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Spatial analysis of annual runoff ratios and their variability across the contiguous U.S.

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SUMMARY

This study examines the spatial patterns of annual runoff ratios and their variability and identifies the determinants of runoff indices for 238 reference basins with low levels of anthropogenic influence and 1352 non-reference basins with substantial levels of anthropogenic influence. Runoff ratios are high and runoff ratio coefficients of variation (CV) are low in coastal Pacific Northwest and Northeast basins, both humid temperate climates. The most significant variable that influences annual runoff ratio for both basin types is the average annual days of measurable precipitation. Snow percent of total precipitation and minimum watershed elevation are common predictors of runoff ratio for both types of basins. Slope percent and Horton overland flow are significant predictors for reference basin runoff ratio, while average annual precipitation, basin compactness, and dam storage are significant predictors for non-reference basin runoff ratio. The variables most significantly influencing runoff ratio CV in both types of basins are the average annual days of measurable precipitation, the precipitation seasonality index, and the base flow index. Horton overland flow is a significant predictor for reference basins, while minimum watershed elevation is a significant predictor for non-reference basins. Spatial autocorrelation of ordinary least squares estimated residuals are reduced by geographically weighted regression (GWR) for all models in both basin types. This study shows that GWR modeling, which takes into account spatial non-stationarity, can create more accurate representations of runoff ratio variability in both basin types. The spatially-varying coefficient values in GWR models also show local specific relationships between runoff indices and various climatic and landscape factors.

1. Introduction

Understanding the spatial patterns of runoff variability as they relate to various landscape factors is a long lasting theme in hydrological sciences (Xu et al., 1996; Kirchner, 2009; Merz and Blöschl, 2009; Troch et al., 2009; Ali et al., 2012). Together with the long-term streamflow data, the advance of geographic information sciences and new spatial models have allowed hydrologists to understand how catchment characteristics explain the complex patterns of runoff indices over large areas (Wagner et al., 2007; Carrillo et al., 2011; Sawicz et al., 2011). Since water resource managers must know not only the magnitude of runoff available but also how variable the runoff is, it is important to identify which landscape and climatic factors affect both runoff ratio, the ratio of streamflow to total precipitation normalized by basin area, and runoff ratio coefficient of variation (CV).

To date, most basin-scale runoff studies have generally focused on a related suite of characteristics, such as atmospheric trends (Bae et al., 2008; Day, 2009; Dibike and Coulibaly, 2005; Kneis et al., 2012), vegetation cover (Fan et al., 2011; Gerten et al., 2004; Nosetto et al., 2012), impervious surface (Cuo et al., 2008; Huang et al., 2008), topography (Jencso and McGlynn, 2011) or geology (Arnau-Rosalen et al., 2008; Freer, 2002). These studies often excel at identifying relative statistical importance of characteristics evaluated, but fail to account for spatial variation and are rarely undertaken at continental scales. Some recent literature on runoff ratio modeling draws inconsistent conclusions as to which landscape characteristics are most influential, with various studies finding that topographic characteristics are more important than climate variability (Hickel and Zhang, 2006; Nippgen et al., 2011), elevation rather than aspect (Smith and Marshall, 2010), or some inconsistent combination of climate, geomorphology,

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Table 1
Overview of basic geographic parameters for reference and non-reference basins used for model development.

General parameters	Reference basin (*n* = 238)				Non-reference basins (*n* = 1352)			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Area (km^2)	22.5	25791.0	1311.6	2318.8	3.4	49592.2	5704.3	9141.1
Mean annual temp (°C)	−1.6	22.5	9.8	4.6	−0.1	22.5	9.6	4.4
Mean annual freezing days	47.3	335.6	209.0	49.6	39.4	333.3	212.9	51.6
Mean annual precipitation (cm)	27.3	377.0	93.5	44.1	20.3	377.0	80.3	32.0
Mean annual precipitation days	27.9	214.8	111.5	35.2	26.6	224.2	102.5	29.1
Mean annual runoff (cm)	0.1	339.0	45.5	44.8	0.1	317.0	30.4	27.5
Stream density (km km^{-2})	0.1	1.2	0.7	0.2	<0.1	1.5	0.7	0.2
Mean elevation (m)	13.5	3646.0	702.5	691.5	11.7	3330.7	775.8	803.2
Mean slope (%)	<0.1	58.8	14.0	13.4	<0.1	49.0	9.5	9.5
WD_Basin	27.9	214.8	111.5	35.2	26.6	224.2	102.5	29.1
Slope_Pct	<0.1	58.8	14.0	13.3	<0.1	49.0	9.5	9.5
Perhor	<0.1	33.7	5.5	6.4	<0.1	44.2	5.5	6.0
Elev_Min_Basin	2.0	3003.0	391.3	493.6	15.0	2800.0	469.8	596.7
Snow_Pct_Prcp	0.0	72.3	20.9	16.9	0.0	73.3	21.5	15.9
Avg_Ann_Prcip	27.3	377.0	93.5	44.1	20.3	377.0	80.3	32.0
Basin_Compact	0.3	3.6	1.7	0.5	0.2	3.5	1.4	0.5
Stor_Nor_2009	<0.1	298.0	4.5	22.9	<0.1	3191.1	69.2	174.7
Precip_Seas_Ind	<0.1	0.7	0.2	0.2	<0.1	0.7	0.2	0.2
BFI	11.2	85.4	46.4	15.3	9.5	87.0	46.9	16.2

WD_Basin = Watershed average of annual number of days of measurable precipitation (PRISM); Slope_Pct = Mean watershed slope (percent); Perhor = Modeled Horton overland flow (percentage of total streamflow); Elev_Min_M_Basin = Minimum watershed elevation (meters); Snow_Pct_Precip = Snow percent of total precipitation estimate; Avg_Ann_Precip = Average annual precipitation from December to November estimated from monthly PRISM precipitation 1951–2000; Basin_Compact = Watershed compactness ratio, area/perimeter^2 * 100 (higher number = more compact shape); Stor_Nor_2009 = Dam storage in watershed (ML/km^2); Precip_Seas_Ind = Precipitation seasonality index (higher value = more regular temporal distribution), range is 0 (precipitation spread out exactly evenly in each month) to 1 (all precipitation falls in a single month).

and lithology (Berger and Entekhabi, 2001; Detenbeck et al., 2004) as most important to runoff ratio variability.

While nowhere on Earth remains a surface drainage network truly untouched by human activities, comparisons between those systems least impacted and those most impacted by humans offer the best method for distinguishing between natural and anthropogenic effects (Franczyk and Chang, 2009a; Jones et al., 2012; Molle and Floch, 2008; Olang and Fürst, 2011; Vorosmarty and Sahagian, 2000). Human modifications of drainage systems take a variety of forms such that there is no standardized definition of an "impacted" basin, but impervious surface cover, channel modifications and floodplain development are common metrics. To discern the influence of local and regional geography from human impact on runoff ratios and their variability, we compared "reference" and "non-reference" basins as defined by the Geospatial Attributes of Gages for Evaluating Streamflow, Version II, (GAGES II) project (Falcone, 2011).

This study was guided by the goal of defining landscape and atmospheric characteristics that best predict spatial variations in runoff ratios and their variability across the contiguous U.S. during the past 60 years. Four distinct questions were posed in this study.

1. Are there distinct spatial patterns of runoff ratio and runoff ratio CV in the contiguous U.S.?
2. What hydrologic landscape and climatic factors explain the spatial patterns of runoff ratio and runoff ratio CV?
3. Do the determinants of these spatial patterns differ between reference and non-reference basins?
4. Do the relationships between runoff indices and explanatory variables vary over space?

We hypothesized that independent variables shown to be statistically significant predictors for runoff ratios and their variability (hereafter we refer to these runoff indices) would be different between reference and non-reference sites. Climatic factors such as precipitation frequency and proportion of precipitation falling as snow were expected to play a significant role in runoff ratio for all basins evaluated. Topography and geology were expected to drive reference basin runoff ratios, while dam density and channel modifications were expected to drive runoff ratios in non-reference basins. Our final prediction from this study is that spatial models will improve traditional aspatial models and provide the most accurate representation of the complex runoff ratio indices across this large geographic area.

2. Data and methods

2.1. Study area

Our study area covers the contiguous U.S., represented by 1590 stream gauging stations measuring discharge from contributing drainage areas covering slightly over 8,000,000 km^2. These sites represent diverse biogeophysical systems, with contributing drainage areas ranging in size from approximately 5 km^2 to 50,000 km^2, mean annual precipitation ranging from 2.4 cm to 45.2 cm, and mean slope ranging from less than 0.1% to over 50% (Table 1). Gauging stations selected for use in this study were based on inclusion in the U.S. Geological Survey (USGS) GAGES II project and the length of available continuous flow records. All gauging stations included for regression analysis provided at least 60 continuous years of flow records at a monthly time scale.

Study sites were divided into two categories determined by the level of human disturbance as estimated by GAGES II. Gauges draining areas that have been extensively modified by channels or dams, have high densities of roadways and impervious surface, or large amounts of fragmented or developed land cover were classified as non-reference sites (*n* = 1352); gauges draining areas that are least disturbed by human influence were classified as reference sites (*n* = 238) (Falcone, 2011). General descriptive statistics comparing the two classifications are shown in Table 1. Overall, basins from both categories are broadly similar and directly comparable for the purpose of this study; however there are markedly