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A spatially explicit framework for quantifying downstream hydrologic conditions

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ABSTRACT

Continued improvements in spatial datasets and hydrological modeling algorithms within Geographic Information Systems (GISs) have enhanced opportunities for watershed analysis. With more detailed hydrology layers and watershed delineation techniques, we can now better represent and model landscape to water quality relationships. Two challenges in modeling these relationships are selecting the appropriate spatial scale of watersheds for the receiving stream segment, and handling the network or pass-through issues of connected watersheds. This paper addresses these two important issues for enhancing cumulative watershed capabilities in GIS. Our modeling framework focuses on the delineation of stream-segment-level watershed boundaries for 1:24 000 scale hydrology, in combination with a topological network model. The result is a spatially explicit, vector-based, spatially cumulative watershed modeling framework for quantifying watershed conditions to aid in restoration. We demonstrate the new insights available from this modeling framework in a cumulative mining index for the management of aquatic resources in a West Virginia watershed.

1. Introduction

Spatially based investigations of stream ecosystems and their surrounding watersheds have received increasing attention with the expansion of Geographic Information Systems (GISs) technology and improvements in digital datasets and hydrologic modeling techniques. GIS has made it possible to characterize streams and corresponding watersheds by land use/land cover and other abiotic factors, to easily delineate multiple watersheds across large areas, and to construct increasingly spatially explicit models of networked, hierarchical stream ecosystems at multiple spatial scales. GIS offers many useful approaches for characterizing and classifying watersheds and hydrologic systems, and there are several methods of representing hydrologic features within a GIS modeling framework (Fisher and Rahel, 2004). This paper offers a more highly detailed cumulative stream-segment-level watershed networking framework to address watershed characterization and management, and applies the framework by assessing cumulative coal mining impacts on streams in the central Appalachians.

1.1. Background

Numerous previous studies have used GIS to quantify the influence of land use/land cover and other abiotic factors on streams of interest at varying spatial extents. These studies have attempted to relate land use/land cover to instream water quality, habitat, or biota. This is typically performed using a variety of spatial representations of aquatic systems, characterizing land cover along the stream, within a riparian buffer corridor along the stream, or within the entire catchment upstream of the site of interest (Hunsaker and Levine, 1995; Allan, 2004).

The influences of human activities and land use on stream processes are ideally studied through extended, replicated experiments on larger watersheds, however, due to time, cost, and practicality, these interactions are more frequently studied through the use of empirical modeling and GIS techniques (Strayer et al., 2003). Empirical models may be designed to assess the impact of land cover on various response variables such as nutrient flux, fish community composition, benthic macroinvertebrates and others (reviewed by Allan, 2004). Models have also been developed to assess the potential impacts of future land use changes and development-related stream alterations on stream condition (Van Sickle et al., 2004). Additional indicators of ecological condition besides land cover may also be considered at the watershed scale,

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such as landscape pattern, fragmentation, and connectivity (O'Neill et al., 1997), road density and proximity (Bolstad and Swank, 1997; Jones et al., 2001), and number of dams (Jones et al., 1997).

Specific difficulties in classifying streams by landscape variables include the influence of many different, interconnected scale-specific processes, impacts of historical activities such as past mining and landscape alterations (Allan, 2004), and spatial autocorrelation with watershed land cover indicators (King et al., 2005). While the influence of land cover on ecological response may be quantified at varying spatial extents (stream, riparian corridor, watershed), the most effective statistical models of stream ecosystems take into account the spatial scale of mechanisms connecting land cover to ecological response (Strayer et al., 2003).

1.2. Watershed delineation

The automated mapping of watershed boundaries using GIS has been proven to be very useful in the analysis of landscape features and their effect on receiving water bodies (Maidment and Djokic, 2000). There are different approaches to the actual mapping and delineation of watershed or catchment boundaries with GIS. At a broad spatial scale, the U.S. Geological Survey (USGS) has delineated a hierarchical system of watersheds (with the smallest units known as 8-digit hydrologic cataloging units or HUCs) for 2264 surface drainage sub-basins throughout the U.S. (Seaber et al., 1987). Additionally, the Natural Resources Conservation Service is in the process of delineating further subdivisions of the USGS cataloging units at the 10-, 12-, and 14-digit watershed level. However, use of these delineated watersheds for detailed spatial analysis is not ideal due to the relatively large size of the resulting watersheds (even 14-digit watersheds may contain multiple streams and tributaries at the 1:24 000 map scale), arbitrary watershed pour point locations, and boundaries based on drainage area thresholds. In addition to the level of detail, other considerations in using watershed boundaries for watershed-based assessments include accounting for upstream contributing area for any stream segment of interest (cumulative watershed analysis rather than just immediate watershed analysis) (Theobald et al., 2005, 2006). Watersheds can also be delineated for synthetic stream paths (e.g., Maidment, 2002), but the watersheds must be based on arbitrary drainage area thresholds that may not always result in a "one to one" relationship between the stream segment and watershed boundary.

1.3. Spatially explicit watershed modeling

Spatially explicit models serve to view stream ecosystems as interconnected, hierarchical systems of processes operating at various spatial scales, not merely a set of sampling point locations (Fausch et al., 2002). Energy sources, physical habitat, flow regime, water quality and biotic interactions (Mattson and Angermeier, 2007) may all be considered by spatially explicit models. Spatially explicit modeling allows for assessment of cumulative impacts of upstream activities. Cumulative impacts on stream ecosystems can include effects that are compounded over time (past land use activities within the watershed) and/or space (from headwaters to larger rivers) (Sidle and Hornbeck, 1991). Assessment of cumulative impacts to streams from multiple land uses and point and non-point pollution sources is a primary requirement for water quality management practices such as Total Maximum Daily Loads (Houck, 2002). Spatially cumulative impacts from land use activities in the headwater or upstream areas of a river network directly impact downstream areas in many ways, including water quality, bacterial concentrations (Bolstad and Swank, 1997), habitat degradation, and loss of stream connectivity (Fausch et al., 2002).

Modeling streams as networked systems enables cumulative spatial analyses. While GIS-based network models have been created for streams as part of the ArcHydro data model (Maidment, 2002), the cumulative impacts, important for determining the receiving stream conditions and performing restoration activities across scales, are often ignored. Many modeling studies can benefit from the ability to efficiently capture and accumulate upstream landscape attributes as well as the bi-directional network linkages for hierarchical analysis and watershed management.

Analysis of stream systems as networks in a GIS (in addition to watershed-based analyses) has been used extensively in modeling water quality and pollutant loadings (Wemple et al., 1996; Bhaduri et al., 2000). Stream network characteristics such as branch configuration, stream order, drainage density, and confluence density have been investigated for their relationship to instream channel morphology and habitat structure (Benda et al., 2004). Analysis of stream systems as networks of interconnected spatial features allows examination of impacts of activities at one location on downstream (or upstream) locations, and can also include measures of distance along the network (rather than straight-line distance) (Ganio et al., 2005; Olivera et al., 2006).

Typical considerations in modeling watershed systems with GIS include spatial scale and level of detail or specificity, the ability to incorporate cumulative impacts of upstream activities, and the hierarchical, networked structure of stream systems. Several recent efforts have developed GIS-based modeling approaches to link networked watersheds for cumulative analysis of stream systems. Olivera et al. (2006) developed WaterNet, a vector-based, topological model of stream networks developed for the U.S. Gulf Coast. WaterNet algorithms can perform network traces using stream segment attribute tables, and can also calculate cumulative parameters such as total drainage area. Theobald et al. (2005, 2006) describe FLoWS, a set of reach catchment areas and associated GIS tools. Reach catchment areas are defined as edge-matched polygons delineated as areas draining to nearby stream reaches. Stream reaches were defined by Theobald et al. (2005) following the 1:100 000 scale medium resolution National Hydrography Dataset (NHD) as being sections of surface water with similar hydrologic properties. It is important to note that NHD "reach" features are typically, but not always, equivalent to unique stream segments between stream confluences (USGS, 2000). Related analytical tools developed by Theobald et al. (2005, 2006) include the ability to navigate upstream or downstream along the hydrologic network, and the ability to calculate cumulative values for variables calculated at the reach catchment level (such as total cumulative drainage area, etc.). FitzHugh (2005) presents a similar application of the medium resolution NHD with reach catchments, and applies the results with a comprehensive tool to evaluate watershed condition and conservation priorities. NetMap (Benda et al., 2007) also applies a networked watershed-based approach with an even more comprehensive GIS toolset, including aggregation of watershed indices at different levels of detail. NetMap functions include calculations mainly related to erosion, sedimentation, flow, and channel morphology.

1.4. Approach

While each of these approaches integrates delineated watersheds and stream network structure within GIS, our goal was to build upon these approaches by extending the networked watershed and cumulative analysis functions in several ways: the use of higher resolution data inputs, use of a true segment-based (rather than NHD reach-based) watershed–stream linkage, and application of the results to a new index of cumulative mining impacts. This paper provides a methodology for building a spatially explicit networked watershed model based on 1:24 000 scale stream segments and demonstrates the insights learned from calculating cumulative landscape variables important to watershed management. Our approach provides a high resolution, spatially explicit methodology with a 1:1 linkage between stream segments and delineated watersheds. We have mapped the surface drainage from the landscape to each segment in a stream network. At this detailed level of analysis, a single stream segment will have a unique watershed boundary (Fig. 1).

A simple surface mining index is calculated using GIS for watersheds in West Virginia and then summed cumulatively to identify downstream impacts and restoration opportunities at multiple scales. We believe this approach is very applicable to other studies and applications of cumulative indices and provides additional insight into watershed management.

2. Methodology

2.1. Segment-level watershed delineation

Our watershed delineation process consisted of finding stream-segment-level watersheds, similar to the reach catchment areas described by Theobald et al. (2005). The sources or pour points for our delineated watersheds were the stream segments between junctions for the 1:24 000 scale (high resolution) NHD.

Elevation mapped as digital elevation models (DEMs) can be used in hydrological analysis and watershed delineation using Geographic Information System (GIS) procedures. This has been discussed in detail by Jenson and Domingue (1988), Tarboton et al. (1991), Saunders (1999), Maidment and Djokic (2000), and Maidment (2002), among others. Our approach generally followed the recommendations of these authors, but instead of computing synthetically derived streams from the topography to drive the watershed delineation, we used the NHD 1:24 000 streams, available nationwide within the U.S. This is an important difference for three main reasons. First, by using the mapped streams for watershed delineation, we eliminated any bias or subjectivity associated with selecting a drainage area cutoff or threshold in which to derive a stream layer from the flow accumulation grid (Jenson and Domingue, 1988). When a drainage area threshold is used to delineate streams, the same numeric value is typically used for the entire study area, which does not consider other factors that may influence whether the stream is actually present. When using the same stream lines that are present on a 1:24 000 topography map (as is the case with the NHD in West Virginia), we are using the most consistently mapped streams dataset available for the entire state, most closely conforming to USGS mapping standards. Second, by using an accepted stream dataset, mapped streams will more likely conform with regulatory language dealing with impaired streams and/or streams not meeting designated uses. Resource managers benefit from the use of a consistent, accepted stream dataset. And third, the NHD 1:24 000 stream data model already contains tabular flow network and connectivity information for network modeling. When the watersheds are delineated and attributed with the streams to which they correspond, a complete watershed network model becomes available. Limitations of the mapped streams in the 1:24 000 NHD include streams that have subsequently been altered by activities such as road construction or mining, and streams that were inaccurately mapped in the first place.

We define stream segments, our smallest unit of analysis, as mapped NHD "flowline" stream line segments between stream confluences. By contrast, in the NHD data model, an individual stream "reach" feature may consist of multiple line segments, and may include more than one stream confluence, depending on application of NHD reach delineation rules to tributary streams. Therefore, we did not use NHD reach features to delineate watershed pour points, because we wanted watersheds specific to each segment. Instead, we identified segments using the NHD "flowline" features. Braided segments were removed and limited to the main, named stream channel in the NHD.

The elevation data was obtained from a 3-m digital elevation model (DEM) (1/9th arc second) National Elevation Dataset (NED) available for West Virginia (USGS, 2006). The elevation dataset was "hydrologically corrected" in two steps. The first step was to resample the 3 m DEM to 9 m to aid in processing and to preserve a 1:24 000 scale product. The NHD streams were also converted to a raster at 9 m to preserve detail and stream complexity. Raster streams were thinned as recommended by Maidment (2002). Second, after filling sinks in the elevation dataset, all off-stream cells in the elevation dataset were raised by 3 m. The value of 3 m was chosen due to the DEM's horizontal accuracy of 5 m and vertical posting accuracy of 3 m (USGS, 2006) and was consistent with approaches by Franken (2004) and Kost et al. (2002) for areas with varied terrain. This process, referred to as "burning in" streams, ensures more accurate flow direction across the surface.

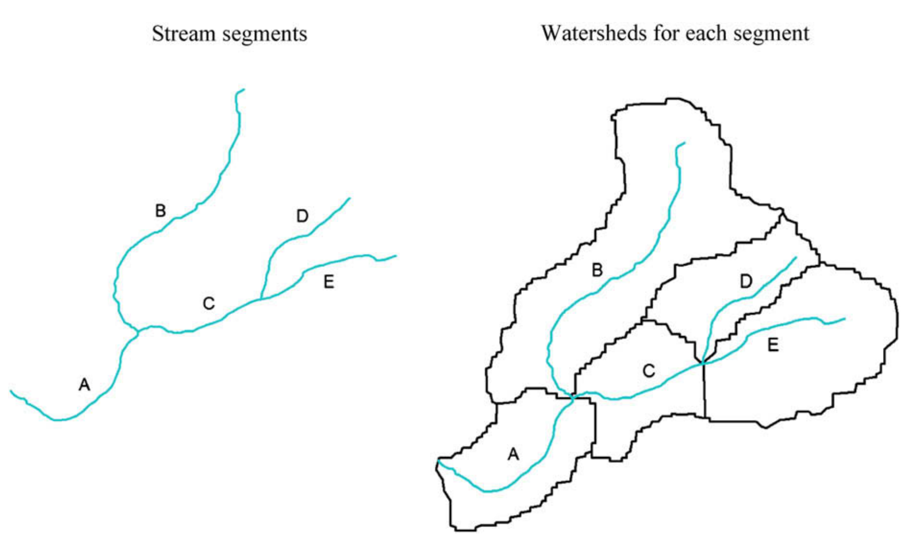


Fig. 1. Stream segments and watersheds for each segment.

The next step was to calculate a flow direction grid in GIS using the ArcGIS software and Spatial Analyst extension (ESRI, 2006). From the flow direction grid, watersheds were delineated for each of the stream segments at pour points. Pour points were used in an automated routine to outline the drainage area for each individual segment, followed by a small amount of manual editing within the GIS software to produce a final map of basin-wide segment-level watersheds, with one watershed per stream segment. Segment-level watersheds allow examination of landscape factors that may directly influence individual stream segments. This approach also assures a one to one mapping of stream segment to watershed boundary for analysis. Fig. 2 shows the delineated watersheds for the Cheat River 8-digit HUC. There are a total of 3940 segment-level watersheds in this 8-digit HUC which average 0.93 km^2 in size.

2.2. Linking the segment-level watersheds

With segment-level watersheds, we now had a unit of analysis that would enable us to capture the landscape to stream interactions at a one to one basis. To effectively account for flow direction or the contributions of "pass-through" watersheds to other watersheds, we needed to link them for cumulative analysis. The USGS NHD stream model contains attributes for each segment based on flow direction. We used the NHD segment-based tabular stream flow data to develop a network of the watershed's flow connectivity, assigned attributes to the watersheds based on the stream's NHD reach code, and constructed a watershed-based flow table to approximate the flow network between watersheds. The flow table model lists each watershed flowing into or out of any

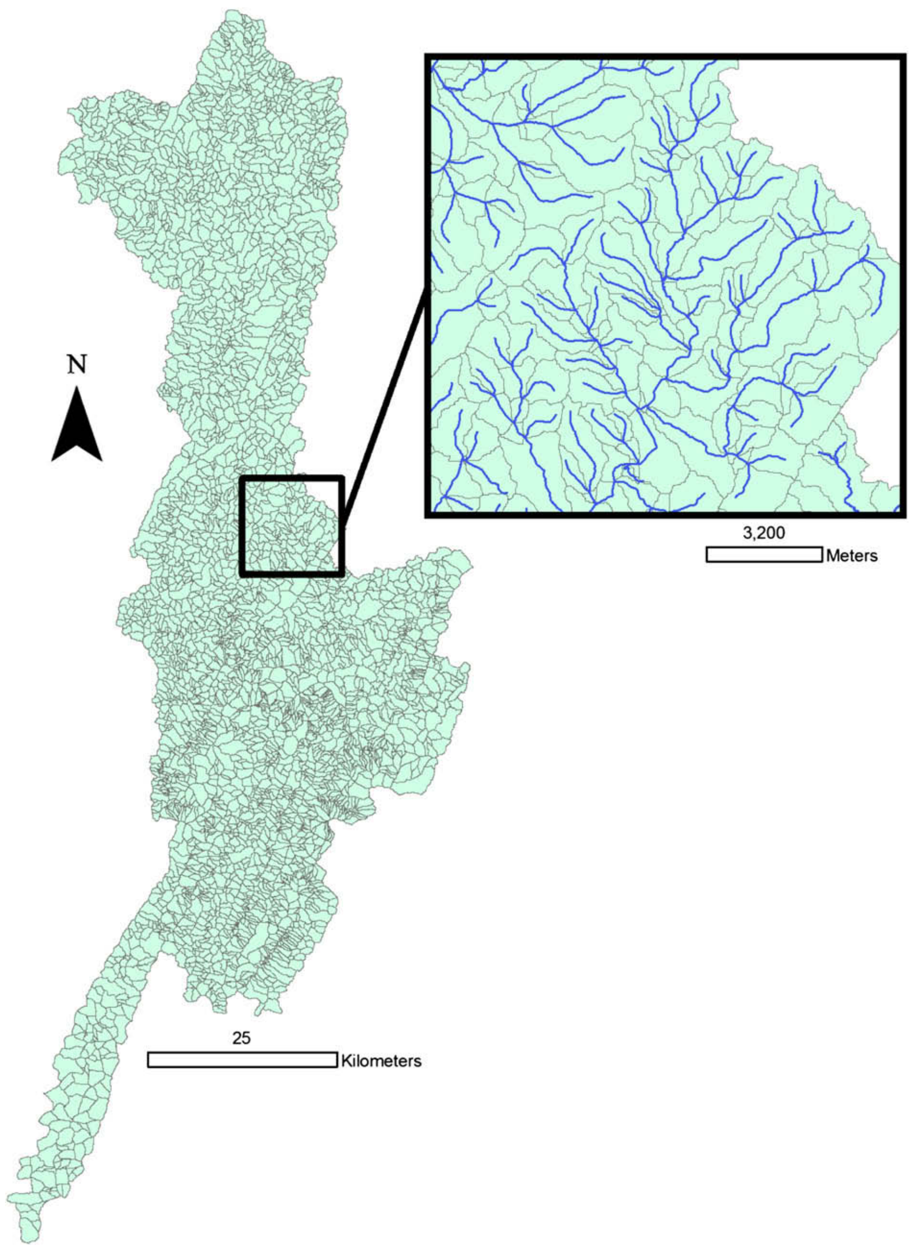
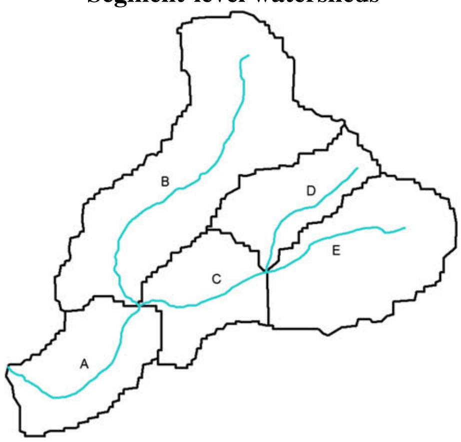


Fig. 2. Delineated segment-level watersheds for the Cheat River 8-digit HUC watershed.

Segment-level watersheds



Flow table linking watersheds

Up	Watershed	Type
none	B	start
none	D	start
none	E	start
D	C	in
E	C	in
C	A	in
B	A	in

Fig. 3. Example of flow table for linking watersheds.

given watershed, as well as headwater watersheds and outlets. Fig. 3 is an example of the flow table for a subset of watersheds. Watersheds labeled as "start" are headwater watersheds and those labeled as "in" are part of the pass-through network.

The watershed dataset, together with the related flow table model, allows us to perform many watershed network-based analyses, including identification of watersheds upstream or downstream from a given location. Computer code written in Visual Basic for Applications within ArcGIS version 9.2 (ESRI, 2006) was used to automate the analysis of the linked watersheds. The computer code allows us to quickly calculate new landscape attributes for the watersheds within the GIS. The automated procedures can be used to determine cumulative area for any watershed (area of all upstream watersheds), as well as any other cumulative measures. This enables us to derive many unique cumulative variables such as the assimilative capacity of water quality and make explicit predictions of biological condition and vulnerability from potential threats. Additional code was also written to enable calculation of distance along stream flow path (on/off-stream) to the closest upstream or downstream feature of interest. For example, for each segment-level watershed, we were able to determine the distance to the closest upstream mining related features, if any (such as coal seams, abandoned mine lands, etc.).

3. Application

3.1. Study area

The study area selected to demonstrate our modeling approach was the Cheat River 8-digit HUC watershed located in north-central West Virginia (Fig. 4). The Cheat is a large (3678 km^2) headwater watershed that has a long history of coal mining activity which includes both surface and deep mines (Anderson et al., 2000). A significant source of pollution in many coal-producing regions of the northeastern U.S. is acid mine drainage (AMD), produced from the exposure of coal seams or mining wastes to oxygen and water (Peck et al., 1979). AMD is a problem in the Cheat River watershed

Fig. 4. Location of the Cheat River 8-digit hydrological unit code watershed in north-central West Virginia.

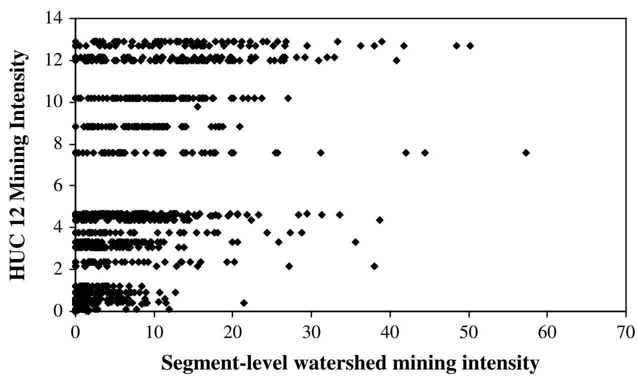


Fig. 5. Mining and segment-level mining intensity.

where up to 26 stream segments are listed as impaired in the lower drainage of the Cheat River from coal mining and related activities (WVDEP, 2006). Acidification of surface waters from these causes has been linked to species losses and altered fish distributions in acid-impacted streams (Carline et al., 1992; Pinder and Morgan, 1995). In the Cheat basin, the water quality of the lower 1255 km^2 of the watershed has been negatively impacted from the spatial distribution of coal mining (WVDEP, 2006) and therefore was the focus of our analysis. To aid in restoration management efforts for the Cheat River watershed, we sought to characterize each individual segment-level watershed by the total area of upstream mining related features.

3.2. Mining index development

The mining features analyzed included coal seam outcrops, mine permit boundaries, abandoned mine locations, and bond forfeiture sites. The coal seam outcrops were mapped from a series of county-based geologic maps from the West Virginia Geological and Economic Survey (Sisler and Reger, 1931). We only included the mapped acidic coal seams that contribute to acid mine drainage related issues. These included the Bakerstown, Lower Kittanning, Pittsburgh, Sewell, Upper Freeport, and Upper Kittanning seams. The mine permit boundaries, abandoned mine locations and bond forfeiture sites were obtained from current on-line digital databases maintained by the West Virginia Department of Environmental Protection (WVDEP, 2004).

All mining datasets were clipped to the study area and analyzed using appropriate GIS techniques. We computed a number of values designed to determine the intensity and geographic position of mining in relation to each segment-level watershed.

A watershed Mining Index (MI) score was developed to quantify the intensity of mining in each watershed by computing the sum of all outcrop lengths within the watershed, divided by the total length of mapped streams in the watershed. The mining index (MI) combined information on coal geology and known mine activity and was calculated as:

$$\mathrm{MI} = \left[\left(\frac{\mathrm{CMD}i}{\max \mathrm{CMD}} + \frac{\mathrm{COD}i}{\max \mathrm{COD}}\right)/2\right] \times 100$$

where CMDi is the cumulative mine density of segment-level watershed i, which was calculated as the cumulative mine area draining to segment-level watershed i divided by the cumulative drainage area of segment-level watershed i. max CMD is the maximum cumulative mine density observed in the entire watershed. CODi is the cumulative coal outcrop density of segment-level watershed i, which was calculated as the cumulative outcrop length of segment-level watershed i divided by the cumulative stream length draining to segment-level watershed i. max COD is the maximum cumulative outcrop density observed in the watershed.

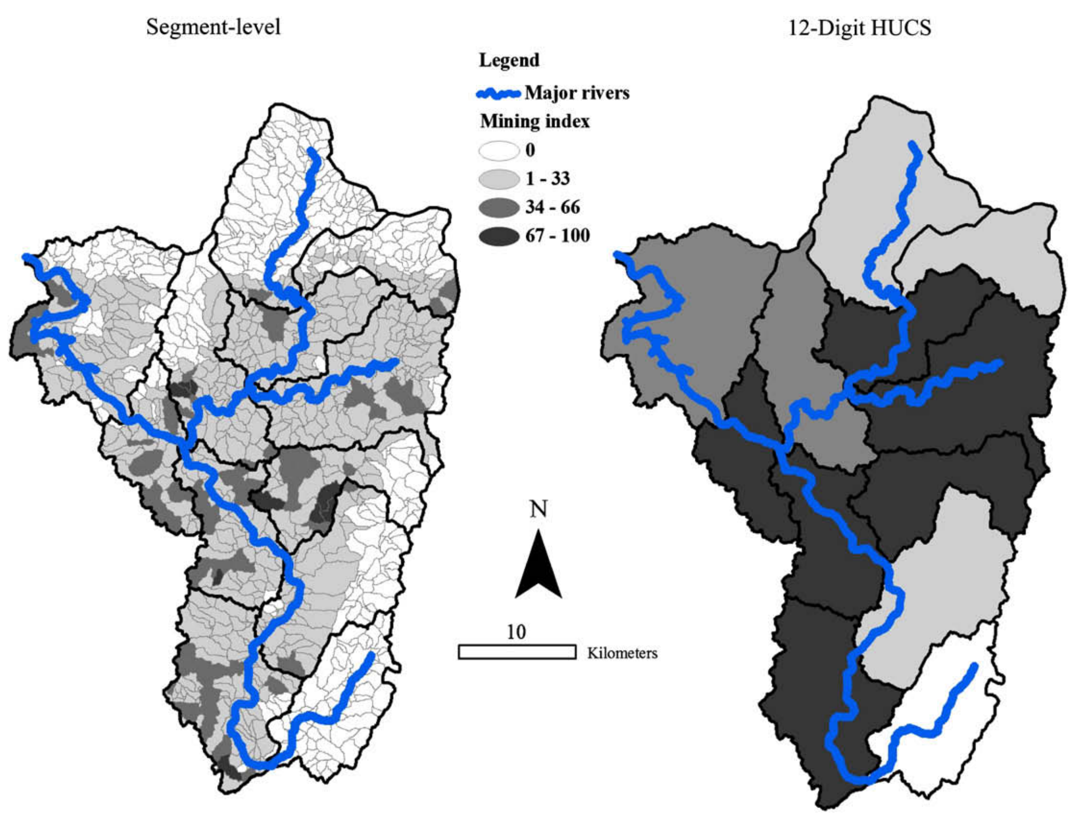


Fig. 6. Mining index for the segment-level and 12-digit HUCS for the lower Cheat watershed.

The mining index calculation results in a value for each segment-level watershed in the study area that varies between zero and 100. The MI can be interpreted as a percentage of the highest possible mining intensity in the watershed. A segment-level watershed with no outcrops draining to it and no known mine areas upstream will have an MI value equal to zero. An MI value of 100 would represent a segment-level watershed that possesses the maximum known mine and outcrop densities. For each segment-level watershed, we calculated the cumulative area for mining polygon features and the cumulative length for coal seam line features.

Coal outcrop length was included in our index because there is a higher level of uncertainty in the mine data than in the coal outcrop data. Permitted mine sites are well mapped; however, abandoned mine lands are not. There presumably are numerous, small, old mines throughout this region that predate mining laws and mine mapping efforts of the West Virginia Department of Environmental Protection. An index that used coal outcrop data only would also be inappropriate, because not all coal seams have been mined to the same extent. Consequently, given that nearly all accessible coal (e.g., coal seams with surface outcrops) has been mined to various degrees, we believe that including coal outcrop data along with mine data provides the best measure of the "likely" degree of mining activity within a given drainage area.

4. Results

In addition to assessing results at the segment-level watershed scale, we also aggregated results up to the Natural Resource Conservation Service (NRCS) 12-digit Hydrologic Unit Code ("12-digit HUC") watershed scale within the lower Cheat River watershed (NRCS, 2008). As an example of management insights at various watershed scales, the mining intensity for the segment-level watersheds was summed for each 12-digit HUC by dividing the sum of the weighted mining intensity by the sum of the stream lengths.

Fig. 5 demonstrates the relationship between segment-level watershed mining intensity and mining intensity at the 12-digit HUC scale. Each symbol represents a specific segment-level watershed in the Cheat River drainage. The important distinction is that relatively "good" segments (i.e., segments with low mining intensity) are found across the full range of watersheds, from those with low impact (i.e., low 12-digit HUC mining intensity) to those characterized by high levels of regional impact.

Fig. 6 illustrates the distribution of low to high mining intensity segment-level watersheds embedded within low to high mining intensity 12-digit HUC watersheds within the Cheat River system. Visualizing streams in this manner allows for their classification on the basis of both local and regional conditions. For example, good condition streams located within heavily impacted regions (i.e., low segment-level mining intensity within high 12-digit HUC mining intensity) and poor condition streams within good condition watersheds (i.e., high segment-level mining intensity within low 12-digit HUC mining intensity).

5. Conclusions

This paper addressed two important issues for enhancing cumulative watershed capabilities in GIS. Our modeling framework focused on the delineation of segment-level watershed boundaries for 1:24 000 scale hydrology in combination with a network model to examine effects cumulatively. The result is a spatially explicit cumulative watershed modeling framework for quantifying watershed conditions to aid in restoration. We demonstrate the new insights available from this modeling framework in a cumulative mining index to aid in the management of aquatic resources in a West Virginia watershed.

The linked segment-level watersheds allowed us to calculate cumulative variables for the mining index. In our study area example, the results also provide insights into the implications of watershed management at various scales. The characterization of the larger 12-digit HUC sub-watersheds allows us to place streams in a regional context which may correspond more closely with stream management activities such as prioritization for reclamation. At both spatial scales, we can characterize impacts to streams in multiple ways. Impacts found directly within the watershed can include the cumulative impacts to stream segments from upstream land uses and location and position of features along the stream network (including distance from potentially affected segments). The use of the two watershed scales provided an applied example of a networked watershed framework for stream condition evaluation within stream systems impacted by various detrimental disturbances.

Local fish community organization is determined by local and regional conditions. Consequently, predicting the local community depends on knowledge of both local and watershed scale conditions. Martin (2004) showed that brook trout (a coldwater species) and smallmouth bass (a warmwater species) tend to co-inhabit coolwater streams that are in close proximity of both warm- and coldwater habitats. Brook trout typically are absent from coolwater streams that are isolated from coldwater habitats, and smallmouth bass are absent from coolwater streams that are isolated from warmwater habitats.

Freund and Petty (2007) demonstrated that stream fish diversity is influenced by local water quality and the general quality of streams within the drainage network. Streams with good water quality located in highly degraded watersheds possessed lower species richness than good streams located within good watersheds. Combined, these studies illustrate the value of quantifying house (i.e., local stream segment) conditions within the context of neighborhood conditions (i.e., conditions at the 12-digit HUC watershed scale). For example, a high quality stream (house) within a poor quality watershed (neighborhood) is expected to have a fish community that differs from a high quality stream located in a high quality watershed. The effectiveness of stream restoration projects on local conditions will depend on the watershed scale context of the restoration activities. McClurg et al. (2007) demonstrated that the effectiveness of acidic stream restoration was maximized when efforts focus on restoring drainage networks rather than isolated stream reaches. This is analogous to focusing efforts on "neighborhood" rather than "house" restoration. Optimal restoration strategies must consider local restoration actions within a regional watershed scale context.

Our modeling technique provides an efficient method for integrating landscape and instream attributes across multiple spatial scales. The technique provides a method for visualizing local stream attributes within a watershed scale context (i.e., a "neighborhood–house" view of aquatic ecosystems), which should facilitate understanding how local and regional processes interact to influence stream communities as well as our ability to design effective aquatic resource restoration programs.

The future opportunities to apply this approach to other land use and water quality issues can allow managers to more accurately describe the interactions at both a local immediate receiving stream and the networked or downstream cumulative impacts for improved watershed management.

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