains exhibited lower BFI values.

Although Figs. 1 and 2 could show the comparison of the base flow index for the digital filter and USGS base flow index methods, comparison of base flow estimates at lower discretized watershed level will capture the spatial variability and provides useful information for regional scale planning. The interpolated base flow estimates were overlaid and averaged at the USGS delineated 8-digit watersheds (HUCs) for comparison or validation with USGS base flow index estimates. [The USGS has delineated the watersheds in the conterminous United States using a nationwide system based on surface hydrologic features in a hierarchical approach. This system divides the country into major regions (2-digit), subregions (4-digit), accounting units (6-digit), and cataloguing units (8-digit). There are 2108 of those 8-digit watersheds and they follow the 18 major river basin configuration].

(a) comparing both the USGS method and digital filter method against manual interpolation for several watersheds, and (b) comparing digital filter method with field estimates on three Illinois watersheds were discussed (Arnold et al., 1995). Although it was not possible to test the accuracy of the base flow estimates across the entire US, comparison of USGS method against the digital filter method can provide validity of the digital filter method.

Regression relationship of base flow index of the USGS BFI method and digital filter method at 8-digit HUCs showed a R^2 value of 0.7 and slope of 1.1. Residuals between USGS BFI method and digital filter method at the 8-digit HUCs (difference in the average base flow index value) indicates that in majority of the 8-digit HUCs (73% of the total 8-digit HUCs), base flow index estimated by filter method was within ±10% of the USGS BFI method (Fig. 4). In 21% of the 8-digit HUCs, base flow index estimated by digital filter method was within ±(10 to 20)% of USGS BFI values. Only in 6% of the total 8-digit HUCs, the base flow index estimates of the filter method were greater than ±20% when compared with the USGS BFI method. Hence, overall results indicated that filter method agreed reasonably well with the USGS BFI method. The residual map also indicates that there were noticeable variations between the two methods in the southwest and rocky mountains, areas where there is irrigation, dam construction and substantial snow melt. This is to be expected as neither method is designed to address these issues. In addition, the variations noticed between the two methods could be due to the differences in gaging stations used (location and streamflow data used) for estimating the base flow index in those areas.

Hydrologic response of the hydrologic landscape regions based on base flow index values

Mean base flow index and mean base flow volume estimated for the HRLs are shown in Fig. 8. Computed values of the total flow volume and mean annual percentage of surface flow and base flow for the HLRs are given in Table 1. Mean base flow as a percentage of total flow for the HLRs ranged from a high value of 62.3% (region 20) to a low value of 37.1% (region 6). A 50% cut off was assumed to identify whether a particular HLR is dominant in surface flow or base flow. Regions with base flow contributions of more than 50% include 1, 2, 14, 15, and 17 through 20 and the remaining were predominant in surface flow. HLRs that were identified to be predominant in base flow and surface runoff from this study were compared with the hydrologic response of HLRs that were proposed on a qualitative basis by Wolock et al. (2004). Wolock et al. (2004) took each descriptive variable in Table 2 and normalized them in a linearising scale of 1–20 for all 20 regions. According to Wolock et al. (2004), the regions in which base flow predominated were regions 1, 2, 4, 5, 7, 12, 14, 16, and 18 through 20 and surface runoff predominated in the remaining regions. These regions are shown by the cells with ''X'' mark in Table 1.

When hydrologic response of HLRs that were identified to be dominant in base flow from the present study were compared with those identified by Wolock et al. (2004), there was general agreement across 14 of the 20 HLRs. From the present study, HLRs 4 and 5, which contain permeable soils and bedrock, have more surface runoff than base flow. HLRs 7 and 12 with permeable soils and impermeable bedrock, also seem to furnish more surface runoff. HLR 15 seems to furnish less surface runoff and more base flow and HLR 16 seems to furnish less base flow and more surface runoff than that inferred by Wolock et al. (2004).

In terms of predicted versus actual (calculated) hydrologic response, 30% of the predicted responses were in er-

[1] USGS has delineated the 18 major river basins in the United States as Water Resources Regions based on hydrological boundary using topography.

[2] Heath has classified the United States into 12 ground water regions (including water) based on geology and rock units.

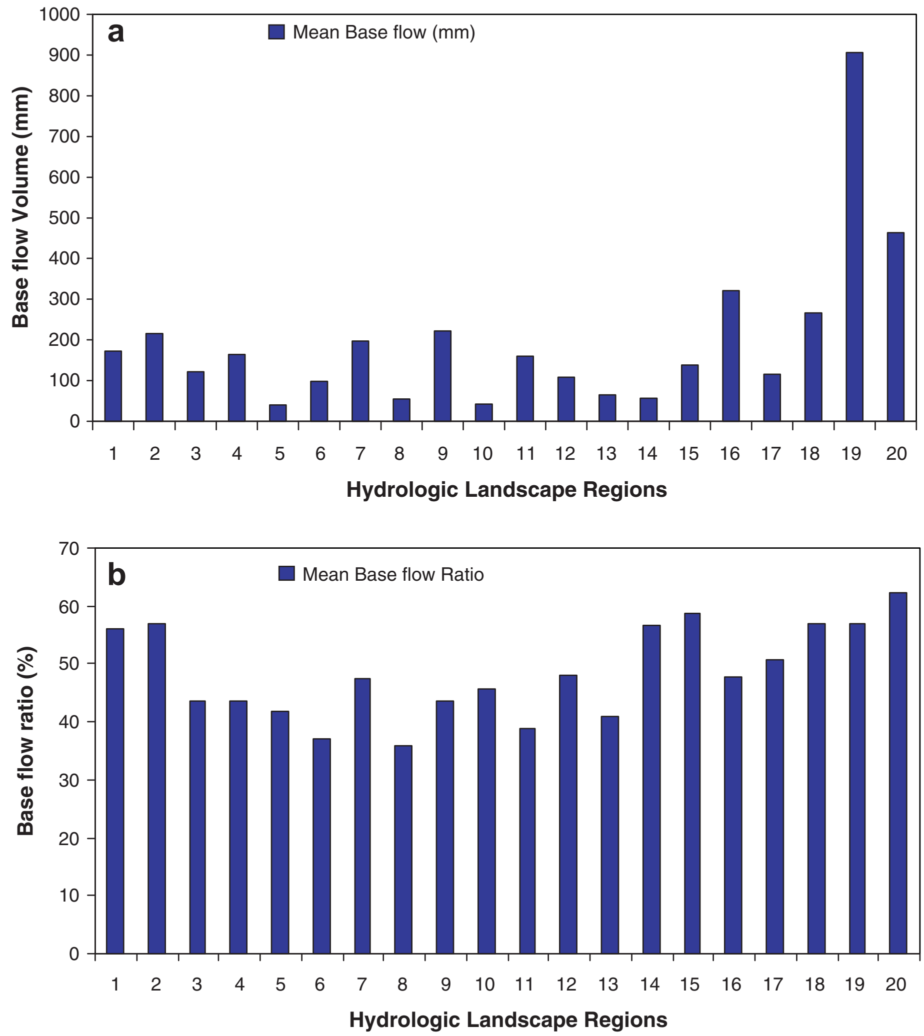

Figure 8 (a) Mean base flow ratio estimated for the hydrologic landscape regions in the United States. (b) Mean base flow volume estimated for the hydrologic landscape regions in the United States.

ror. These areas were in HLRs 4, 5, 7, 12, 15, and 16. Of these areas 7, 12, and 16 are within 5% of the predicted response which is considered to be well within the limit of prediction of such broad groupings (Table 2). Areas with major differences are HLRs 4 (12.6%), 5 (16.6%), and 15 (17.8%). HLR 4 is mapped in parts of the Northeast and Superior Uplands, Glaciated Central Region, and Gulf Coastal Plain (Fig. 2; Heath, 1984). The HLR description indicates this area is predominantly flat, with low relief, moderate bedrock permeability and percent sand in the surface soils, and abundant precipitation (P-PET) (Table 2). The predicted response from the hydrograph separation techniques indicated that overland flow was the predominant process in this region. This mapped region falls within three distinct geologic regions ranging from complex glacial stratiagraphy to varied sandy regions of the Gulf Coastal Plain. Of note in these regions are the high average annual runoff gradients (Gebert et al., 1987), ranging from 5 to 12 in. in the north to 8–20 in. in the south. With such gradients, accurate prediction of hydrologic response would require more detailed delineation of HLRs and a high density of gages. HLR 5 is mapped in the Gulf Coastal Plain, the High Plains, and Alluvial Basins (Heath, 1984, Fig. 2). The HLR description classifies this area as predominantly flat, with gentle to moderate relief, with relatively high bedrock permeability and moderate sand in surficial soils, but rainfall substantially lower than evapotranspiration. Within this region, the predicted response was for more surface runoff while Wolock et al. (2004) predicted more ground water response. Base flow separation techniques in these areas of low total runoff are not very accurate making this difference plausible. Finally, HLR 15 is mapped predominantly in the Alluvial Basin area (Heath, 1984: Fig. 2). The HLR description indicates this area contains moderate to moderately high relief, low percentage of flatland, moderate bedrock permeability and moderate percentage of sand in the surficial soil. Evapotranspiration exceeds rainfall.

The predicted response was more for ground water contribution while Wolock et al. (2004) response showed more surface runoff. Again, in areas of low total runoff (less 0.2 in.), base flow separation methods are questionable. In addition, recent study by Maurer et al. (2004) indicates that in such areas, more detailed delineations of HLR is warranted for accurate prediction of hydrologic response. The

Table 2 Mean values of land-surface form, geologic texture, and climate characteristics for HLRs (Adapted from Wolock et al., 2004)

HLR	Total flatland (%)	Flatland (%) in upland	Flatland (%) in lowland	Relief (m)	Bedrock permeability class	Sand (%)	Precipitation − PET (mm/yr)
1	92.5	36.5	56.0	50	5.8	69.7	213
2	82.8	28.2	54.6	73	2.7	61.9	64
3	86.0	28.3	57.8	98	5.8	20.1	119
4	82.7	29.8	52.9	73	2.6	36.0	323
5	78.0	20.2	57.8	233	4.0	39.0	−338
6	90.6	22.7	67.9	68	1.8	18.8	119
7	64.0	27.5	36.5	110	1.2	33.5	320
8	71.2	30.6	40.6	132	1.3	17.9	−58
9	41.7	17.4	24.3	213	4.9	22.4	394
10	37.5	16.5	21.1	290	4.9	30.1	−305
11	41.9	19.4	22.5	130	1.6	15.8	333
12	22.3	4.1	18.2	641	2.1	46.3	−191
13	30.3	11.4	18.9	257	1.5	24.0	−180
14	16.0	0.4	15.6	1225	4.1	47.9	−582
15	8.2	1.3	7.0	769	4.2	26.4	−249
16	10.8	3.3	7.5	452	1.5	33.6	505
17	7.6	1.2	6.4	665	1.5	29.6	−173
18	2.0	0.2	1.8	1174	1.2	40.7	−8
19	4.8	0.3	4.4	1129	2.2	39.5	1156
20	1.7	0.1	1.7	1966	1.4	41.7	11

m = meters; PET = potential evapotranspiration; mm/yr = millimeter/year.

Table 3 Sample statistics for annual base flow (in mm) for the HLRs

Sample size (HLR)	Minimum	Maximum	Std. dev.	Mean	25th	50th	75th	90th
N = 20	39.89	906.01	197.04	196.53	73.47	149.37	20.72	449.50

authors found subdivision of the State of Nevada into 16 regions was necessary in order to classify the hydrologic landscape. In Nevada, HLRs are being used as a framework to represent various hydrologic settings as part of a statewide evaluation of ground water susceptibility and vulnerability to pollution.

As mentioned earlier, it is to be noted that the qualitative description of each HLR was defined by classifying the variables in Table 2 on a relative scale among the 20 HLRs and therefore does not reflect the absolute values. Given the scale involved and the differences in the procedures used between the present study and that of Wolock et al. (2004), the differences in hydrologic responses in 6 regions are possible. Inferences made from this analysis were: (a) the qualitative hydrologic response assigned for HLRs by Wolock et al. (2004) were verified using the hydrologic responses for HLRs assigned on a quantitative basis from the present study and they seemed to agree overall; (b) for large scale planning and management strategies, qualitative descriptions made by Wolock et al. (2004) for analyzing the response of flow within an HLR was considered to be reasonable; and (c) further verification on the hydrological responses within an HLR, however, may be necessary for planning local scale studies.

Overall, the hierarchical approach, used by Wolock et al. (2004) is meant to provide a useful classification of landscapes at the regional scale for use in a variety of environmental management efforts. However, since hydrological processes interactions between controls are implicitly considered in this method, there is no room for specifying potential changes in the relative importance of controls with location or scale in a given HLR (Buttle, 2006). The study by Maurer et al. (2004) as well as statements by Wolock et al. (2004) acknowledge that the HLR could be used at a finer resolution, depending on the application. This study has shown that the classification approach appears to have merit in predicting regional variations of the hydrological landscape response. While differences in expected responses have been noted, it is thought that these are a product of the cited complexity in terrain, and perhaps, choice of discriminating variables.

Relationship of base flow index and volume with hydro-geological variables used for defining the HLR

In order to ascertain the relative importance of the descriptive variables used to delineate the HLR in the prediction of mean base flow index, Pearson's correlation table (Table 4) and a stepwise multiple regression was performed on the descriptive variables with base flow index value being the

Table 4 Pearson correlation for HLR variables and base flow index

Relief	P-PET	Sand	Bedrock	Total flatland	% Upland	% Lowland
−0.7324 (0.0002)	0.0054 (0.9820)	0.6703 (0.0012)	0.0899 (0.7061)	−0.5076 (0.0223)	−0.5035 (0.0236)	−0.4871 (0.0294)

The top number is the correlation value and the lower number is the probability for the 20 samples.

dependent variable. Pearson correlation table (Table 4) showed the correlation values and probability values of error of the descriptive variables (terrain, geology and climate variables) of HLRs with respect to the mean base flow index. Results of the correlation indicated that relief and percentage of sand were highly correlated to base flow index (Table 4).

The best fit equation from the stepwise regression resulted from the variables including relief and percentage of sand is

$$\text{Base flow index} = 33.5435 + 0.0091\ \text{Relief} + 0.3034\ \text{Sand} \tag{3}$$

where

Base flow index = base flow in percent,
Relief = maximum elevation minus minimum elevation in the watershed in meters,
Sand = percentage of sand in soil,
Relief and percentage of sand values are used from Wolock et al. (2004).

The coefficient of determination (R^2) estimated for Eq. (3) is 0.79 and the standard error of estimation is 3.84. Significance test was performed for the independent variables used in Eq. (3) using the regression coefficients and the standard error of the regression coefficients (Table 5) and this test showed relief and percentage of sand are highly significant.

A similar analysis was carried out to predict the volume of base flow in mm. Pearson's correlation (Table 6) indicated that the major variables correlated with the amount of base flow were relief and effective rainfall. The best fit equation resulted from the stepwise regression is

$$\text{Base flow} = 60.43 + 0.2145\ \text{Relief} + 0.4283\,P - (\text{PET}) \tag{4}$$

where

Base flow = Base flow volume in mm by HLR,
Relief = Relief in meters by HLR,
P = Precipitation in mm by HLR,
PET = Potential evapotranspiration in mm by HLR,
Relief and $P -$ PET are used from Wolock et al. (2004).

The regression coefficients for relief and effective rainfall (P-PET) are shown to be significant (Table 7). The R^2 estimated for Eq. (4) is 0.93 and the standard error of estimation is 54.75. Regression Eq. (4) indicates that area favorable for ground water development would have high effective rainfall and high gradients from streams to

Table 5 Results of significance test for the stepwise regression analysis of the base flow index

Estimate	Std. errors	*t*-Value	*P*-value
33.5435	2.3377	14.3492	6.24E−011
0.0091	0.0017	5.2916	5.98E−005
0.3034	0.0630	4.8151	0.0002

Table 6 Pearson correlation for HLR variables and base flow volume

Relief	P-PET	Sand	Bedrock	Total flatland	% Upland	% Lowland
0.5032 (0.0237)	0.7787 (5.25E−005)	0.1877 (0.4280)	−0.2310 (0.3272)	−0.4023 (0.0787)	−0.3654 (0.1131)	−0.4063 (0.0755)

The top number is the correlation value and the lower number is the probability for the 20 samples.

Table 7 Results of significance test for stepwise regression analysis of the mean base flow volume

Estimate	Std. errors	*t*-Value	*P*-value
60.4324	17.2463	3.5041	0.0027
0.2145	0.0240	8.9378	7.8E−008
0.4283	0.332	12.9138	3.25E−010

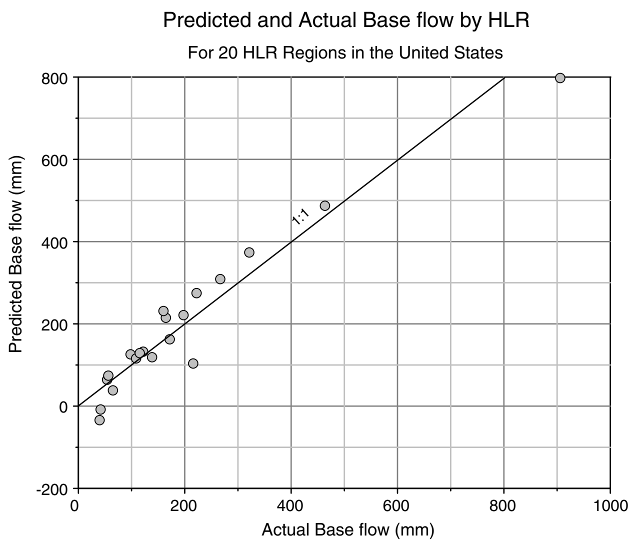

Figure 9 Actual and estimated base flow volume using stepwise regression relationship.

divides as also inferred by Olmsted and Hely (1962) in their study.

As an additional validation, a regression relationship (Fig. 9) was developed between actual base flow volume estimated for HLR (Fig. 8b) and the base flow estimated from the regression Eq. (4) and it showed good agreement.

The influence of basin relief on base flow is supported by many studies including Sefton and Howarth (1998), Gustard et al. (1989), Vogel and Kroll (1992), Berger and Entekhabi (2001) and Mazvimavi et al. (2004). The present study has shown that topography has influence on the base flow and study of McGuire et al. (2005) supports this. The relationship of base flow to geological characteristics of the basin is indicated by several authors (Bingham, 1986; Rutledge and Mesko, 1996; Lacey and Grayson, 1998; Neff et al., 2005). Similarly, a study by Mwakalila et al. (2002) indicated that there is a strong correlation between values of base flow with climate and geology in semi arid areas. The use of precipitation minus PET is supported by Wolock and McCabe (1999), who indicated that most (91%) of the spatial variability in mean annual runoff was explained by the spatial variability of mean annual precipitation minus mean annual potential evapotranspiration. Berger and Entekhabi (2001) and Sankarasubramanian and Vogel (2002) support similar use of such indices in continental scale modeling of rainfall–runoff relationships.

Results of the regression (Eqs. (3) and (4)) also suggest that the descriptive variables used in constructing the HLRs can be used to define mean values of shallow ground water flow within the regions. The percentage of base flow is tied to relief and surface permeability (percentage of sand) and the amount of base flow is tied to relief and effective precipitation within HLR. Similar to the approach used in this study, Neff et al. (2005) used hydrograph separation techniques and landscape features to predict the base flow index. They constructed two models, a geology model and a geology-surface water model which were based on more detailed analysis of surficial geology and amount of water bodies within the watersheds. Predicted BFI values were within 10–20% of the BFI calculated by hydrograph separation analysis, similar to results obtained in this study.

Summary and conclusions

The base flow index has been estimated from daily streamflow records using a recursive digital filtering method and a raster grid map of the results was developed for the conterminous United States. The base flow index estimated by the digital filter method showed good agreement with the USGS BFI method and both methods showed similar regional trends. GIS interpolation procedure was used for estimating base flow index from point data and extrapolate to a continuous surface. The error introduced by this interpolation was also quantified.

The base flow volumes were also estimated for the conterminous United States using the base flow index estimated from the digital filter method. It is important to note (Fig. 2) that although the base flow index seemed to be high in western part of the United States including parts of Columbia River Basin, Great Lake Basin, Missouri and Upper Colorado River Basins, the estimated base flow volume (Fig. 5) available seemed to be lower in the order of 50 mm. The low base flow volumes observed for these regions are due to the limited total flow occurring in those regions. This clearly indicates that low flow (base flow) conditions are critical for water quality and quantity management. Mean base flow index and volume estimated for HLRs (Fig. 8) also showed similar observation. The base flow index and volume estimates made for the conterminous United States from this study would be helpful for many studies related to water quantity and quality planning and management. Base flow information from this study could also be used for research purposes including hydrologic model validation of surface and base flow components.

Base flow indices and base flow volumes were estimated for given HLRs for regionalization purpose. This analysis indicated that mean hydrologic characteristics of the HLR inferred qualitatively by Wolock et al. (2004) were in agreement with quantitative estimates made from this study in most of the HLRs defined for the conterminous United States.

The estimated base flow volume was analyzed to determine general relationships with hydrological characteristics such as climate, terrain, and geological characteristics using the HLRs of the United States. Pearson's correlation table and a stepwise multiple regression were performed to ascertain the relative importance of the descriptive variables (such as relief, effective rainfall, and percentage of sand) to discriminate the HLRs in terms of BFI and base flow volume. Results of the correlation indicated that

(a) relief and percentage of sand were highly correlated to base flow index, and
(b) the amount of base flow volume (in mm) depends on the gradient and the amount of effective rainfall.

Regression results also suggest that the hydro-geologic descriptive variables used in constructing the HLRs can be used to define mean values of shallow ground water flow within the regions. However, further testing is needed to ascertain if such equations or relationships could be used to define flow within an HLR.

Recent studies involving use of regressions to estimate base flow have illustrated the need to incorporate more detailed information at the local scale. Stuckey (2006) indicated that base flow could be predicted within standard error of 21–23% from 195 gages in Pennsylvania and surrounding states. However, the regression model used other variables such as contributing drainage area, mean annual precipitation, percentage of the basin underlain by carbonate rocks, percentage of forested area, and percentage of urban area.

Delin et al. (2007) used the results of base flow separation coupled with soil characteristics (specific yield) and climate to calculate a regional regression equation used to predict statewide recharge in Minnesota. Neff et al. (2005) used base flow separation coupled with surficial geology classes and percentage of surface water to predict base flow at ungaged sites within the Great Lakes with regression models.

The above studies indicated the usefulness of regional base flow separation for prediction of general ground water contribution to streams in ungaged areas. These studies also indicated that many of the variables used in the HLR approach are also those variables found to be most important in local studies for prediction of base flow. While such inferences are possible, several limitations need to be addressed. The base flow values represent the average for the region over the long term and cannot reflect seasonal or inter-annual variations. Accuracy of the values is related to the hydrograph separation techniques although they are reproducible, are not physically based. Finally, the modeled results are limited by the general nature of the HLR units, and the detail inherent in the various data sets. HLR concept has been shown to be a useful planning tool which can be used to delineate common hydrologic behavior within the landscape of the United States as was proposed by Wolock et al. (2004).

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References

Arnold, J.G., Allen, P.M., 1999. Validation of automated methods for estimating base flow and ground water recharge from streamflow records. Journal of the American Water Resources Association 35 (2), 411–424.

Arnold, J.G., Allen, P.M., Muttiah, R., Bernhardt, G., 1995. Automated base flow separation and recession analysis techniques. Ground Water 33, 1010–1018.

Berger, K.P., Entekhabi, D., 2001. Basin hydrologic response relations to distributed physiographic descriptors and climate. Journal of Hydrology 247, 169–182.

Bingham, R.H., 1986. Regionalization of winter low-flow characteristics of Tennessee streams. US Geological Survey Water-Resources Investigations Report 86-4007.

Buttle, J., 2006. Mapping first order controls on streamflow from drainage basins: the T^3 template. Hydrological Processes 20, 3415–3422.

Delin, G.N., Healy, R.W., Lorenz, D.L., Nimmo, J.R., 2007. Comparison of local to regional scale estimates of ground water recharge in Minnesota, USA. Journal of Hydrology 334, 231–249.

Gebert, W.A., Graczyk, D.J., Krug, W.R., 1987. Average annual runoff in the United States, 1951–1980. US Geological Survey Hydrologic Investigations Atlas HA-710.

Gustard, A., Roald, L.A., Demuth, S., Lamadjeng, H.S., Gross, R., 1989. Flow Regimes from Experimental and Network Data (FrEND), 1 Hydrological Studies. Institute of Hydrology, Wallingford, UK, 344pp.

Heath, R.C., 1984. Ground water regions of the United States. US Geological Survey Water Supply Paper 2242.

Institute of Hydrology, 1980. Low flow studies. Wallingford, UK, Institute of Hydrology, Research Report 1.

Lacey, G.C., Grayson, R.B., 1998. Relating base flow to catchment properties in Southeastern Australia. Journal of Hydrology 204, 231–250.

Lyne, V., Hollick, M., 1979. Stochastic time variable rainfall runoff modeling. In: Proceedings of the Hydrology and Water Resources Symposium Berth, 1979. National Committee on Hydrology and Water Resources of the Institution of Engineers, Australia, pp. 89–92.

Mau, D.P., Winter, T.C., 1997. Estimating ground water recharge from streamflow hydrographs for a small mountain watershed in temperature humid climate, New Hampshire, USA. Ground Water 35 (2), 291–304.

Maurer, D.K., Lopes, T.J., Medina, R.L., LaRue Smith, J., 2004. Hydrogeology and hydrologic landscape regions of Nevada. USGS Scientific Investigations Report, 2004-5131.

Mazvimavi, D., Meijerink, A.M.J., Stein, A., 2004. Prediction of base flows from basin characteristics: a case study from Zimbabwe. Hydrological Sciences 49 (4), 703–715.

McCuen, R.H., 1989. Hydrologic Analysis and Design. Prentice Hall, pp. 355–360.

McGuire, K.J., McDonnell, J.J., Weiler, M., Kendall, C., McGlynn, B.L., Welker, J.M., Seibert, J., 2005. The role of topography on catchment-scale water residence time. Water Resource Research 41. doi:10.1029/2004WR003657, W05002.

McMahon, T.A., Mein, R.G., 1986. River and Reservoir Yield. Water Resources Publication, Littleton, CO, 368pp.

Mwakalila, S., Feyen, J., Wyseure, G., et al, 2002. The influence of physical catchment properties on base flow in semi-arid environments. Journal of Arid Environment 52, 245–258.

Nathan, R.J., McMahon, T.A., 1990. Evaluation of automated techniques for base flow and recession analysis. Water Resources Research 26 (7), 1465–1473.

Neff, B.P., Day, S.M., Piggott, A.R., Fuller, L.M., 2005. Base flow in the Great Lakes. US Geological Survey Scientific Investigations Report 2005-5217.

Nolan, B.T., Healy, R.W., Taber, P.E., Perkins, K., Hitt, K.J., Wolock, D.M., 2007. Factors influencing ground-water recharge in the eastern United States. Journal of Hydrology 332, 187–205.

Olmsted, F.H., Hely, A.G., 1962. Relation between ground water and surface water in Brandywine Creek Basin, Pennsylvania. US Geological Survey Professional Paper 417-A.

Omernik, J.M., Bailey, G.E., 1997. Distinguishing between watersheds and ecoregions. Journal of the American Water Resources Association 33 (5), 935–949.

Piggott, A.R., Molin, S., Southam, C., 2005. A Revised Approach to the UKIH Method for the Calculation of Base Flow. National Water Research Institute, Canada.

Pinder, G., Jones, J.F., 1968. Determination of ground water component of peak discharge from the chemistry of total runoff. Water Resources Research 5 (2), 430–445.

Reay, W.G., Gallagher, D.L., Simmons Jr., G.M., 1992. Groundwater discharge and its impact on surface water quality in a Chesapeake Bay inlet. Ground Water 28 (6), 1121–1133.

Rochelle, B.R., Steven, D.L., Church, M.R., 1989. Uncertainty analysis of runoff estimates from a runoff contour map. Water Resources Bulletin, American Water Resources Association 25 (3), 491–498.

Rutledge, A.T., 1993. Computer programs for describing the recession of ground water discharge and for estimating mean ground water recharge and discharge from streamflow records. US Geological Survey Water-Resources Investigations Report 93-4121.

Rutledge, A.T., Daniel, C.C., 1994. Testing an automated method to estimate ground water recharge from streamflow records. Ground Water 32 (2), 180–189.

Rutledge, A.T., Mesko, T.O., 1996. Estimated hydrologic characteristics of shallow aquifer systems in the Valley and Ridge, the Blue Ridge, and Piedmont physiographic provinces based on analysis of streamflow recession and base flow. US Geological Survey Professional Paper 1422-B.

Sankarasubramanian, A., Vogel, R.M., 2002. Comment on Paper ''Basin hydrologic response relations to distributed physiographic descriptors and climate'' by Karen Plaut Berger, Dara Entekhabi, 2001. Journal of Hydrology 247, 169–182. Journal of Hydrology 263, 257–261.

Scanlon, B.R., Keese, K.E., Flint, A.L., Flint, L.E., Gaye, C.B., Edmunds, V.M., Simmers, I., 2006. Global synthesis of groundwater recharge in semiarid and arid regions. Hydrological Processes 20 (15), 3335–3370.

Sefton, C.E.M., Howarth, S.M., 1998. Relationship between dynamic response characteristics and physical descriptors of catchments in England and Wales. Journal of Hydrology 211, 1–16.

Simon, A., Dickerson, W., Heins, A., 2004. Suspended-sediment transport rates at the 1.5-year recurrence interval for ecoregions of the United States: Transport conditions at the bankfull and effective discharge? Geomorphology 58 (1–4), 243–262.

Sloto, R.A., Crouse, M.Y., 1996. HYSEP: a computer program for streamflow hydrograph separation and analysis. US Geological Survey Water-Resources Investigations Report 96-4040.

Smakhtin, V.Y., 2001. Low flow hydrology: a review. Journal of Hydrology 240, 147–186.

Stuckey, M.H., 2006. Low flow, base flow, and mean flow regression equations for Pennsylvania streams. US Geological Survey Scientific Investigations Report 2006-5130.

Vogel, R.M., Kroll, C.N., 1992. Regional geohydrologic–geomorphic relationships for the estimation of low flow statistics. Water Resources Research 28 (9), 2451–2458.

Wahl, K.L., Wahl, T.L., 1988. Effects of regional ground water declines on streamflows in the Oklahoma Panhandle. In: Proceedings of Symposium on Water-Use Data for Water Resources Management: Tucson, Arizona. American Water Resources Association, pp. 239-249. Data accessed in March 2003. Available from: <http://www.usbr.gov/pmts/hydraulics_lab/twahl/bfi/bfi_beaver_river.pdf>.

Wahl, K.L., Wahl, T.L., 1995. Determining the flow of comal springs at New Braunfels, Texas, in Proceedings of Texas Water'95, August 16–17, 1995, San Antonio, Texas: American Society of Civil Engineers, pp. 77–86. Data accessed in March 2003. Available from: <http://www.usbr.gov/pmts/hydraulics_lab/twahl/bfi/texaswater95/comalsprings.html>.

White, K., Slotto, R.A., 1990. Base flow frequency characteristics of selected Pennsylvania streams. US Geological Survey Water-Resources Investigations Report 90-4160.

Winter, T.C., 2001. The concept of hydrologic landscapes. Journal of the American Water Resources Association 37 (2), 335–349.

Wolock, D.M., 2003a. Base-flow index grid for the conterminous United States: US Geological Survey Open-File Report 03-263. Data accessed in March 2006. Available from: <http://water.usgs.gov/lookup/getspatial?bfi48grd>.

Wolock, D.M., 2003b. Flow characteristics at US Geological Survey streamgages in the conterminous United States: US Geological Survey Open-File Report 03-146. Data accessed in March 2006. Available from: <http://water.usgs.gov/lookup/getspatial?qsitesdd>.

Wolock, D.M., McCabe, G.J., 1999. Explaining spatial variability in mean annual runoff in the conterminous United States. Climate Research 11, 149–159.

Wolock, D.M., Winter, T.C., McMohan, G., 2004. Delineation and evaluation of hydrologic-landscape regions in the United States using geographic information system tools and multivariate statistical analyses. Environmental Management 34 (1), 71–88.