Hydrologic Resource Sheds and the U.S. Great Lakes Applications

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Abstract: “Hydrological resource shed” is defined as a geographic area that contributes material (e.g. water, nutrients, and sediments) over one time interval, passing through a location of interest over another time interval. While similar to the concept of watershed, this relatively new concept has some unique features. First, the boundary of a watershed is delineated by topography and relatively more stable. The boundary of a hydrologic resource shed, however, is delineated by the contributing sources of water and materials to a river or lake during hydrologic events, and changes over both space and time. Second, the concept of watershed emphasizes temporal distribution of water and materials within a given space, and the hydrologic resource shed focuses on both temporal and spatial distribution of water and materials within a changing space. Third, the concept of hydrologic resource shed incorporates the space–time variability in studying watershed patterns and processes. Taking advantage of current tracing, remote sensing, mapping, and modeling technologies, hydrologic resource shed provides a new way of discovering, understanding, and simulating the transport and distribution of water and materials across multiple space and time scales. An example is presented for computing the hydrologic resource shed distributions using a hydrologic model, Distributed Large Basin Runoff Model (DLBRM) in the Maumee River watershed in western Lake Erie Basin of the U.S.

Key words: hydrologic resource shed; runoff; hydrologic model; DLBRM; Lake Erie

1 Introduction

The watershed (land draining into a stream or lake at a given location) has been widely recognized as a basic unit for hydrologic research and water resources management (Chow et al. 1988; U.S. Environmental Protection Agency 1995; National Research Council 1999; Croley et al. 2008). Watershed boundaries are delineated from topographic data, characterized by discontinuities in the flow pathways of water and the water-borne material transported downstream (Post et al. 2007; Croley et al. 2008). As a hydrologic system, watershed boundaries span a large range of environments, spatial and temporal scales, from a small tributary with an area of a few hectares to a continental river basin (such as the Mississippi River Basin) of a few million square kilometers over intervals of minutes, hours, and days, to centuries (Paola et al. 2006; Croley et al. 2008). The moving boundaries of watershed and related channels control the spatial and temporal patterns of physical, chemical, and biotic processes in a watershed (Chow et al. 1988; NRC 1999; Paola et al. 2006; Croley et al. 2008). But as time scale expands, processes can also change the spatial patterns of the watershed. For example, from water (minutes to hours) to sediment (centuries and up) scale, sediment flux including storage and transport changes the channel geometry and size and shape of floodplains (Paola et al. 2006). Despite the interactions between the watershed patterns and processes, in numerous water resources applications, channel networks and watershed boundaries have been traditionally considered as static (Paola et al. 2006). The evolution of the watershed boundary and channel geometry and the multiple scales of water (minutes to hours), sediment (hours to centuries), and tectonic (centuries and up) are inadequately considered (Paola et al. 2006). This lack of consideration has limited the capacity of the scientific community in understanding and predicting watershed responses to natural and anthropogenic changes accurately across mul-
tiple spatial and temporal scales (Paola et al. 2006; Post et al. 2007). For example, at present, watershed responses to climate and land use changes cannot be predicted with confidence (Paola et al. 2006). How does the space-time variability of precipitation affect the rates of sediment and nutrient generation and transport (Paola et al. 2006)? Where does the sediment or nutrient come from and how is it being transported downstream to the watershed outlet and floodplain? How does the large scale watershed pattern arise from small scale local interactions (Paola et al. 2006)? To better tackle important questions like those, researchers have called for the development of a predictive science of earth surface dynamics by taking advantage of the advances in tracing, mapping, remote sensing, and modeling technologies over the past few decades to reliably understand, model, and predict the interwoven physical, biological, geochemical, and human dynamics that collectively shape the Earth’s surface (Paola et al. 2006). Moving toward this direction, we describe a relatively new concept, the hydrologic resource shed in modeling and predicting the material generation and transport in a watershed across multiple temporal and spatial scales in this article. We first define the concept of a hydrologic resource shed, and then give an application example in a Great Lakes watershed. Subsequently we discuss the potential applications of the hydrologic resource shed in watershed research and management.

2 Hydrologic Resource Shed

Watersheds are logical divisions of the natural landscape, usually with easily defined boundaries (NRC 1999). Over the years, the watershed concept has also been extended to other fields such as water resources and atmospheric studies. For example, Michel (2000) used the concept of hydrocommons (defined as the hybrid basins created by linking water sending and receiving basins by conveyance systems such as storage reservoirs and aqueducts) to evaluate impacts of removal of the natural boundaries of both sending and receiving basins on altered hydrology, water quality, ecosystems, economies and land use patterns in both the sending and receiving watersheds (Michel 2000; Croley et al. 2008). “Air shed” has been used in defining, simulating, and monitoring the sources of pollutant emissions, transports, and deposits in metropolitan areas or regions for air quality management (Tullar and Suffet 1975; Chang and Cardelino 2000; Croley et al. 2008). Others have used hydronregion in understanding the role of regional hydrologic influences in fish species richness (Oswood et al. 2000; Santoul et al. 2004; Croley et al. 2008).

Applying the concept of watershed to analyzing the spatial dynamics of consumers and resources in ecology, Power and Rainey (2000) proposed the concept of resource sheds, “source areas for resources consumed by individuals during their lifetimes” to link the landscape features with functions and processes of food webs and ecosystems. Croley et al. (2008) generalize the definition of resource shed to encompass source areas from which materials are derived for an individual, population, or location during one time interval and arriving at a location, (1) during another time interval (type 1), (2) during several time intervals and arriving during the last time interval (type 2), or (3) during the same time interval (type 3). For hydrologic resource shed, materials include anything that can be carried downstream by water, such as nutrients, organic matter, sediments, organisms, prey items, or pollutants. Fig. 1 shows examples of resource shed. Materials were departing from different source areas at 4, 5, and 6 days prior and arriving at the location of interest (e.g. watershed outlet) at day 6. Subsequently, Croley et al. (2008) have rigorously defined a set of procedures for delineating hydrologic resource sheds across multiple spatial and temporal scales mathematically the first time (see Croley et al. 2008 for a detailed description of the mathematical equations). Considering some parts of an area may supply more material to the location of interest than
other parts, Croley et al. (2008) use the material's areal density rate of change with departure and arrival times (mass/area/time/time) to represent the resource shed distributions over a location of interest. Fig. 2 is an example of resource shed distribution for Fig. 1. More materials were arriving at the location of interest from areas closer to the location than further away.

While similar to the concept of watershed, the hydrologic resource shed has the following unique features. First, the boundary of a watershed is delineated by topography and relatively more stable. The boundary of a hydrologic resource shed, however, is delineated by the contributing sources of water and materials to a river or lake (landscape features) during hydrologic events (physical forcing variables), and changes over both space and time (e.g. the resource shed of sediments in a watershed changes from one storm event to another) (Croley 2008). Second, the concept of watershed emphasizes temporal distribution of water and materials within a given space, and the hydrologic resource shed focuses on both temporal and spatial distribution of water and materials within a hydrologic space (Croley et al. 2008). Third, the concept of hydrologic resource shed incorporates the space-time variability in studying interactions of physical, biological, geochemical, and human dynamics in watershed patterns and processes (Paola et al. 2006). Taking advantage of current tracing, remote sensing, mapping, and modeling technologies, the hydrologic resource shed provides a new way of discovering, understanding, and simulating the transport and distribution of water and materials across multiple space and time scales. It can help resource managers better design, implement, track, and manage water quality programs in a study area (Croley et al. 2008).

3 Example: Maumee River Resource Sheds

Hydrologic resource sheds can be computed from spatially distributed watershed hydrology models; material placed anywhere in the watershed will appear at the watershed outlet (mouth) over a period of time (Croley et al. 2008). For illustration, we use the hydrologic model, Distributed Large Basin Runoff Model (DLBRM) to model hydrologic resource sheds in the Maumee River, a large watershed with a drainage area of 17 541 km² in western Lake Erie Basin. The Maumee River watershed was divided into 17 541 1-km² cells. The DLBRM was applied to each of the cells to trace the material departing the cell over time intervals and compute the amount arriving at the mouth either in a same time interval or different time interval.

The DLBRM was developed by the Great Lakes Environmental Research Laboratory and Western Michigan University. It represents a watershed by using 1-km² (or other size) grid cells. Each cell of the watershed is composed of moisture storages of the upper soil zone (USZ), lower soil zone (LSZ), groundwater zone, and surface, which are arranged as a serial and parallel cascade of “tanks” to coincide with the perceived basin storage structure (Fig. 3). Water enters the snow pack, which supplies the basin surface (degree-day snowmelt). Infiltration is proportional to this supply and to saturation of the upper soil zone (partial-area infiltration). Excess supply is surface runoff. Flows from all tanks are proportional to their amounts (linear-reservoir flows). Mass conservation applies for the snow pack and tanks; energy conservation applies to evapotranspiration (ET). The model computes potential ET from a heat balance, indexed by daily air temperature, and calculates actual ET as proportional to both the potential and storage. It allows surface and subsurface flows to interact both with each other and with ad-
jacent-cell surface and subsurface storages. Each cell's inflow hydrographs must be known before its outflow hydrograph can be modeled and the DLBRM arranges calculations by flow network to assure this. It is implemented to minimize the number of pending hydrographs in storage and the time required for them to be in storage. The model uses the same routing network for lateral flows between all surface storages, all upper soil zone storages, all lower soil zone storages, and all groundwater zone storages. It has been applied extensively to riverine watersheds draining into the North America's Laurentian Great Lakes for use in both simulation and forecasting (Croley and He 2005, 2006; Croley et al. 2005, 2008; He and Croley 2007; He et al. 2009). The unique features of the DLBRM include: 1) use of readily available climatological, topographical, hydrologic, soil, and land use databases; 2) applicability to large watersheds; and 3) analytical solutions of mass continuity equations (for details, see Croley and He 2005; 2006; Croley et al. 2005; He and Croley 2007).

The DLBRM requires 15 parameters for each of the cells. Input variables to the DLBRM include, for every cell in the watershed grid, daily precipitation and air temperature, solar isolation, elevation, slope, flow direction, land use, depths (cm) of USZ and LSZ, available water capacity (%) of USZ and LSZ, soil texture, permeability (cm/hr) of USZ and LSZ, Manning's coefficient values, and daily flows. These variables are derived from multiple databases of climate, topography, land use, soil, hydrology, and hydrography. The model is calibrated for all cells by systematically searching the 15 spatial-average-parameter space by using gradient search techniques to minimize the root mean square error between modeled and actual basin outflow. The spatial variations of each parameter are taken as the same as a function of selected watershed characteristics; for example the upper soil zone capacity from cell to cell is proportional to measurements taken from the field (Croley and He 2005, 2006; Croley et al. 2005, 2008; He and Croley 2007).

Fig. 4 shows example hydrologic resource sheds for the Maumee River on January 1, 1950 from 1, 7, and 31 days of previous loading (Croley and He 2006; Croley et al. 2008). The brightest areas (higher concentrations or densities) correspond to cells contributing about 0.015% of the total flow on January 1, 1950. The darkest areas (lower concentrations or densities) are close to zero. The southern and western ridgelines are prominent as is a line to the north that marks the boundary between Ohio and Michigan (AB in Fig. 4). This boundary is an artifact of data standard differences in the two States' definitions of some soil properties. Point C in Fig. 4 identifies the mouth of the watershed. The first map in Fig. 4 shows a little response from the previous day's light rain near the mouth of the watershed. The second and third maps show most response along the edges of the watershed farthest from the mouth (Croley et al. 2008). Analysis of the historical precipitation record shows there was not much rainfall over the prior 4 days but there was a large amount 5 days prior in the southwest area. Also, spatially uniform rainfall fell over the entire watershed 7 days prior, 11–13 days prior, 15 days prior, 21–22 days prior, and 29 days prior. The bright spot corresponds to the large

![Fig. 4 Maumee Resource Sheds on January 1, 1950 from prior days of loading:](image)
peak 5 days earlier; the area closer to the mouth is relatively dark in the second and third maps because the only supplies there (seven or more days earlier) had already run off and were not part of the flow on this day. Comparison of the last two maps indicates that precipitation events prior to 7 days changed the picture very little. This is because the response of the watershed to supply is quick, on the order of 1 to 6 or 7 days, depending on location within the watershed. Most of all supplies falling more than 6 or 7 days ago had already runoff and did not form a part of the flow on this day (Croley et al. 2008).

4 Summary

This article discusses the concept of a hydrologic resource shed and its unique features in hydrologic research and water resources management. Hydrologic resource shed is a geographic area contributing material, over one time interval, passing through a location of interest over another time interval. Compared to the watershed concept, the hydrologic resource shed focuses on both temporal and spatial distribution of water and materials within a changing space, and its boundary changes over both space and time. It incorporates the space-time variability in studying watershed processes and patterns. Subsequently, the article illustrates the use of a spatially distributed hydrologic model (DLBRM) to define hydrologic resource sheds on the Maumee River watershed in western Lake Erie Basin.

While relatively new, hydrologic resources sheds utilize current tracing, remote sensing, mapping, and modeling technologies to provide a new way of discovering, understanding, and simulating the role of the space-time variability in watershed processes and patterns, and have potential applications in watershed research and management. In water quality management, hydrologic resource sheds can be used to predict the movement of sediments, nutrients, microbial, and harmful algal bloom formation and transport. For example, combining DLBRM with hydrodynamic and particle tracking models, Raikow et al. (2010) delineated resource shed spatial extent for selected locations of interest in Lake Erie over varying time intervals, and revealed the relative contributory importance of subwatersheds to those locations in the Lake. Currently, research is underway to add material transport capabilities to the DLBRM to produce resource sheds and their distributions for nutrients, sediment, insecticides, and microbes that may be of more direct use in prediction of harmful algal blooms and beach closings than simply water transport (Croley et al. 2008). Displays of resource sheds and their distributions for over 30 Great Lakes watersheds are produced near real time daily (for details, see http://www.glerl.noaa.gov/res/Programs/pep/reourceshed/maps/maps.php).

In climate science, hydrologic resource sheds can help researchers link climate and land use changes to changes in runoff, sediment yield, and nutrient loadings across channel networks over multiple timescales. In ecology research, resource sheds can be used to define functional relationships between the movements of nutrients across habitat, reach, network, and watershed, and associated responses of ecosystems at multiple scales -population, food web, community, and ecosystem over daily, weekly, monthly, annual or decade scales (Lowe et al. 2006; Power 2006).

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References


“水资源域”概念在美国五大湖的应用

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摘要：“水资源域”为在某一时段向河口或某一地点,传送水、水中营养物、泥沙或其它物质的空间范围。这一新概念与“流域”概念既相似又不同: 1) 流域边界以地貌特征来确定,相对稳定。而水资源域的边界以水文事件中的水和物质传播范围来确定, 随时空而变化; 2) 流域强调给定空间范围内水和物质的时间分布, 而水资源域强调水和物质随时间和空间二者相互变化的动态分布; 3) 水资源域综合考虑了不同尺度的时空即时变化对水资源及物质传播的影响。这一新概念应用遥感、空间分析、追踪及模拟技术分析流域空间模式与过程, 为水资源探索、分析、模拟及预测提供了一种全新的方法与途径。该文以美国伊利湖茅密河为例, 应用分布式大流域模型计算了水资源域的分布。

关键词: 水资源域; 径流; 分布式大流域模型; 伊利湖