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Temporal Variation in Spatial Sources of Discharge in a Large Watershed

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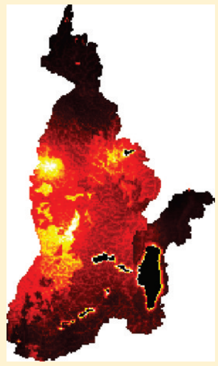
S Supporting Information

ABSTRACT: We examined how the spatial configuration of source areas for runoff varied over time in a large watershed, in order to understand processes governing material loading to rivers. Discharge source areas within the Fox River watershed (Wisconsin, US) were mapped for two individual discharge events. The spatial distribution of source areas varied between and over the duration of individual discharge events. Relative contribution to runoff by land cover types within source areas was quantified and compared to areal abundance of land covers in the watershed. Contributions of runoff by land cover types varied over time. Moreover, the degree to which different land cover types acted as source areas differed from their abundance in the watershed. Hence, areal quantifications of land cover within a watershed may not accurately represent what land covers are source areas over given time periods. Therefore, a source-area-based approach may yield more accurate spatial analysis of material loading patterns than a watershed-based approach.



INTRODUCTION

Spatially delineating source areas supplying contaminants, nutrients, or other materials to distant locations is necessary for effective management of natural resources and protection of human health. The U.S. Safe Drinking Water Act, for example, mandates wellhead protection zones defined by the zone of contribution—the surface and subsurface areas supplying groundwater to wells.[1] Within atmospheric chemistry, area-of-influence analyses are used to identify source areas supplying atmospheric pollutants to cities.[2] Methods to determine source areas for surface water and its chemical and biological constituents, however, lag behind groundwater hydrology and atmospheric chemistry.[3] Lack of an ability to apportion geographic source areas for water observed within the hydrograph of a storm flow event, for example, impedes progress in the spatial quantification of nonpoint contaminant sources.[4] Spatial delineation of surface water source areas could be applied forensically to specific cases in which contamination has been detected at a downstream receptor (i.e., a point location) or studied generally to understand how land use affects material loading to rivers.

Resource shed analysis was created to advance source area delineation for surface waters in watersheds and open-water ecosystems.[3,5] Borrowed from food web ecology,[6] a "resource shed" in the present context is an area supplying materials to a downstream receptor over a specified time period. While the potential source area for water exiting a river mouth is restricted to the borders of the river's watershed, differential spatial patterns of precipitation and geologic drainage characteristics will cause different geographic areas within a watershed to act as source areas (i.e., areas substantially contributing to discharge observed at the downstream receptor) at different times. Thus, the configuration of a watershed-based resource shed is dynamic and can change from one storm event to another.

In the last 5 years, several studies have been conducted to define and apply the concept of resource sheds at the watershed scale. Croley et al.[5] defined watershed-based resource sheds in mathematical terms, described the adaptation of a spatially explicit hydrologic runoff model for resource shed delineation, and observed some properties of resource sheds. Raikow et al.[3] described open water-based resource sheds (i.e., in lakes), linked these resource sheds with the resource sheds of the contributing watershed, and demonstrated model validation. Recently, Sayama et al.[4] have developed a different time−space accounting scheme that can be used with hydrologic models to yield source areas and have demonstrated its application in two small watersheds. Despite these developments, no surface water/source area delineation method has been applied to the delineation of source areas or land covers potentially loading contaminants or other materials to rivers.

An important methodological question must be considered before resource shed analysis can be applied to this problem,

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however. Complete spatial delineation of source areas requires the time intervals over which material movement occurs to be specified. Resource sheds are classified as type 1, type 2, or type 3 resource sheds, depending on when materials leave their source and when they arrive at the receptor.[5] For the specific purpose of identifying source areas supplying waterborne materials to a specific location of interest (i.e., a receptor) within a watershed, type 2 resource sheds are applicable. A type 2 resource shed defines the source location for all materials originating (or departing their source) during a time interval and arriving at the receptor during a final portion of that time interval. In a watershed, the water exiting a river mouth over any time period is a collection of parcels that left different source areas at different times, moved through the watershed with varying travel times, and converged at the mouth. Therefore, watershed-based type II resource sheds include the time interval over which material arrives at the receptor (e.g., discharge exiting a river mouth over the course of a day) and extend back in time over a longer interval or "lookback period" to when the material left its source.[3,5] Fortunately, in a watershed, the lookback period needed to delineate complete type II resource sheds is finite. Thus, the water that arrives at a river mouth over the course of a day can be traced back to its source areas in the watershed. This is because potential source areas for the parcels arriving at the mouth of a river are spatially confined within the border of the watershed and temporally confined to the moment after precipitation hits the ground; looking further back in time would improperly include airborne precipitation and atmospheric movement in the source area.[3]

This study was an initial application of resource shed analysis as a method for studying material loading to rivers. The primary purposes were to delineate source areas for water in a large watershed, to identify underlying land covers in these source areas, and to examine temporal patterns in source area configuration and land use contribution to discharge. We also evaluated land use contribution as defined by source-areas as a driver of mercury contamination (see Supporting Information). We present the first temporal examination of river discharge source areas and evaluation of land cover as potential nonpoint source contributors to runoff as a function of contribution to discharge.

■ MATERIALS AND METHODS

The 16,537-km^2 Fox River watershed, which includes the Wolf, Upper Fox, Lower Fox, and Lake Winnebago catchments (Wisconsin, US), drains into Green Bay, an inlet of Lake Michigan (Figure S1, Supporting Information). The Fox River watershed was initially chosen as a study area from those watersheds for which resource shed data were available due to its mercury contamination (see Supporting Information). Two discharge events, measured at the mouth of Green Bay, WI, by the Lake Michigan Mass Balance Study,[7] were examined in this study, one in 1994 (occurring from July 2, 1994, to July 29, 1994) and the other in 1995 (occurring from August 13, 1995, to September 9, 1995; Figure S2, Supporting Information). These discharge events were chosen for comparison because they were of similar magnitude and duration and occurred during similar seasons, but they had very different mercury concentrations (Figure S2; see Supporting Information for discussion of mercury). Although initially motivated in choosing discharge events for study due to disparate mercury levels, the choice of dates is immaterial to general evaluation of source area analysis. That is, temporal patterns in resource shed configuration and land use contribution to discharge can be evaluated for any discharge event and are independent of water constituents.

Resource sheds were calculated using the Great Lakes Environmental Research Laboratory's (GLERL) distributed large basin runoff model (DLBRM), a spatially explicit hydrologic model used for various surface runoff applications.[8,9] Adaptation of the DLBRM to resource shed analysis is detailed in Croley et al.[5] Using this model, the Fox River watershed was divided into 1 km^2 cells that consisted of the surface, soil layer, and groundwater zone through which travel precipitation, snowpack melt and runoff, and surface runoff. The model analyzed these cells as a cascade of moisture storage "tanks" that simulated the storage structure of the watershed, taking into account evapotranspiration, surface runoff, and subsurface percolation from the cell, and simulated the hydrological processes for the entire watershed sequentially, calculating the contribution of individual watershed cells to total discharge on a specific day over the specified lookback period. Each day of each discharge event was analyzed independently. These 1-day periods, over which discharge exited the river mouth, represented the time interval during which water arrived at the receptor. To calculate the type II resource sheds for each discharge event, lookback periods of increasing length were used, beginning with a lookback period of 1 day and continuing to a lookback period of 31 days. This lookback period represented the time interval over which water left its source area. Croley et al.[5] used a 31-day lookback period to evaluate the Maumee River watershed (Ohio, US). While 31 days was the maximum calculation available, this time period was reasonable, because it was a compromise between a potentially sufficient lookback period and practical computation limitations.

To evaluate whether the 31-day lookback period sufficiently captured the complete resource shed for each discharge event, cumulative change in the spatial configuration of the resource sheds was examined over the duration of the lookback period. If cumulative change reached an asymptote near 100% before the lookback period reached 31 days in length, then a 31-day lookback period was interpreted as sufficient to encompass the entire resource shed (i.e., adding additional time to the lookback period would result in little, if any, further change in resource shed configuration). The occurrence of large changes in spatial configuration at or near the 31-day lookback period would indicate insufficient time to encompass the entire resource shed.

Fox River resource shed data from the DLBRM consisted of the absolute contribution of individual watershed cells (in cm d^{-1}) to total discharge exiting the river mouth on a specific date considered over the specified lookback period. Using ArcGIS 9.x (ESRI Inc., Redlands, CA), these data, provided as text files, were imported as a series of tables into a geodatabase (i.e., a database designed to work with spatial data). Prior to analysis and display of the resource shed data, the absolute contribution values were multiplied by 10^{12} so that the values could be read by the ArcGIS software. The tables were added to an ArcMap session, and the adjusted absolute contribution data plotted (based on coordinate values in the data tables) and converted to grids, using the ArcGIS point to raster conversion tool, for geospatial analysis and display. In order to analyze the cumulative change in shape of the resource sheds, the change in perimeter size was evaluated for contribution classes (n = 10) for each day in a date's 31-day lookback period. These contribution classes were defined by natural groupings or breaks in the absolute contribution data (i.e., Jenks natural breaks classification; http://resources.arcgis.

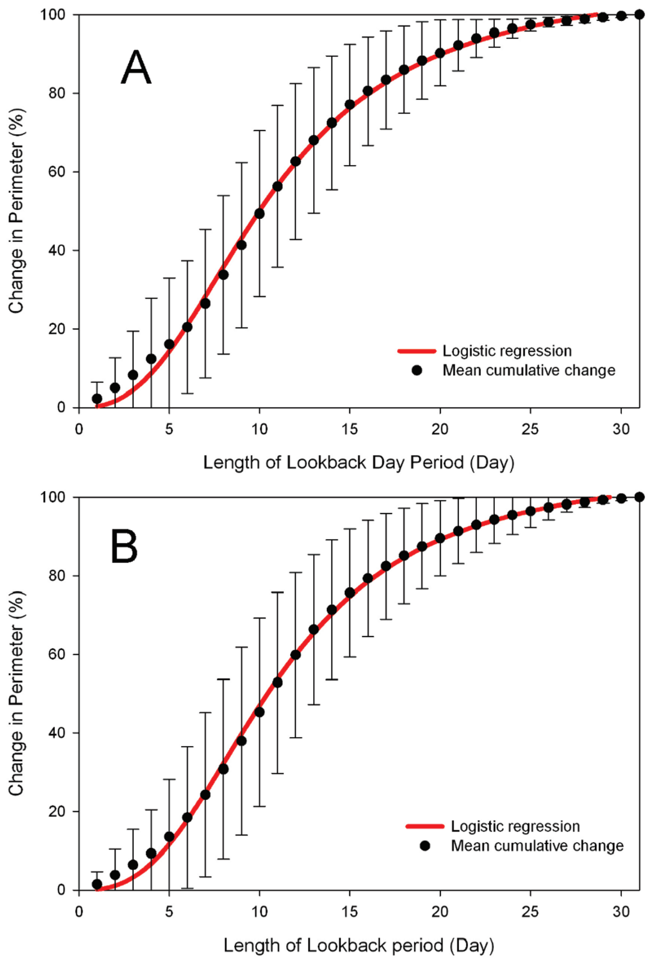

Figure 1. Cumulative change in resource shed configuration with increasing lookback period for the 1994 and 1995 discharge events. Data are mean cumulative change (±1 standard deviation) in the perimeter of cells contributing to total discharge. Each point is the mean change seen after *n* lookback days, using data from each day in the (A) 1994 discharge event (July 2−29, $n = 26$) and (B) 1995 (August 13−September 9, $n = 28$) discharge event. Curves are logistic regressions (1994, $p < 0.0001$, $R^2 = 0.88$; 1995, $p < 0.0001$, $R^2 = 0.87$).

com, accessed December 2010). Using a Python script, the grids were reclassified to fit the Jenks natural breaks classification and then converted to a shapefile. Perimeter length was summarized for each natural break class, and using the maximum change observed in maps between lookback day 1 and lookback day 31, change in perimeter length was calculated for each individual day of both discharge events. Temporal patterns in source area configuration were evaluated by mapping the complete type II resource sheds (using the 31-day lookback period) for water exiting the river mouth over the course of a day for each individual date of a discharge event. The resulting maps showed the contributions over the entire watershed for specific departure and arrival time intervals.

Analyses of land cover underlying the source areas were conducted for each day of both discharge events. Particular attention was paid to July 20, 1994, and August 21, 1995, because mercury concentrations were recorded at the river mouth on those dates and differed markedly from each other (unfiltered total Hg: 182.6 and 31.6 ng L^{-1} Hg_T, respectively;[10] Figure S2, Supporting Information). Limnological parameters measured during LMMB on those dates were also compared. Land cover data used in analysis was derived from LANDSAT satellite imagery acquired in 1991−1993 [Wisconsin Initiative for Statewide Cooperation on Landscape Analysis and Data (WISCLAND), http://dnr.wi.gov/maps/gis/datalandcover.html#overview]. Land cover was evaluated using WISCLAND land classes, with the exception of wetland land covers, which were delineated further using wetland subclasses (Table S1, Supporting Information). Each cell of the resource shed data was attributed with its underlying land cover classification(s). The absolute contribution to total discharge exiting the river mouth over the course of an individual day was summed for all cells of a particular land cover classification, so that total contribution of each land cover class to overall discharge could be assessed. To relate absolute contribution in cm d^{-1} to total discharge at the river mouth (in m^3 s^{-1}), the total contribution was multiplied by the following conversion factor: (area of the watershed in m)/(8.64×10^6).

■ RESULTS AND DISCUSSION

As the lookback period lengthened, the natural break classification of cells contributing to total discharge showed more fragmentation, causing the perimeter length of the classes to change. This occurrence suggests that perimeter length served as an adequate metric of resource shed spatial configuration. Figure 1 shows the cumulative percent change in spatial configuration of the type II resource sheds, using cell perimeter length for the 1994 and 1995 discharge events with increasing lookback period (1994, $p < 0.0001$, $R^2 = 0.88$; 1995, $p < 0.0001$, $R^2 = 0.87$). The actual change in resource shed spatial configuration for water exiting the mouth of the Fox River on July 20, 1994 (as a function of increasing lookback period), is illustrated in Movie S1 of the Supporting Information.

In both the 1994 and 1995 discharge events, 95% of the cumulative change in resource shed configuration was achieved by lookback day 23 and 99% by lookback day 28. Therefore, the 31-day lookback period was sufficient to capture complete type II resource sheds and delineate source areas for water leaving the mouth of the Fox River over the course of a day in both discharge events. Croley et al.[5] qualitatively reported little change in the appearance of the type II resource sheds generated for January 1, 1950, in the Maumee River watershed (OH) after increasing the lookback period beyond 7 days and attributed this to the Maumee watershed being highly reactive (i.e., responding quickly to surface supply). The Maumee River watershed (17,060 km^2) is similar in size to the Fox River watershed, suggesting that a 31-day lookback period is likely sufficient for delineating type II resource sheds in watersheds of this general size and smaller; shorter lookback periods may be sufficient for watersheds with increased watershed reactivity (i.e., quick responses to surface supplies) or lower mean residence times.

The spatial distribution of source areas varied between and over the duration of the individual discharge events. During the 1994 event, discharge on the first day originated primarily in the southwestern, north central, and extreme northern areas of the watershed (Figure 2 and Movie S2, Supporting Information); these are source areas for baseflow and are represented by the darker colors in the contribution color spectrum, because discharge on this day was low. Discharge then originated from areas near the mouth, with source areas moving upstream over time. A hotspot developed in the central portion of the watershed, fading in contributory importance over the remaining

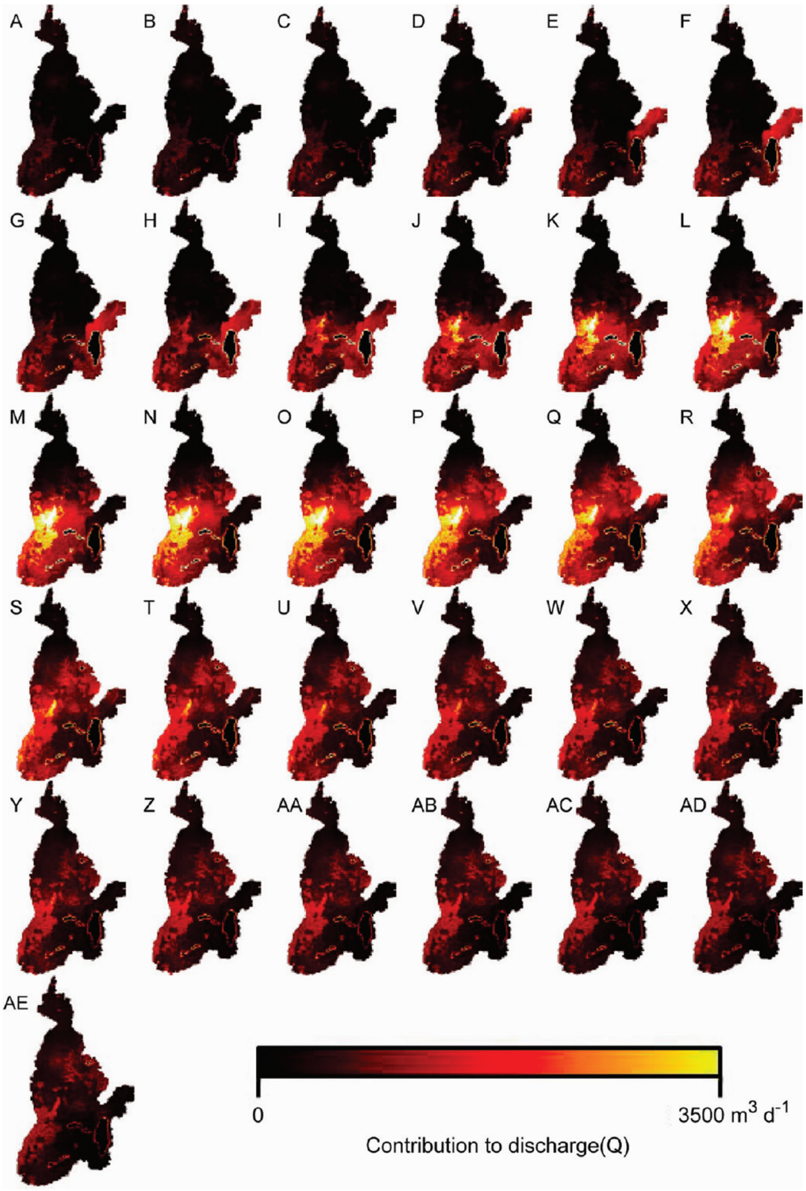

Figure 2. Resource sheds for water exiting the Fox River watershed at Green Bay, WI, during a discharge event. Source areas for water exiting the river mouth over the course of a day (type II resource sheds with 31-day lookback period) are shown beginning with (A) July 1, 1994 ending with (AE) July 31, 1994. This temporal sequence can also be viewed in Movie S2 (Supporting Information).

duration of the 1994 discharge event, while, concurrently, areas further upstream in the western, southwestern, and north central portions of the watershed contributed significantly to discharge. As discharge fell, so too did the contribution of source areas, ultimately returning to baseflow conditions. Source areas for baseflow, however, were subtly different than those prior to the discharge events, with areas that were hotspots during discharge events continuing to contribute to baseflow discharge. Source-area patterns differed during the 1995 discharge event, with four hotspots developing, as illustrated in Figure S3 (Supporting Information). During both events, resource shed patterns were consistent with temporal patterns of discharge measured independently at the river's mouth, with the greatest amount of contribution to discharge (denoted by the brightest colors in the resource shed illustrations) coinciding with peaks in the hydrograph (i.e., in the middle of the event).

No obvious difference distinguished land covers supplying discharge on July 20, 1994, and August 21, 1995, because source areas for water exiting the river mouth on these dates contained generally similar heterogeneous distributions of land cover types (Figure 3). Moreover, despite different hotspots present in the resource sheds, the relative contribution of land cover types to discharge on these dates was similar (Figure 4). Not surprisingly, limnological parameters and concentrations of nutrients and contaminants measured at the river mouth on these dates were almost identical (Table S2, Supporting Information). The relative contribution of land cover types to discharge on both dates differed, however, from the abundance of those land cover types in the watershed (Figure 4). Agricultural land accounted for 44% and 42% of discharge sources on July 20, 1994, and August 21, 1995, respectively, while only 38% of the watershed consists of agricultural land. Similar patterns occurred for grassland and

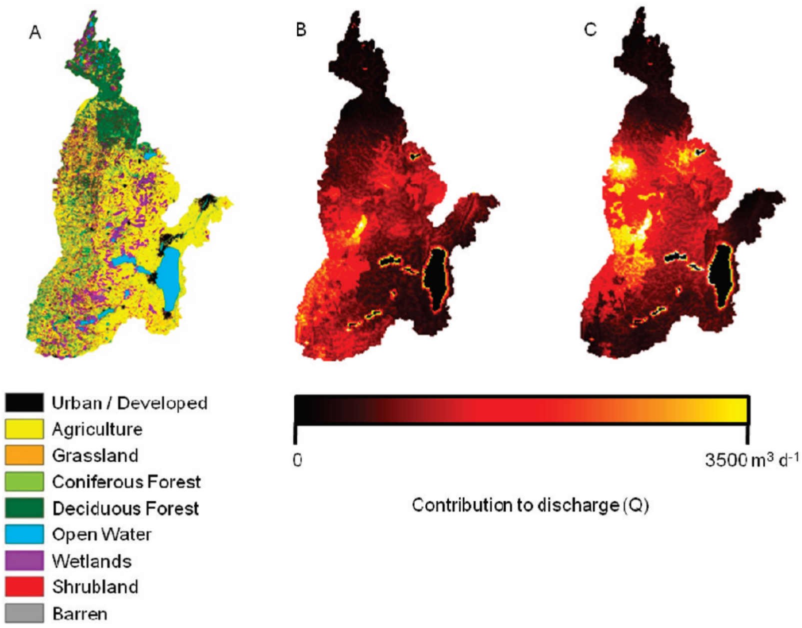

Figure 3. Land covers and resource sheds in the Fox River watershed (WI). (A) Land covers derived from the WISCLAND; wetland subclasses considered independently in the study are grouped in this figure for simplicity of illustration (purple). (B, C) Type II resource sheds (with 31-day lookback periods) showing absolute contribution to discharge exiting the mouth of the Fox River at Green Bay, WI, on (B) July 20, 1994, and (C) August 21, 1995.

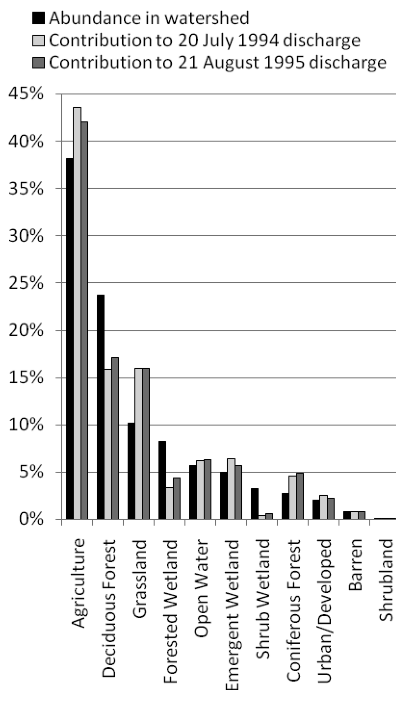

Figure 4. Relative percent contribution of land cover types to total discharge from the Fox River (WI) on July 20, 1994 (light gray), and August 21, 1995 (dark gray), in relation to the relative abundance of those land covers in the watershed (black). Relative abundance was calculated by assigning each 1 km^2 cell used in the resource shed model its underlying land cover, as derived from the WISCLAND. Relative percent contribution to total discharge depicts the degree to which a land cover acted as a source of water for the discharge on that date.

coniferous forest, while deciduous forest and wetlands were underrepresented as sources areas. Regions of relatively homogeneous land cover, consisting primarily of deciduous forest in the north and agricultural land in the southeast, existed, but they were not important source areas on either date. Thus, the degree to which a receptor integrates runoff from various regions or land covers is a function of the physical configuration of the resource shed, not the presence of regions or land covers in a watershed. Moreover, differential spatial distribution of source areas between time periods should have more marked effects on temporal patterns of limnological parameters when land cover types are clumped at large scales. Hence, we can hypothesize that when source areas are dominated by a few land covers, limnological parameters measured at downstream sites should be similar to those of watersheds with few land cover types.

Drainage of particular land cover types changed over time in both discharge events (Figure 5). In both years, the relative importance of agricultural land covers increased quickly at the beginning of the discharge event; contribution by agricultural land cover was the first to increase in 1994 and increased at an even faster rate in 1995. The shape of the curves describing land cover contribution to discharge generally mirrored the hydrograph: drainage rose during the beginning of the event, crested, and then fell (Figure 5A,C). Different land cover types, however, crested at different times, especially during the 1995 event (Figure 5C). Observed patterns of contribution were generally subtle, again reflecting the heterogeneous distribution of land cover types in source areas. Had source areas been made up of large, relatively homogeneous parcels of different land covers, peaks in drainage (i.e., contribution to discharge) and relative percent contribution to discharge would likely have been more widely separated for the various land cover types.

Our results illustrate that the determination of which land covers contribute water to overall discharge, and potentially serve as nonpoint sources of contamination or material loading, can be improved through source-area analyses. Temporal patterns in the limnological parameters of discharge from a watershed are influenced by different land cover types in spatial patterns independent of the general land cover in the watershed. Indeed,

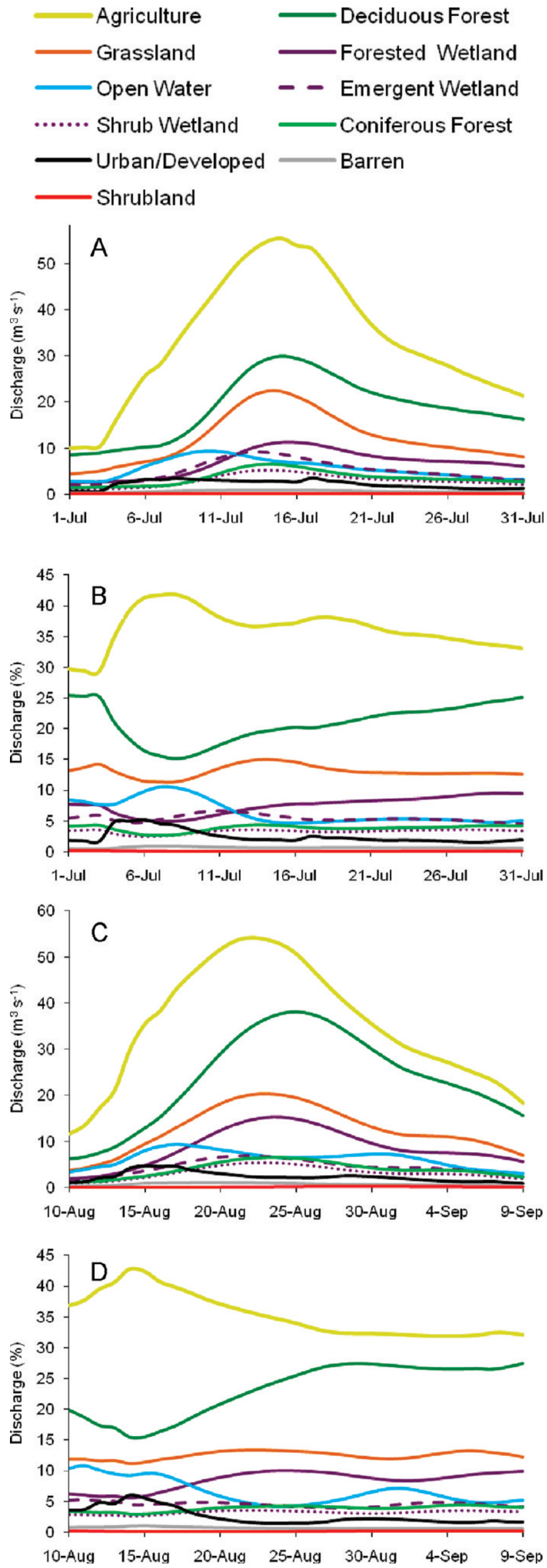

Figure 5. Temporal patterns of contribution to total discharge by individual land cover types in the Fox River watershed (WI). (A) Discharge contributed by land covers and (B) relative percent contribution of those land cover types to total discharge over the course of a July 1994 discharge event. (C) Discharge contributed by land covers and (D) relative percent contribution of those land cover types to total discharge over the course of an August 1995 discharge event.

variance observed in previous analyses of land cover influence on material loading to rivers might be explained by discrepancies between total areal representation of land covers in the watershed and the land cover of actual source areas. Therefore, a source-area-based approach, rather than a watershed-based approach, should improve study, understanding, and ultimately management of material loading to rivers.

■ ASSOCIATED CONTENT

Supporting Information. A detailed discussion of mercury loading to rivers; tables identifying the classifications used in the land cover analysis (Table S1) and limnological parameters, nutrients, and contaminants measured at the river mouth on both study days (Table S2); figures showing the study site, the Fox River hydrograph, total mercury concentration (1994 and 1995), and the resource sheds for the 1995 discharge event (Figures S1−S3); and two movies, one illustrating resource sheds for water exiting the mouth of the Fox River on July 20, 1994, and the other illustrating the resource sheds over the course of the 1994 discharge event (Movies S1, S2). This material is available free of charge via the Internet at http://pubs.acs.org.

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■ DISCLOSURE

Although this work was reviewed by US EPA and approved for publication, this paper does not necessarily reflect official agency policy.

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