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Watershed area ratio accurately predicts daily streamflow in nested catchments in the Catskills, New York

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ABSTRACT

Study region: The Catskills region of New York State is largely forested and dominated hydrologically by stream watersheds with few natural lakes. The area experiences intensive water resources management and ecosystem monitoring due to its strategic role as the principal water supply for New York City.

Study focus: We analyzed average daily flows in nested and non-nested pairs of gaged watersheds in the Catskills to assess whether daily flow in ungaged watersheds can be calculated based on watershed area ratios.

New hydrological insights for the region: Watershed area ratio was the most important basin parameter for estimating flow at upstream sites based on downstream flow. The area ratio alone explained 93% of the variance in the slopes of relationships between upstream and downstream flows. Regression analysis indicated that flow at any upstream point can be estimated by multiplying the flow at a downstream reference gage by the watershed area ratio. This method accurately predicted upstream flows at area ratios as low as 0.005. We also observed a very strong relationship ($R^2 = 0.79$) between area ratio and flow–flow slopes in non-nested catchments. Our results indicate that a simple flow estimation method based on watershed area ratios is justifiable, and indeed preferred, for the estimation of daily streamflow in ungaged watersheds in the Catskills region.

1. Introduction

The estimation and modeling of water availability and quality for water supply and ecological assessment requires reliable estimation of flow (Vogel et al., 1997). The U.S. Geological Survey (USGS) maintains an extensive network of stream gages for this purpose. However, recent budget cuts have resulted in reductions in the total number of gages in the network, especially in headwater catchments. Consequently, future water resources development projects, and studies of chemical fate and transport in surface waters are likely to require streamflow data at ungaged sites. The ability to estimate flow in ungaged catchments is therefore important for water resources planning and environmental management.

Historically, flow rates in ungaged catchments have been estimated using a variety of techniques. Perhaps the earliest and most common technique for estimating daily flow in an ungaged catchment is the watershed area ratio method. The area ratio method is used to estimate flow in an ungaged catchment when a nearby gaged watershed is present for use as

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a reference. The method estimates flow at an ungaged location by multiplying the measured flow at the nearby reference gage by the area ratio of the ungaged to gaged watersheds (Archfield and Vogel, 2010):

$$Q_{\text{ungaged}} = Q_{\text{gaged}} \times \frac{A_{\text{ungaged}}}{A_{\text{gaged}}} \quad (1)$$

in which Q represents streamflow and A represents watershed area. A major assumption of the area ratio method is that flow scales directly with watershed area. That is, as watershed area increases, flow rate increases at some fixed rate per unit area. This means that the flow per unit area is the same at both the ungaged location and gaged reference location. Other techniques include empirical regional regression models (Riggs, 1990), use of flow duration curves (FDCs) (Castellarin et al., 2004), and models developed from rainfall-runoff relationships (Post and Jakeman, 1999).

The choice of reference gage in the area ratio method has generally been determined by geographic proximity to the ungaged watershed of interest, or by locating a watershed that should share a similar hydrologic response as the ungaged watershed of interest (Archfield and Vogel, 2010). Mohamoud (2008) suggests choosing the closest stream gage, while Smakhtin (1999) suggests that several reference stream gages should be used in order to smooth out any timing-related issues between the ungaged and reference locations. Recently, Archfield and Vogel (2010) suggested a “Map Correlation Method”, a new technique for identifying the most correlated stream gage based on watershed characteristics and hydrologic response.

The watersheds in the Catskills Mountain region of New York State feed into the principal water supply reservoirs for New York City. Consequently, New York has a keen interest in monitoring streamflow in the watersheds. To this end, the city provides financial support to augment the network of gages maintained by the USGS. This dense network provides an opportunity to examine the scaling of flow in watersheds with nested gages. We hypothesized that the watershed area ratio (Eq. (1)) could accurately predict mean daily streamflow at the upstream locations in nested pairs of stream gages (Hypothesis 1). If true, then daily flow at any ungaged site can be easily estimated since all of the major streams in the region are gaged near the water-supply reservoirs. Additionally, we hypothesized that the prediction of flow using the area ratio method would be better in nested stream gage pairs than in non-nested stream gage pairs (Hypothesis 2), and that prediction in non-nested pairs would be best when the gages are closest to each other (Hypothesis 3).

2. Setting

This study is set in the Catskills Park of New York State (Fig. 1). The Catskills region is a mountainous area that contains many small streams, and a very high concentration of currently and historically active USGS stream gaging stations. The bedrock is comprised of relatively flat-lying sedimentary rocks (primarily sandstones and mudrocks) of Devonian age, which have been uplifted and tilted slightly to the west (Ver Straeten, 2013). Subsequent erosion produced a network of narrow river valleys. The geologically recent glacial activity in the Catskills is largely responsible for the region’s surficial bedrock, soil, and hydrologic characteristics. Glacial scour and erosion caused by meltwater deepened and re-routed existing drainages, creating a dense network of streams with few natural lakes (Fig. 1) (Rich, 1934).

Most of the region’s soils are underlain by glacial till, which has had significant influence as a parent material on the development of the soils, as well as their corresponding hydrologic response (Kudish, 2000). Although plot-scale heterogeneity in soil texture is common, the overwhelming majority of soils in the Catskills are classified as inceptisols, characterized by a sandy loam texture and poor horizon development (Kudish, 2000). Fragipans, dense cement-like layers that impede root growth and water infiltration, are also fairly common and widespread throughout the region (Kudish, 1979). Average soil depth to C horizon or bedrock in 25 upland catchments was estimated to be 57 ± 2.5 cm (Johnson, 2013), though soils in valley bottoms can be much deeper. Shallow upland soils produce a relatively uniform and flashy hydrologic response to rainfall and snowmelt events.

As a region, the Catskills are largely forested, though quite varied in composition (Kudish, 2000). At the lowest elevations, southern hardwoods are found, dominated by white and red oak, American chestnut and hickory. As elevation increases, southern hardwoods give way to northern hardwoods, dominated by yellow birch, American beech, and sugar maple, and at higher elevation, boreal forests with red spruce, balsam fir and paper birch. On the highest peaks, pockets of alpine meadow vegetation can still be found.

The climate in the Catskills is characterized by cold winters and moderately warm summers. Average annual temperature at the Winnisook site on Slide Mountain is approximately 5 °C (Stoddard and Murdoch, 1991). Precipitation is distributed evenly through the year, with an annual precipitation gradient from the northern Catskills (90–100 cm yr^{-1}) to the southern part of the region (150–160 cm yr^{-1} in the upper East Branch of the Neversink River watershed) (Stoddard and Murdoch, 1991). Precipitation comes from both coastal storms from the south and frontal systems from the west. At Biscuit Brook, in the southern Catskills, approximately 15% of the annual precipitation falls as snow (Stoddard and Murdoch, 1991).

The soils and forests of the Catskills region produce surface waters of exceptional quality. Beginning in the early 20th century, New York City built six reservoirs in the region, which now provides more than 90% of the city’s drinking water. The water provided by these reservoirs is sufficiently pure that it is delivered to residents without filtration (National Research Council, 2000).