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Hydrologic regionalization to assess anthropogenic changes

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SUMMARY

Within the past few decades, Minnesota's land use change has responded rapidly to prevailing economic growth conditions, resulting in hydrologic characteristic alterations of the landscape and shifting the hydrologic balance of its watersheds. Regionalization using mean annual and mean monthly streamflow values was used to delineate hydrologic regimes with distinct temporal flow variations. By identifying hydrologic relationships between watersheds through an initial regionalization of mean annual streamflow time-series data, hydrologic regimes, each composed of watersheds with common hydrologic controlling variables, were identified. This paper summarizes how by applying factor analysis techniques to complete a statewide regionalization for Minnesota, hydrologic regimes were identified, each with a specific hydrologic signature; varying between three and four runoff periods of different durations. A geographic information system database was established to display the results of the regionalization and to identify hydrologic regime changes between the 1936–2008, 1936–1980, and 1950–2008 analysis intervals. Results delineated five hydrologic regimes for each of the three analysis periods. By focusing on each specific regime, further analyses were completed to identify significant increasing and decreasing trend characteristics. Review of the temporal variation for each regime using Kendall Tau trend analyses suggests that although variation in annual precipitation has an important influence on hydrologic variability, land cover and management proved to be a more direct controlling agent. Understanding the consequences of anthropogenic land use change on hydrologic processes within each defined regime should be the focus of future analyses.

1. Introduction

Land use change, including agricultural management, urbanization and timber harvesting, has historically responded to economic development and government incentives. These changes continue to progress and will likely accelerate to satisfy demands of an increasing global population. Research has focused on the link between vegetative cover, hydrologic processes and water quality; however, the consequence of anthropogenic land use change on hydrology has received minimal attention (DeFries and Eshleman, 2004).

The effects of these anthropogenic land use changes can be examined using a hydrologic systems analysis. This holistic approach looks at data from a broad sense and refines results to represent a specific homogeneous response unit. It promotes multi-scale and interdisciplinary research and produces results which could be applied to multiple study areas. Although numerous examples exist on the complex behavior of hydrology, catchment hydrology continues to be operating under a reductionist paradigm (Sivapalan, 2005). While it is important to understand processes occurring at a fine scale, a holistic system approach is necessary to advance research and address today's most perplexing water resources problems; specifically those attributed to anthropogenic changes.

The holistic theory of hydrology requires that actual predictions be based or conditioned on observations at the catchment scale to identify the influence of the underlying spatial heterogeneities in landscape properties (Winter, 2001; Wolock et al., 2004; Sivapalan, 2005; McDonnell et al., 2007; Troch et al., 2008). While the complexity and differences between catchments can be overwhelming, it has been hypothesized that there are distinct underlying structures shared between catchments; identification and characterization of such structures can lead to the development of hydrologic relationships between structural characteristics and hydrologic response that have general applicability for hydrologic prediction (Wagener et al., 2007). Identifying and characterizing the shared structures through a system analysis provides insight for further investigation necessary at more local levels to address specific water management related issues.

Watersheds are "self-organizing" systems, whose characteristics result from adaptive ecological, geomorphic, and land-forming processes; therefore, they produce geometric patterns valuable to

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hydrologic analysis and predictions (Sivapalan, 2005). By identifying these patterns through an initial regionalization using mean annual streamflow time-series data for watersheds extending across a large area, hydrologic regimes, each composed of watersheds with common hydrologic controlling characteristic structures, have been identified (Bartlein, 1982; Lins, 1985; Lins, 1997; Sophocleous, 1992; Diekrüger et al., 1999; Maurer et al., 2004; Shmagin and Kanivetsky, 2006; Kahya et al., 2008). To fully understand the hydrologic system, further analyses could then focus on the set of watersheds defined by each regime to identify the dominant controlling structure(s) and advance the understanding of the connections between structure(s) and hydrologic response. For example, recharge varies spatially because the controlling structure, including precipitation, soil and geology, vegetation and land use, topography, land form and depth to groundwater, vary in nature and size (Lerner et al., 1990).

Previous research in Minnesota has indicated that, on a statewide scale, streamflow characteristics are correlated to hydrogeological units (Shmagin and Kanivetsky, 2002). These units are stationary landscape characteristics which do not change with time. Those characteristics which may change with time include drainage management, vegetation/land cover and precipitation. As stated by Johnston and Shmagin (2008), before one can evaluate the impact of future climate change or land use change on streamflow, it is necessary to first understand past spatio-temporal patterns of streamflow variability and their relationship to hydrogeological landscape characteristics.

To recognize the geographic variations in streamflow across Minnesota, this paper describes how by applying factor analysis techniques to complete a statewide regionalization for Minnesota and adjacent areas, five regimes with unique hydrologic signatures were identified. A trend analysis of each regime was completed and the hydrologic signature variation identified within each regime was determined to correspond to ongoing anthropogenic land use changes.

2. Regionalization

2.1. Watershed delineation

USGS gauging station locations and mean annual streamflow data for 129 sites throughout Minnesota and surrounding states were downloaded from the USGS Water Data for the Nation website (USGS, 2010b). Gauging station data in the US is generally considered to be accurate to ±5% (Rantz, 1982). Data was sorted and 69 sites were selected for further analysis based on consistent, consecutive available annual data. Three analysis periods were chosen based on the time intervals with the greatest number of watersheds with available data. These intervals are discussed further in Section 3. To identify possible anthropogenic influences on streamflow characteristics, the objective was to select two slightly overlapping intervals; one initiating prior to the major human-induced land use alterations including the switch from mixed crop (perennials, row crops) agriculture to primarily row crop agriculture and associated enhanced land drainage, and the second beginning later to capture any resulting effects on streamflow. The third interval combines the two shorter intervals into one extended analysis period.

Table 1
List of USGS gauging stations that were used for each analysis period.

USGS gauging station	Delineated drainage area (km^2)	Delineated analysis period			USGS gauging station	Delineated drainage area (km^2)	Analysis period		
		1936–1980	1936–2008	1950–2008			1936–1980	1936–2008	1950–2008
4010500	1576	.	.	.	5211000	8665	.	.	.
4024000	8834	.	.	.	5227500	15363			.
4027000	1546			.	5270500	2678	.		
4027500	705			.	5275000	1447	.		
5046000	4468	.	.	.	5280000	7128	.	.	.
5050000	3080			.	5286000	4017	.	.	.
5051500	10215			.	5291000	1046	.	.	.
5054000	17215	.	.	.	5292000	3001			.
5058000	10341			.	5294000	2239	.		
5059000	13932			.	5300000	2490	.		
5059500	14035	.	.	.	5304500	4862			.
5062000	2526	.	.	.	5311000	16152	.	.	.
5062500	2418	.			5313500	1720	.	.	.
5064000	4052				5315000	670			.
5066500	3199	.	.	.	5316500	1630	.	.	.
5069000	1087			.	5317000	3379	.	.	.
5074500	5233	.			5320000	6214			.
5075000	5901	.			5320500	2870			.
5076000	2553	.	.	.	5333500	3998	.		
5078500	3587	.	.	.	5340500	16183	.	.	.
5079000	13548	.	.	.	5356000	2029	.	.	.
5084000	1023			.	5356500	4240	.	.	.
5085000	1413			.	5374000	2969	.		
5087500	661			.	5385000	3234	.		
5090000	1809	.	.	.	5421000	2724	.	.	.
5100000	5897	.	.	.	5457000	1034			.
5104500	1113			.	5458500	4331			.
5107500	2818	.			5459500	1323	.	.	.
5127000	3163	.	.	.	5476000	3229	.	.	.
5127500	3673	.	.	.	5479000	3326			.
5128000	7051	.	.	.	6481000	11297			.
5129000	1269	.			6483500	4108			.
5130500	467			.	6485500	21631	.	.	.
5131500	4346	.	.	.	6606600	6455	.	.	.
5132000	3841	.							