

HYDROLOGIC—HYDRAULIC—ECOLOGIC RESOURCE SHEDS

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ABSTRACT

We can quantify source areas contributing material to a location during various time periods as *resource sheds*. Various kinds of resource sheds and their source material distributions are defined. For watershed hydrology, we compute resource sheds and their source material distributions with a spatially distributed hydrology model by tracing material departing from a *cell* (say 1 km²) over one time interval and arriving at the watershed mouth in another time interval. This requires modeling all cells, but only tracing contributions from one at a time. By then combining these simulations for all cell loadings, we construct a map of the contributions over the entire watershed for specific departure and arrival time intervals. We then combine results of several sets of simulations to determine the source distribution for any time period and infer resource sheds from these mappings. For lake circulation, we discuss the construction of resource sheds and their source distributions in the lake, by using lake circulation models to drive particle tracers in reverse time, and subsequent correction. We present Maumee watershed examples, discuss methods of computation reduction and linkage with lake circulation models, construct joint resource sheds in Lake Erie, and suggest areas of extension.

KEY WORDS

Water supply distribution and nonpoint source mapping.

1. Introduction and Background

Accurately defining the spatial boundary of resource distribution and transport is essential to the understanding and management of resource dispersion over multiple spatial and temporal scales. Ecologists have sought to spatially delimit otherwise intuitive ecological units such as ecosystems [1]. Where changes in ecological conditions are abrupt, such as at the land-water interface of a coast for example, ecosystem boundaries appear distinct. Yet the phenomenon of ecological subsidy, or donor-controlled supply of resources supporting food webs spatially distinct from source areas, blurs otherwise distinct ecosystem boundaries [2]. Embracing this common fea-

ture of food webs, Power and Rainey [3] proposed the explicit delineation of ecological subsidy in space through the “resource shed”, or “source areas for resources consumed by individuals during their lifetimes”. Hence processes, rather than physical landscape features alone, can define geographic areas of ecological relevance to systems under study. Indeed, Power and Rainey [3] observed that landscape features such as topography, coupled with physical forcing variables, can determine the shape of resource sheds. In the present study, resource sheds are determined by the movement of water, and hence are relevant to water-borne materials. Moreover, we generalize the definition of resource shed to encompass source areas from which materials are derived for an individual, population, or location, over a specified time period. In this definition materials can include nutrients, organic matter, sediments, organism propagules, prey items, or pollutants; i.e. anything transportable by water. Hence a resource shed is a geographic area from which originate materials over a specific time period that subsidize food webs or that are donated to a location at a specific time. Applying this concept, Ben-David et al. [4] investigate the variable resource sheds created by the movements and behavior of river otters and their impacts on nutrient cycling, changes in productivity and in community structure and function, and landscape heterogeneity of terrestrial communities.

The boundary of a hydrological resource shed is delineated by the contributing sources of water and materials to the watershed mouth (landscape features) during hydrologic events (physical forcing variables). Thus hydrological resource sheds have a dynamic border, or rather a border relevant to a specific time period during which physical forcing variables operate (e.g. the resource sheds of water or sediments in a watershed change from one storm event to another). The resource shed concept focuses on both temporal and spatial distribution of water and materials within a changing space. This concept is relatively new and not yet well developed. For example, what are the theoretical principles for defining resource sheds? What are appropriate spatial and temporal scales of resource sheds? How do we integrate spatial modeling

techniques with currently available computing technology to define and model resource sheds? Despite these challenges, we believe the concept of resource sheds provides a new way of displaying, understanding, and discovering the transport and distribution of water and materials and has the potential of helping resource managers better track and manage source loadings in a study area.

Here, we define resource sheds and propose analysis procedures to determine them. We first describe various resource shed definitions, providing different views of information that are related, which we then demonstrate. We also describe various resource shed distributions (source density of material of interest over the resource shed) and then demonstrate their relationships. We present methodologies for computing hydrological resource sheds within watersheds and lakes. We apply the methods to several examples in the Maumee River watershed in northwestern Ohio and Lake Erie (which the Maumee River enters) and link their resource sheds.

2. Resource Sheds

Consider a location with a material passing through it (e.g., water, pollutant, sediment, microbes). Where did this material come from and how long did it take to reach the location? We can quantify the answer by defining *resource sheds* for this location corresponding to areas in which departing materials at one time arrive at the location of interest at another time. Figure 1 shows example travel time isochrones for source material at successively earlier start times.

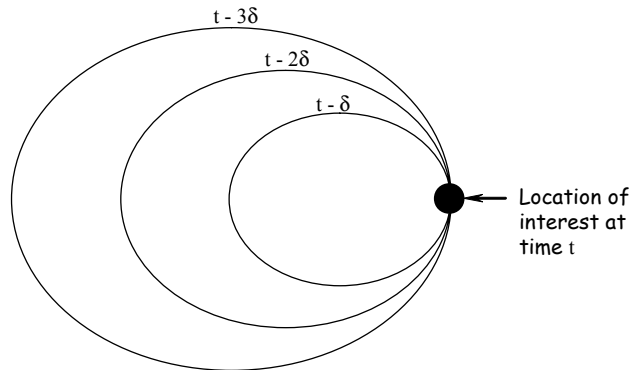


Figure 1. Example Source Travel-Time Isochrones.

Thus, the inner-most line in Figure 1 denotes the location of all material that started moving at time $t - \delta$ and arrived at our location of interest (LOI) at time t . The area contained within this isochrone represents the source area (resource shed) of material departing in the last δ time interval. For convenience, consider only discrete time in intervals of δ and define $V_{i,j}$ as the set of all locations, representing the resource shed, for materials departing during the time interval of length δ prior to time i (the i^{th} time interval) and arriving at the LOI during the j^{th}

time interval. Figure 2 shows example resource sheds based on Figure 1 for $t = 6$ and $\delta = 1$.

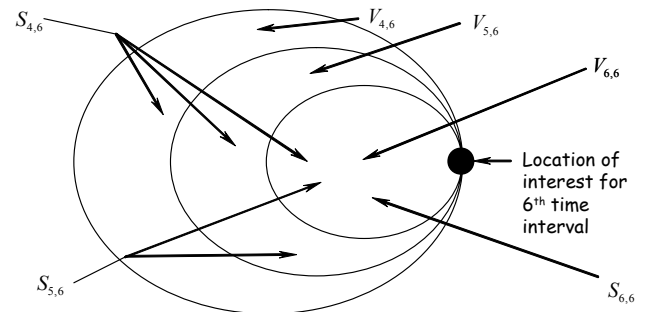


Figure 2. Example Resource Sheds.

(Figure 2 and all remaining figures portray mutually exclusive $V_{i,j}$, $i = j, j-1, j-2, \dots$ for clarity. However, all resource shed definitions and derivations herein apply without loss of generality for the general case of overlapping $V_{i,j}$.) By accumulating these V -type resource sheds (where material departs in one time interval and arrives in another) over consecutive start times, we can build resource sheds $S_{i,j}$ for materials departing during time intervals i, \dots, j and arriving at the LOI during the j^{th} time interval, as shown by the S 's in Figure 2.

$$S_{i,j} = \bigcup_{m=i,j} V_{m,j} \quad (1)$$

Also define $T_{i,j}$ as the resource shed for materials departing during time intervals i, \dots, j and arriving at the LOI also during time intervals i, \dots, j . Note that

$$T_{i,j} = \bigcup_{m=i,j} S_{i,m} \quad (2)$$

3. Material Densities

While these definitions refer to the spatial extent of a contributing area, they do not address the differences between parts of a contributing area. Some parts of an area may supply more material to our location of interest than other parts. We can quantify this distribution information by mapping over the resource shed the portion of the material contributed to the LOI. Figure 3 shows a resource shed $V_{i,j}$. For every cell c within $V_{i,j}$ the fraction of material appearing at the LOI in time interval j that departed in time interval i from area A_c is $p_{i,j,c}$ (where A_c is cell c 's area). By accumulating over consecutive start times we can build resource shed *distributions* representing the material fraction arriving at the LOI in time interval j that departed during time intervals i, \dots, j from area A_c as $q_{i,j,c}$. It can be shown [5] that

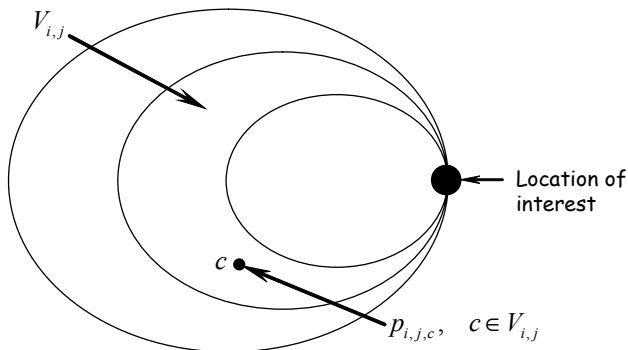


Figure 3. Example Resource Shed Source Distribution.

$$q_{i,j,c} = \sum_{m=i,j} p_{m,j,c} \quad (3)$$

Likewise, represent the material fraction arriving during time intervals i, \dots, j that departed during time intervals i, \dots, j from area A_c as $u_{i,j,c}$. Again [5],

$$u_{i,j,c} = \sum_{m=i,j} \gamma_{i,j,m} q_{i,m,c} \quad (4)$$

where $\gamma_{i,j,m}$ is the fraction of all material arriving at the LOI during time intervals i, \dots, j that arrived in time interval m ($i \leq m \leq j$).

4. Estimating Hydrological Resource Sheds

In a watershed, we compute resource shed distributions from spatially distributed watershed models; material

placed anywhere in the watershed will appear at the watershed outlet (mouth) over a period of time. We calculate the material appearing at the mouth (our LOI) at any time, contributed by a specific area. (This requires modeling all cells, but only tracing contributions from one.) By combining all of these simulations, we construct a map of the fraction contributed over the entire watershed.

We use the Great Lakes Environmental Research Laboratory's Distributed Large Basin Runoff Model (DLBRM) to model watershed flows into Lake Erie from the Maumee River watershed in northwest Ohio; see Croley and He [6] for DLBRM details. The watershed outlet is to the northeast; the Maumee is a very "flashy" watershed that responds quickly to surface supply. Figure 4 shows example resource sheds for the Maumee River on January 1, 1950 for 1, 7, and 31 days of previous loading. In Figure 4, the brightest areas correspond to cells contributing about 0.015% of the total flow on January 1, 1950. The darkest areas are close to zero. Note several things about Figure 4. The southern and western ridgelines are prominent as is a line to the north that marks the boundary between Ohio and Michigan (AB in Figure 7). This boundary reflects the differences in the two States' definitions of some soil properties and so is an artifact of data standard differences. Point C in Figure 4 identifies the mouth of the watershed. The first map in Figure 4 shows a little response from yesterday's light rain near the mouth of the watershed; the second and third maps show most response along the edges of the watershed furthest from the mouth. Inspection of rainfall maps shows there is not much rainfall over the prior 4 days but there is a large amount 5 days prior in the southwest area. Also, spatially

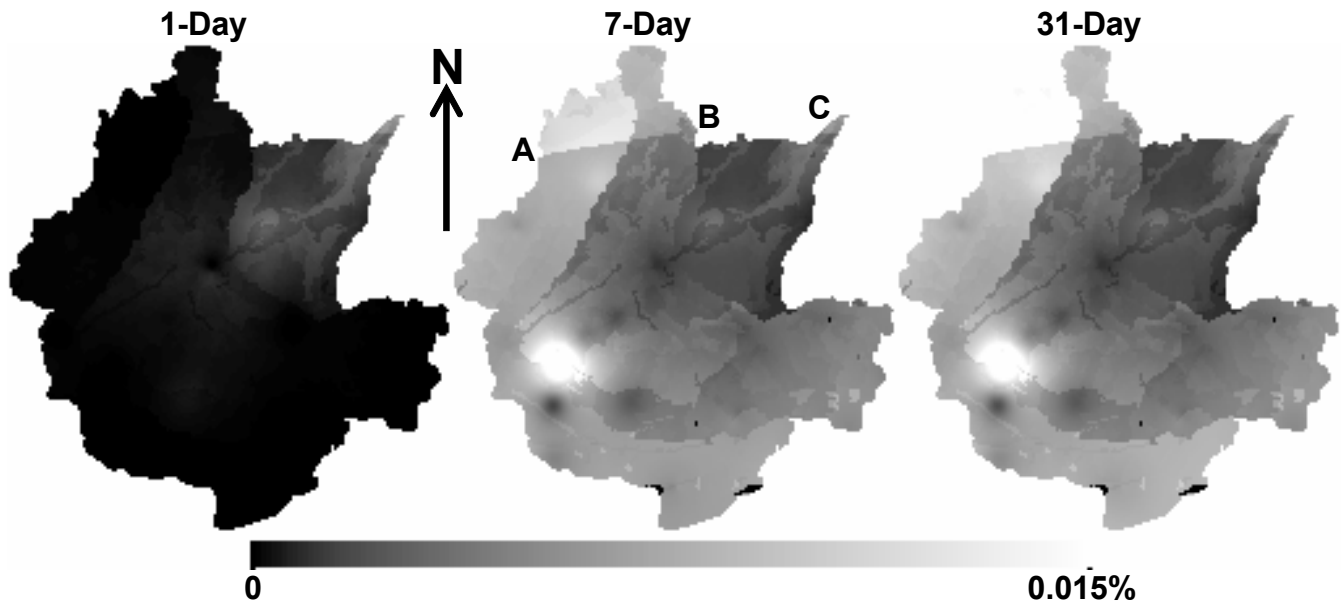


Figure 4. Maumee Resource Sheds on January 1, 1950 from prior days of loading:

1-day:	$q_{\text{January 1, 1950, January 1, 1950, } c}$	$c = 1, \dots, 17,541;$
7-day:	$q_{\text{December 26, 1949, January 1, 1950, } c}$	$c = 1, \dots, 17,541;$
31-day:	$q_{\text{December 2, 1949, January 1, 1950, } c}$	$c = 1, \dots, 17,541.$

uniform rain-fall fell over the entire watershed 7 days prior, 11-13 days prior, 15 days prior, 21-22 days prior, and 29 days prior. We can see the bright spot corresponding to the large 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 are not part of the flow on this day. Note also that what happens prior to 7 days changes the picture very little (compare the last two maps). 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 all supplies falling more that 6 or 7 days ago have already runoff and do not form a part of the flow on this day.

5. Estimating Lake Resource Sheds

In a lake, resource sheds may be computed with a lake circulation model in which particles (tracers) are defined at a given LOI and the model is run backward in time from a specified time. The locations of the particles at earlier times define the extent of the resource shed. By releasing the same number of particles each day in the backward simulation, one can estimate resource sheds for various prior periods to the date in question. The density of the particle distribution over the resource shed defines the fraction of material contributed. The example in Figure 5 shows only a small sampling for clarity.

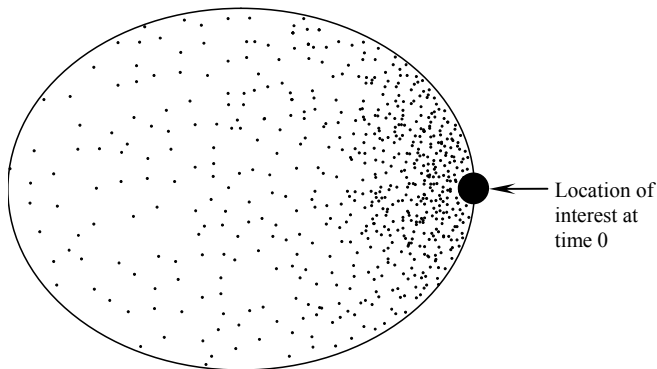


Figure 5. Example Estimating Resource Shed Distribution by Tracking Particles Backward In Time.

By counting the number of particles in area A_c for specified departure and arrival time intervals i and j and dividing by the sum of such numbers for all c , we estimate the material density $\hat{p}_{i,j,c}$. Thus, backward time particle tracing where the same number of particles are released each day in the backward simulation gives only the spatial distribution of each time interval's contributions to the location of interest during the last time interval, but not the spatial-temporal distribution. Therefore,

$$p_{i,j,c} = \phi_{i,j} \hat{p}_{i,j,c} \quad (5)$$

where $\phi_{i,j}$ = fraction of all material arriving during time interval j that originated over all cells during time inter-

val i [5]. We expect that $\phi_{i,j} \rightarrow 0$ as $i \rightarrow -\infty$ and that $\phi_{i,j} < \phi_{m,j}$ for $i < m < k < j$ where k is the date/time of the peak contribution. Also note that

$$\sum_{i=-\infty,j} \phi_{i,j} = 1 \quad \forall j \quad (6)$$

We would have information on $\phi_{i,j}$ indirectly in a forward simulation that uses a loading pattern with specified dynamic inputs and outputs from all rivers and channels. If we use the backward simulation, then we have to supply $\phi_{i,j}$ either from additional small forward simulations or other considerations.

6. Linking Resource Sheds

We desire to (eventually) extend a lake's resource shed back into a contributing watershed, requiring the joining of resource sheds, estimated with different techniques, through the mouth of the watershed. See Figure 6 where the superscripts denote Lake (L) and Watershed (W).

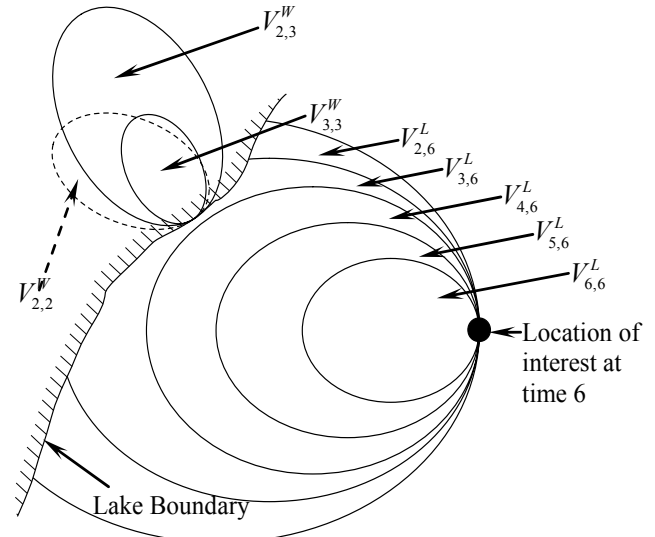


Figure 6. Example Lake Resource Shed Just Touching Watershed Mouth Three Time Units Ago.

Looking at fractions of material moved,

$$p_{i,j,c}^C = p_{i,j,c}^L + \sum_{m=i,j} \beta_{m,j} p_{i,m,c}^W \quad (7)$$

where the superscripts denote Lake (L), Watershed (W), and Combined (C), and where $\beta_{m,j}$ is the fraction of material arriving at the location of interest in the lake in time interval j that came from the watershed mouth in time interval m .

We can do an example coupling of Lake Erie and Maumee River resource sheds and their distributions by using

the watershed model to calculate $p_{i,m,c}^W$ in (7) and the backward-tracking circulation-particle model to calculate $\hat{p}_{i,j,c}$ in (5) and $\beta_{i,j}$ in (7). By taking $\phi_{i,j}$ as the 1-parameter gamma distribution of time lag with a mean of -30 days, we can use (5) to compute $p_{i,j,c}^L$ in (7), and use (7) to compute material densities for the entire watershed—lake system. Equations (3)—(4) applied to $p_{i,j,c}^C$, give us resource shed densities for other definitions.

Shown in Figure 7 are coupled resource shed densities for material originating over the indicated periods ending on August 31 and passing through the location of interest over that same period. They were calculated by using the hydrology model for the Maumee watershed and the Princeton Ocean Model applied to Lake Erie circulation at the Great Lakes Program of the University of Buffalo. (Note that both the lake and watershed resource sheds are calculated from daily average meteorology over 1983—2002). Lake Erie is depicted with a constant gray tone not to be confused as part of the spectrum of resource shed density values. The location of interest is Western Basin Lake Erie Site 835 just adjacent to the tip of the arrow in Figure 7. There we see that on August 31, the 1-day resource shed does not extend into the watershed (flow from Maumee actually takes about two days to reach the location of interest at this time of year). The latter resource sheds do extend into the Maumee watershed and intensify as we look over longer prior periods.

7. Conclusion

A resource shed is the area contributing material, over one time interval, passing through a location of interest over another time interval. We looked at resource shed concepts and discussed several interpretations. We provided general definitions of resource sheds and derived expressions for: 1) resource sheds where materials departing during one time interval arrive at the location of interest during a later time interval, 2) resource sheds where materials departing during a sequence of time intervals arrive at the location of interest during the last of those time intervals, and 3) resource sheds where materials departing during a sequence of time intervals arrive at the location of interest during that same sequence of time intervals. We also expressed each in terms of each other. We then provided general definitions of resource shed distributions and derived expressions for the distributed amount of source material within a resource shed, for all three definitions of same. We also expressed each of the resource shed distributions in terms of each other.

We discussed the estimation of resource shed distributions (corresponding to all three definitions) within a watershed through the use of a spatially distributed hydrology model in which the watershed area consists of discrete cells, introduced a specific hydrologic model for use

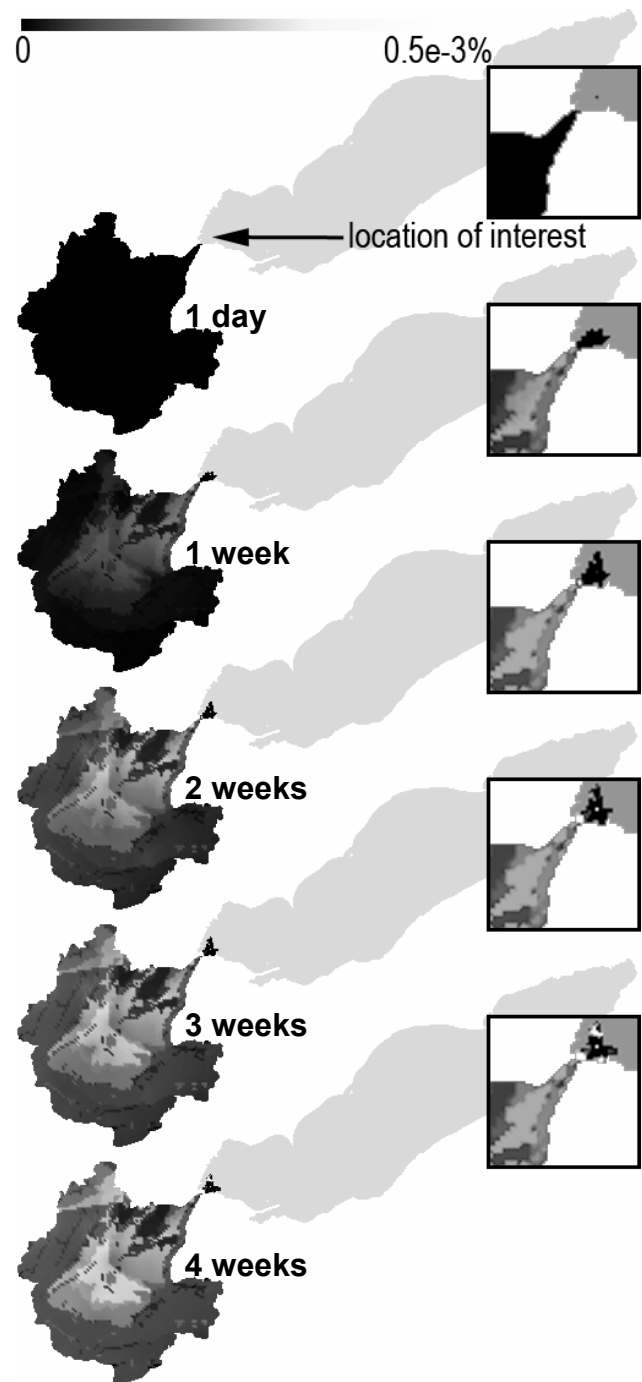


Figure 7. Maumee—Erie Resource Shed for Average August 31 Conditions for Site 835.

on the Maumee River watershed in Ohio, and calculated example resource shed distributions for material passing through the watershed outlet on January 1, 1950 for 3 different periods of previous loadings. We also discussed the estimation of resource shed distributions within a lake through the use of a spatial lake circulation model run backward in time into which particles are introduced and counted during the simulation

Finally, we considered the joining of a resource shed beginning in a lake and progressing (as we consider longer

prior periods of flow for a given date) into the adjoining watersheds that contribute to the lake. We derived definitions and relations for the combined resource sheds and the combined resource shed distributions. We depicted the joint resource shed distribution for the Lake Erie—Maumee watershed system in an example application.

The large amount of computation sometimes required in the construction of resource sheds and their distributions encourages methods to reduce calculations. We could calculate resource shed distributions over only a sample of watershed cells and then interpolate for the other cells. There are of course alternate resolution trade-offs and a few spatial interpolation technique trade-offs. Also, we could order resource shed computations, when more than one resource shed is computed, to save on computations. Ordering should make sense when contiguous dates and durations are considered or in near real time where yesterday's computations are extended one day in today's.

It should be possible to extend this work in several ways. Currently, we are linking hydrological watershed resource sheds and their distributions with lake resource sheds generated via different methods, as exemplified here. We plan to produce, for the World Wide Web, a dynamic linking of several Lake Erie watersheds with the lake to produce joint resource sheds and their distributions associated with about 35 locations of interest in the lake and extending into the tributary watersheds. Also, as we add material transport capabilities to our hydrologic model, we will 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. Finally, in support of these latter predictions, we are also building a daily near real time generator of resource sheds and their distributions and plan to move to hourly as the model develops further.

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References

- [1] Cousins, S. H., Countable ecosystems deriving from a new food web entity. *Oikos*, 57, 1990, 270-275.C.
- [2] Polis, G. A., W. A. Anderson, and R. D. Holt, Toward an integration of landscape and food web ecology. *Annual Review of Ecology and Systematics*, 28, 1997, 289-316.
- [3] Power, M. E., and W. E. Rainey, Food webs and resource sheds: towards spatially delimiting trophic interactions, in Hutchings, M.J., E.A. John, and A.J.A. Stewart (Eds.), *The Ecological Consequences of Environmental Heterogeneity*, Blackwell Science, Oxford, U.K., 2000, 291-314
- [4] Ben-David, M., G. M. Blundell, J. W. Kern, J. A. K. Maier, E. D. Brown, and S. C. Jewett, Communication in river otters: creation of variable resource sheds for terrestrial communities. *Ecology*, 86(5), 2005, 1331.
- [5] Croley, T. E., II, C. He, J. F. Atkinson, and D. F. Raskow, Resource Shed Definitions and Computations. NOAA Tech. Memo. GLERL-141, Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan, 2007, 43 pp.
- [6] Croley, T. E., II, and C. He, A watershed surface and subsurface spatial intraflows model. *Journal of Hydrologic Engineering*, 11(10), 2006, 12-20.