A HYDROLOGICALLY NETWORKED WATERSHED MODEL FOR EVALUATING AMD TREATMENT SCENARIOS[1]

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Abstract. A GIS-based decision support system was developed to aid in restoration planning by integrating various chemical and ecological modeling components that the West Virginia Water Research Institute has developed over the past five years. Using the popular GIS platform of ArcMap, computer code was written in Visual Basic .Net environment to develop an extension for GIS to visually illustrate remediation and alternative outcomes. Building upon the existing 1:24,000 segment level or "reachshed" delineation of watersheds for all of WV and a network model to examine pass through issues, the user is able to compare treatment options and locations for building spatially explicit AMD restoration plans. The advantage of the system is its straightforward mass-balance water quality model and logical decision alternative matrix with costs and ecological benefits. It is possible to visually iterate and illustrate outcomes downstream of various treatment/restoration scenarios. The result is a spatially explicit cumulative watershed modeling framework for quantifying stream conditions at multiple scales.

Additional Key Words: spatial decision support system, cumulative analysis, GIS

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[1] Paper was presented at the 2008 National Meeting of the American Society of Mining and Reclamation, Richmond, VA, ***New Opportunities to Apply Our Science*** June 14-19, 2008. R.I. Barnhisel (Ed.) Published by ASMR, 3134 Montavesta Rd., Lexington, KY 40502

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Proceedings America Society of Mining and Reclamation, 2008 pp 1217-1231
DOI: 10.21000/JASMR08011217
`http://dx.doi.org/10.21000/JASMR08011217`

Introduction

The watershed approach to water quality management has its legislative roots in the 1972 Clean Water Act (CWA). While water quality concerns focused on point sources for the first twenty years, the stated goal of the CWA was to clean-up and protect U.S. water bodies from both point and nonpoint sources (NPS) of pollution. Since the pollution from major point sources has been reduced, the importance of NPS pollution control to further improve the nation's water quality has become evident. The change in focus to NPS issues is reflected in the watershed approach to water quality regulation and management – an integrative approach that addresses both point and nonpoint sources of pollution. The watershed approach attempts to increase stakeholder involvement to simultaneously improve and provide the political support for the localized management decisions needed to reduce water quality problems. Implementation of this approach often takes form through the development of Total Maximum Daily Load (TMDL) plans. TMDL plans reflect the total maximum daily load of identified pollutants that a stream assimilates while still meeting designated uses. Successful implementation of the watershed strategy depends critically on useful and accurate information and methods to guide decisions.

Acid mine drainage (AMD) is the most common environmental problem associated with coal mining and remains the number one water quality problem in West Virginia. AMD is defined as mine-water runoff with high concentrations of acidity, Fe, Mn, Al, and suspended solids toxic to aquatic life (Squillace and Dotter, 1990). The latest West Virginia Water Quality Status Assessment (WVDEP-DWR, 2006) lists AMD as the primary pollutant in 477 stream segments totaling 2,427 miles. In West Virginia, as in other states with water quality problems, resource managers consistently ask similar questions when examining water quality problems at the watershed level. These questions include:

1) What is the extent of the water quality problem?
2) Where are the problems occurring in the watershed?
3) Where should sampling or monitoring locations be established to assess the problem more accurately?
4) Where should best management practices (BMPs) or reclamation plans be focused to address the problems?

The abundance of “where” questions point out the spatial nature of such problems. The West Virginia Water Research Institute at West Virginia University has adopted a multidisciplinary approach to watershed analysis that uses a Geographic Information System (GIS) as the building block for information and technology transfer. This paper describes the development and components of a GIS-based and hydrologically networked watershed model for evaluating abatement scenarios.

Previous Watershed Applications

A number of GIS-based applications have been developed to help answer watershed management questions. Moore (1991), Wilson (1996), and Deliman et al. (1999) provide extensive overviews of the watershed approach as it pertains to watershed modeling systems. This section highlights some of the more popular systems and how the approach presented in this paper was different to address specific issues related to AMD with segment level watersheds and a network model.

The Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) modeling system developed by the Environmental Protection Agency's (EPA's) Office of Water was designed to examine environmental information, support analysis, and provide a framework for examining management alternatives (Lahlou, et al. 1998). Working at the watershed level, BASINS supports analysis at various scales using appropriate models based on data availability. Three models in BASINS include the Nonpoint Source Model (NPSM), which uses an interface with EPA' s Hydrologic Simulation Program-FORTRAN (HSPF version 10) (Johanson et al., 1984), QUAL2E for pollutant fate and transport (USEPA 1995); and TOXIROUTE for a screening-level stream routing model (USEPA 1985). Developed to support the total maximum daily load (TMDL) program, much of the development work has focused on the analysis of expected loadings with less emphasis on the implementation or decision support side of the TMDL issue. The current BASINS implementation adds functionality through GIS interface.

Penn State University’s Environmental Resources Research Institute developed the ArcView Generalized Watershed Loading Function (AVGWLF) modeling system, based on the GWLF model developed by Haith and Shoemaker (1987), to assist the Pennsylvania Division of Environmental Protection in watershed assessments and TMDL development. AVGWLF simulates nutrient and sediment loads within Pennsylvania by deriving input data for the user and comparing simulated loads within an impaired watershed with loads for a nearby “reference” watershed. Originally structured for Pennsylvania, AVGWLF relies on the use of statewide data sets for deriving estimates for critical model parameters that exhibit significant spatial variability within the state (Evans et al. 2001).

The Watershed Analysis Risk Management Framework (WARMF) is a stand-alone Windows GIS based TMDL decision support system for watershed management that includes tools for pollution calculation and a consensus module to guide stakeholders through a consensus building process. The consensus module helps stakeholders reach consensus on a watershed management plan based on available data (Chen et al. 1999).

GIBSI: A Spatial Decision Support System for Integrated Watershed Management allows water resource management decision makers to explore different options for modeling watersheds (in terms of both quality and quantity). The system is composed of a GIS, a relational database management system, physically based simulation models, and the QUAL2E water quality model (Rousseau et al. 1997).

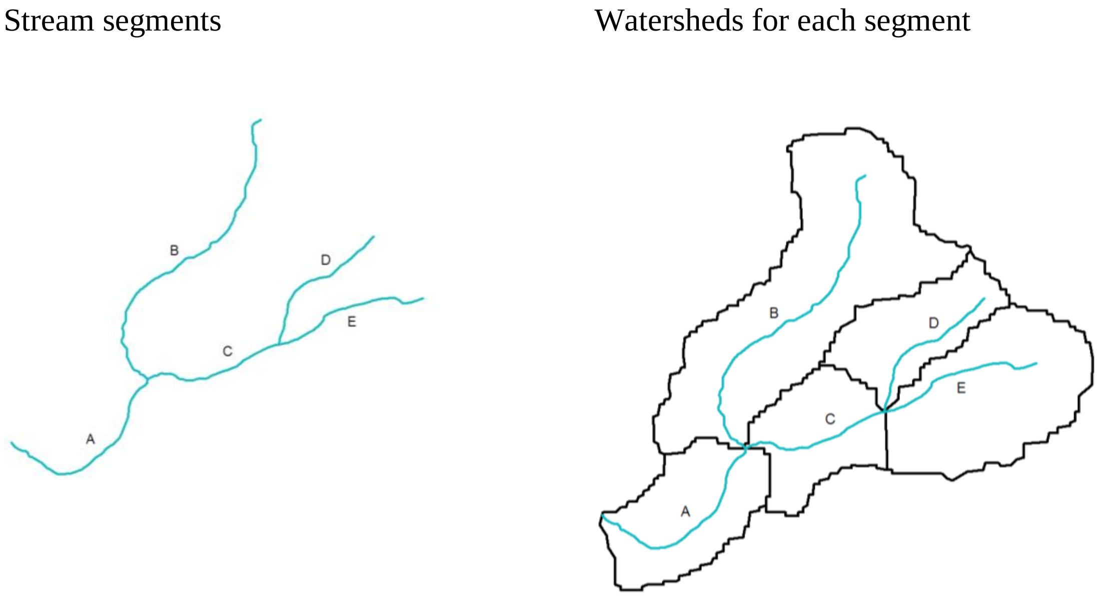
Fulcher et al. (1996) sought a method to enhance the long-term sustainability of agriculture and rural communities through locally based planning and management at the watershed scale. The Watershed Management Decision Support System (WAMADSS) builds on ESRI Arc/Info software to evaluate the effects of alternative land use/management practices (LUMPs) on farm income, soil erosion and surface water quality at the watershed scale.

One of the previous spatial decision support systems used in WV by the Department of Environmental Protection was the Watershed Characterization and Modeling System (WCMS). The WCMS provides a set of tools for analyzing potentially affected streams, flow paths, stream flow estimation and the transport of instream pollutants conservatively as an ESRI ArcMap extension (Fletcher and Strager, 2000; Strager and Fletcher, 2000). What distinguishes WCMS from the previously discussed modeling applications is the spatially explicit approach to nonpoint source pollution and the specific decision support modules.

This paper builds on the main components of the WCMS by extending the spatially explicit focus to hydrologically networked watersheds. Under that goal, the objectives were to (1), link watersheds with a flow network model to account for connectivity between watersheds for cumulative analysis, (2) integrate a mass balance calculation that is updated downstream when water quality information is know or sampled, (3) provide treatment costs based on flow and modeled water quality, (4) integrate ecological benefits, and (5) enable the user to evaluate treatment scenarios as a true decision support system.

Methodology

One of the challenges of representing or modeling hydrologic features with GIS is in attempting to effectively account for the many interactions that occur in the hydrologic cycle (Maidment, 2002). One of these challenges is the linking of overland surface flow to the receiving stream or water body. For example, at the immediate receiving stream level, based on the scale of river or stream system mapped, one watershed or catchment boundary must be delineated to track water flow to the receiving segment (Fig. 1).


Stream segments

Watersheds for each segment

Figure 1. Stream segments and watersheds for each segment

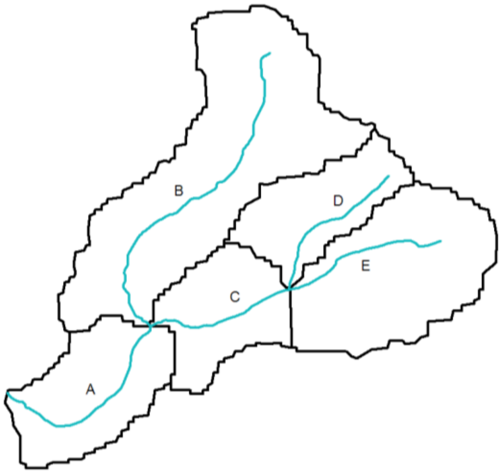
Because watersheds are essentially “closed systems” in terms of surface hydrologic flow, the pour point or outlet of the watershed is a function of the upstream characteristics of the landscape. Watersheds that represent stream segments which are headwater or first order will always have a “one to one” relationship between the watershed extent and receiving stream. In the United States, the United States Geologic Survey (USGS) hydrologic unit code classification system is based primarily on drainage area cutoffs for watershed delineation and not the spatial scale of the stream or river. This classification often results in more than one stream segment per watershed boundary and limits spatially explicit modeling of the interactions occurring for each stream.

The hydrological network model for watershed requires both watersheds delineated for each stream or segment and the flow connectivity known between the watersheds. The watershed delineation process consisted of finding non-overlapping, stream-segment-level watersheds similar to the reach catchment areas described by Theobald et al., (2005). The sources or pour points for the delineated watersheds were the stream segments between junctions for the 1:24,000 scale "High Resolution" National Hydrography Dataset (NHD). The advantage of using the NHD stream product is that it is an officially recognized surface water dataset for the US.

Elevation mapped as digital elevation models (DEMs) can be used in hydrological analysis and watershed delineation using Geographic Information System (GIS) procedures. This procedure has been discussed in detail by Jenson and Domingue (1988), Tarboton (1991), Saunders (1999), Maidment and Djokic (2000), and Maidment (2002) among others. The approach generally followed the recommendations of these authors but instead of computing synthetically derived streams from the topography, the NHD streams were used as the main hydrology feature.

Segment-level watersheds could not be used 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, it was necessary to link them for cumulative analysis. The USGS NHD stream model contains attributes for each segment based on flow direction. The stream model provided a network of the watershed's flow connectivity using the 1:24,000 NHD hydrology route structure conflated to the segment-level watershed scale. Appropriate attributes could then be used for the watersheds based on the stream's NHD reach code. This assignment enabled the development of a watershed flow table to approximate the flow network between watersheds. The flow table model lists each watershed flowing into or out of any given watershed, as well as headwater watersheds and outlets. Figure 2 is an example of the flow table for a subset of watersheds which includes the upstream watershed and the type.

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

Figure 2. Example of flow table for linking 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 the user to perform many watershed network-based analyses, including identification of watersheds upstream or downstream from a given location. To aid in analysis, computer code was written in ArcGIS Visual Basic Applications (Razavi, 2002) to automate the analysis of the linked watersheds. The computer code allows new landscape attributes to be calculated 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 for analysis or distances upstream to a particular feature. These procedures enable derivation of many unique cumulative variables for analysis including the assimilative capacity of water quality and make explicit predictions of biological condition and vulnerability from potential threats. The connectivity of watersheds delineated at this scale can provide important information for analyzing the impacts from various upstream land cover alterations.

Developed Spatial Decision Support System

The segment-level watersheds and flow table linking the watersheds is the background framework that enables downstream water quality modeling using a mass balance model and cost spreadsheets. The developed spatial decision support system is based on these principals and is called the Mass Balance Accumulator (MB Accumulator). Figure 3 below highlights the typical work flow for using this system.

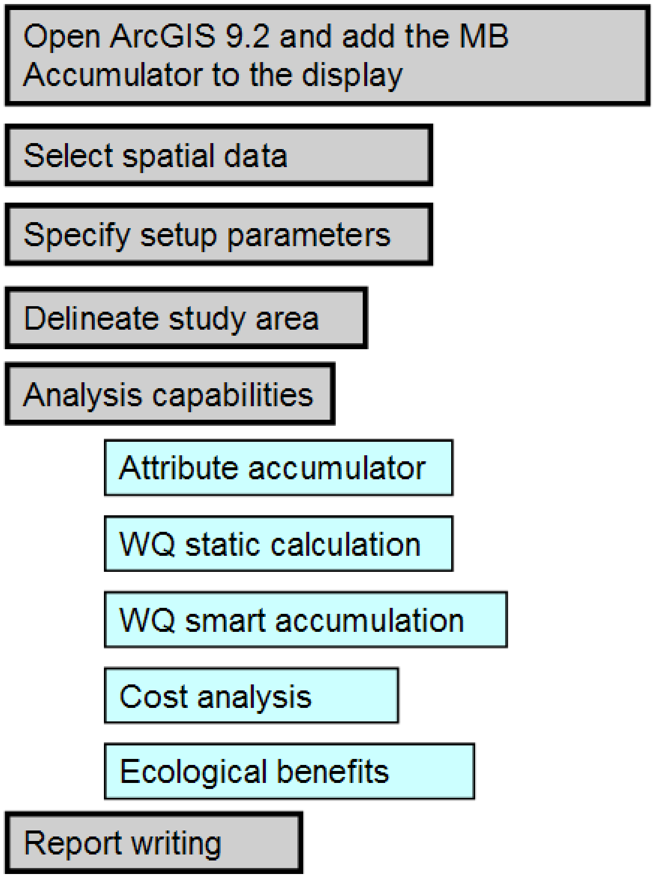


Figure 3. Typical Work Flow in ArcGIS

Working within ArcGIS software the user can select appropriate spatial data they wish to display for an area such as topography, land cover and use, water quality sampling locations, mine permits, etc. To use the MB Accumulator, there are some specific datasets that need to be setup. These include 1:24,000 National Hydrography Data (NHD) streams, a flow table, and the segment-level watersheds or reachsheds. Figure 4 shows the MB accumulator toolbar and the data setup form.

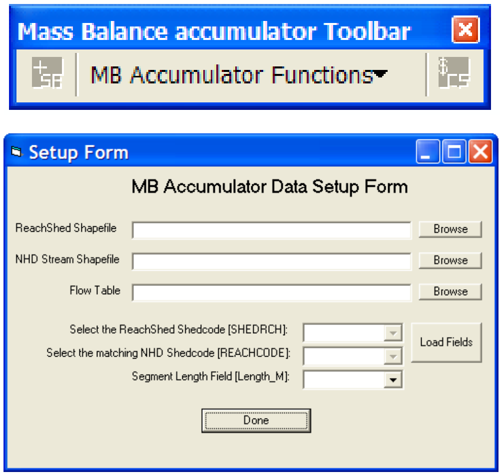


Figure 4 highlights the toolbar and setup form developed within ArcGIS 9.2 software

After the data setup form is completed, a use can create a subset of watersheds for a study area. This is accomplished by using the study area tool. All of the upstream segment-level watersheds are selected from the flow table and output as the new study area extent for further analysis. This is shown in Fig. 5.

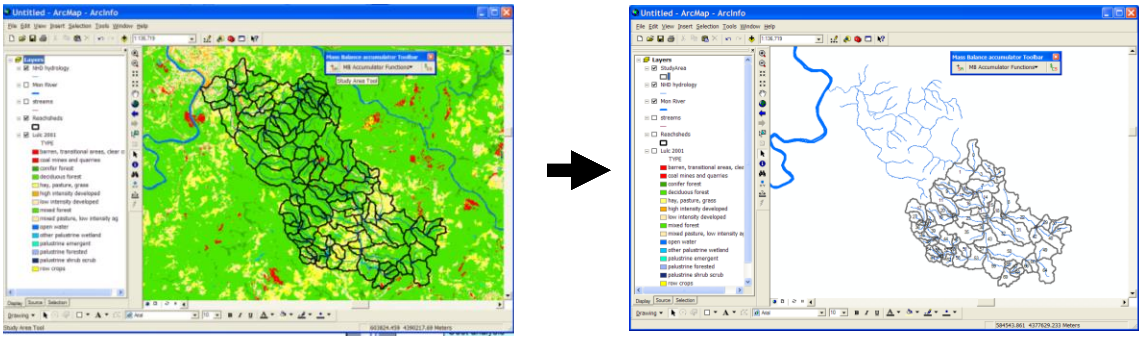
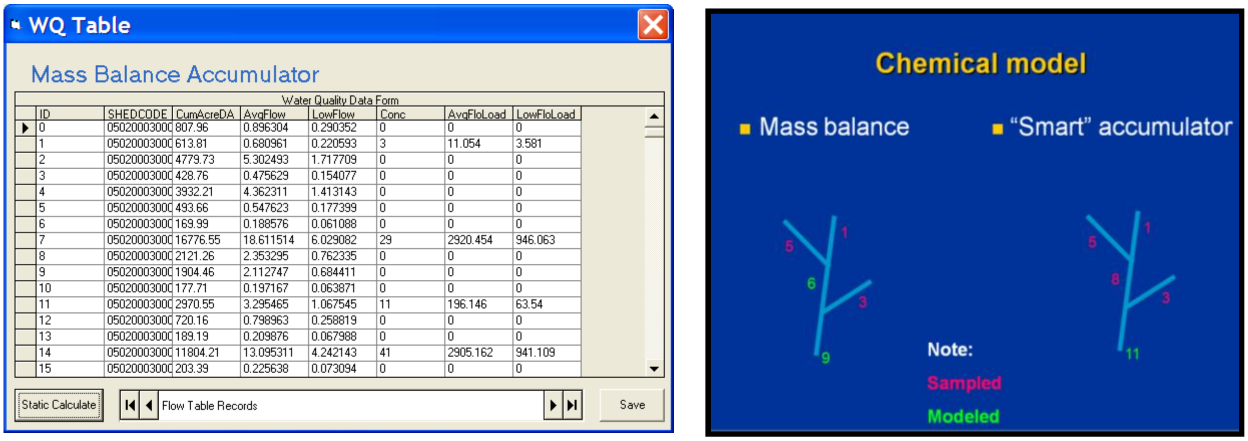


Figure 5. Subset study area watersheds defined with networked flow table

Once a study area is defined, five main analysis capabilities are available for the user. These include an attribute accumulator, water quality static calculation, water quality smart accumulator, cost analysis, and ecological benefits.

The attribute accumulator was designed to allow watershed scale variables to be accumulated in the downstream direction to capture true cumulative information. The water quality calculation is similar to the attribute accumulator but takes a "smart" approach. This simply means that if known water quality data points exist in the downstream segment, it is used as the known value instead of the modeled output. Stream flow is estimated using average annual, low flow, and monthly averages as calibrated against USGS gauges in the vicinity of the study area. A graphic showing the mass balance accumulator and smart accumulator concept is shown in Fig. 6.



Mass Balance Accumulator

Water Quality Data Form

	ID	SHEDCODE	CumAcreDA	AvgFlow	LowFlow	Conc	AvgFloLoad	LowFloLoad
▶	0	05020003000	807.96	0.896304	0.290352	0	0	0
	1	05020003000	613.81	0.680961	0.220593	3	11.054	3.581
	2	05020003000	4779.73	5.302493	1.717709	0	0	0
	3	05020003000	428.76	0.475629	0.154077	0	0	0
	4	05020003000	3932.21	4.362311	1.413143	0	0	0
	5	05020003000	493.66	0.547623	0.177399	0	0	0
	6	05020003000	169.99	0.188576	0.061088	0	0	0
	7	05020003000	16776.55	18.611514	6.029082	29	2920.454	946.063
	8	05020003000	2121.26	2.353295	0.762335	0	0	0
	9	05020003000	1904.46	2.112747	0.684411	0	0	0
	10	05020003000	177.71	0.197167	0.063871	0	0	0
	11	05020003000	2970.55	3.295465	1.067545	11	196.146	63.54
	12	05020003000	720.16	0.798963	0.258819	0	0	0
	13	05020003000	189.19	0.209876	0.067988	0	0	0
	14	05020003000	11804.21	13.095311	4.242143	41	2905.162	941.109
	15	05020003000	203.39	0.225638	0.073094	0	0	0

Chemical model

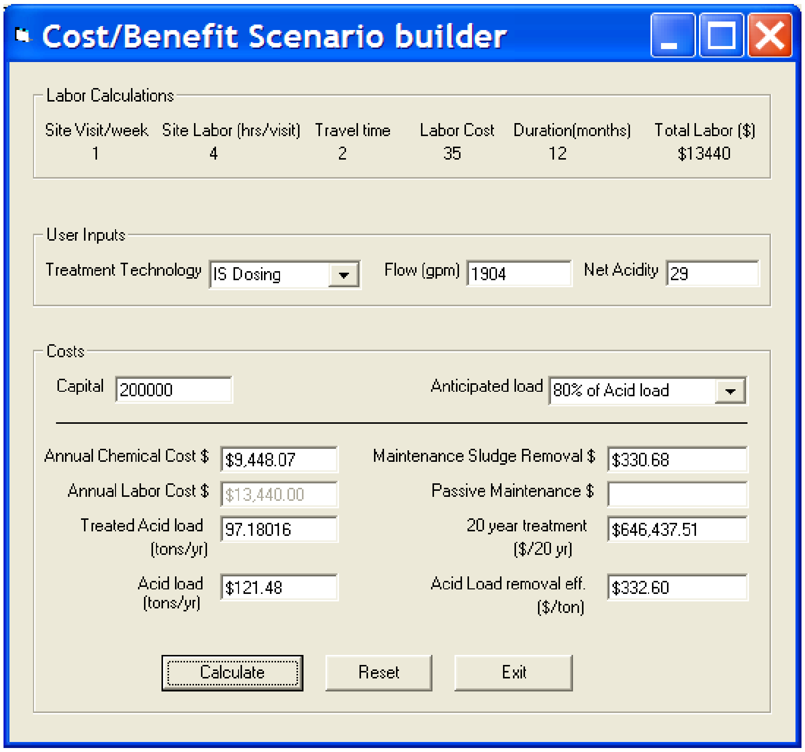
- Mass balance
- "Smart" accumulator

Note:
Sampled
Modeled

Figure 6. Mass balance accumulator dialog and chemical model for handling downstream sampled data.

Costs of treatment are reported for downstream locations and can be identified spatially from the GIS graphical output. Figure 7 shows costs associated with instream dosing (IS Dosing) under specific site parameters and capital costs. Other treatment technologies in the system include limestone sand dump and an active dozer cost

Restoration benefits are captured in ecological benefits or eco units (Petty and Thorne, 2005). The eco unit is a measure of total stream surface size and is used indicate the quality of a stream in relationship to a fishery function. Values range from zero to one. The highest quality segments receive weighting values of 1.0, which implies that the segment is functioning at 100% of that expected for stream segments in that region. Highly degraded (i.e., impaired) water bodies receive weighting values of 0.0, which indicates that the segments are failing to function as ecological habitats. Most stream segments are of intermediate quality, and consequently, receive intermediate weightings (Petty and Thorne, 2005). This benefit measure has been integrated into the MB Accumulator as both a static site by site calculation or as a cumulative calculation. Figure 8 shows the eco unit dialog.



Cost/Benefit Scenario builder

Labor Calculations

Site Visit/week	Site Labor (hrs/visit)	Travel time	Labor Cost	Duration(months)	Total Labor ($)
1	4	2	35	12	$13440

User Inputs

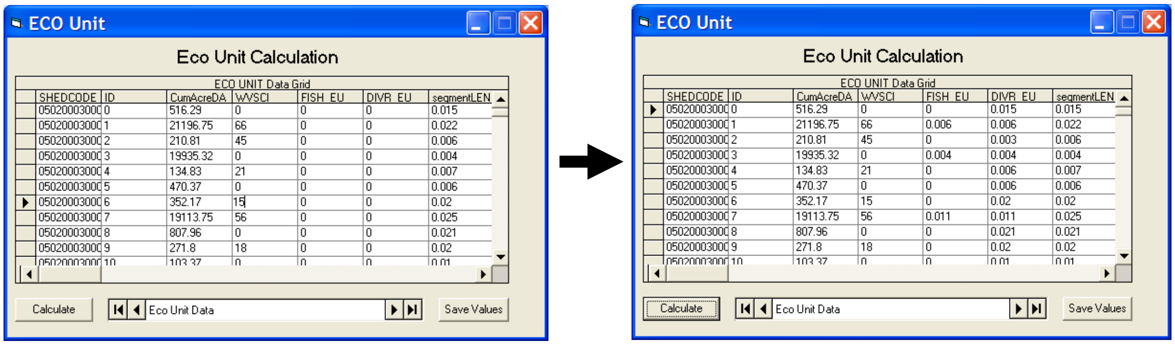
Treatment Technology: IS Dosing
Flow (gpm): 1904
Net Acidity: 29

Costs

Capital: 200000
Anticipated load: 80% of Acid load

Annual Chemical Cost $: $9,448.07
Annual Labor Cost $: $13,440.00
Treated Acid load (tons/yr): 97.18016
Acid load (tons/yr): $121.48
Maintenance Sludge Removal $: $330.68
Passive Maintenance $:
20 year treatment ($/20 yr): $646,437.51
Acid Load removal eff. ($/ton): $332.60

Figure 7. Cost estimator for common AMD pollution abatement



ECO Unit

Eco Unit Calculation

ECO UNIT Data Grid

SHEDCODE	ID	CumAcreDA	WVSCI	FISH EU	DIVR EU	segmentLEN
05020003000	0	516.29	0	0	0	0.015
05020003000	1	21196.75	66	0	0	0.022
05020003000	2	210.81	45	0	0	0.006
05020003000	3	19935.32	0	0	0	0.004
05020003000	4	134.83	21	0	0	0.007
05020003000	5	470.37	0	0	0	0.006
05020003000	6	352.17	15	0	0	0.02
05020003000	7	19113.75	56	0	0	0.025
05020003000	8	807.96	0	0	0	0.021
05020003000	9	271.8	18	0	0	0.02
05020003000	10	103.37	0	0	0	0.01

ECO Unit

Eco Unit Calculation

ECO UNIT Data Grid

SHEDCODE	ID	CumAcreDA	WVSCI	FISH EU	DIVR EU	segmentLEN
05020003000	0	516.29	0	0	0.015	0.015
05020003000	1	21196.75	66	0.006	0.006	0.022
05020003000	2	210.81	45	0	0.003	0.006
05020003000	3	19935.32	0	0.004	0.004	0.004
05020003000	4	134.83	21	0	0.006	0.007
05020003000	5	470.37	0	0	0.006	0.006
05020003000	6	352.17	15	0	0.02	0.02
05020003000	7	19113.75	56	0.011	0.011	0.025
05020003000	8	807.96	0	0	0.021	0.021
05020003000	9	271.8	18	0	0.02	0.02
05020003000	10	103.37	0	0	0.01	0.01

Figure 8. Eco unit calculation dialog within the MB Accumulator program

Summary and Discussion

This paper described a watershed modeling framework that was integrated into a spatial decision support system called the Mass Balance Accumulator. The MB Accumulator is a programmed extension for GIS software. The primary goal of the system was to provide consistent technical information and to help develop estimates of costs and benefits of alternative actions. The MB Accumulator provides a visual, graphical representation of the complex, spatial nature of watershed issues and facilitates discussion and development of alternative strategies. The approach provides hydrological modeling functions and decision support capabilities to either an experienced GIS analyst or a non-technical user. Much of the power of the system comes from attention to detail in data development and the hydrological modeling capabilities present in GIS. Components of the current application are being used to develop treatment plans in AMD impacted watersheds in WV.

This process can aid in developing practical solutions and guide decisions for addressing watershed and water quality problems. An example of the output reports that are possible from the application are shown for a WV watershed in Fig. 9.

A primary impetus for developing this system was to provide a methodology for systematically assembling and using GIS data to choose among or rank alternative projects or decisions. To this end, a multiple criteria decision making framework will be integrated in the future as another component of the decision support system to aid in this process.

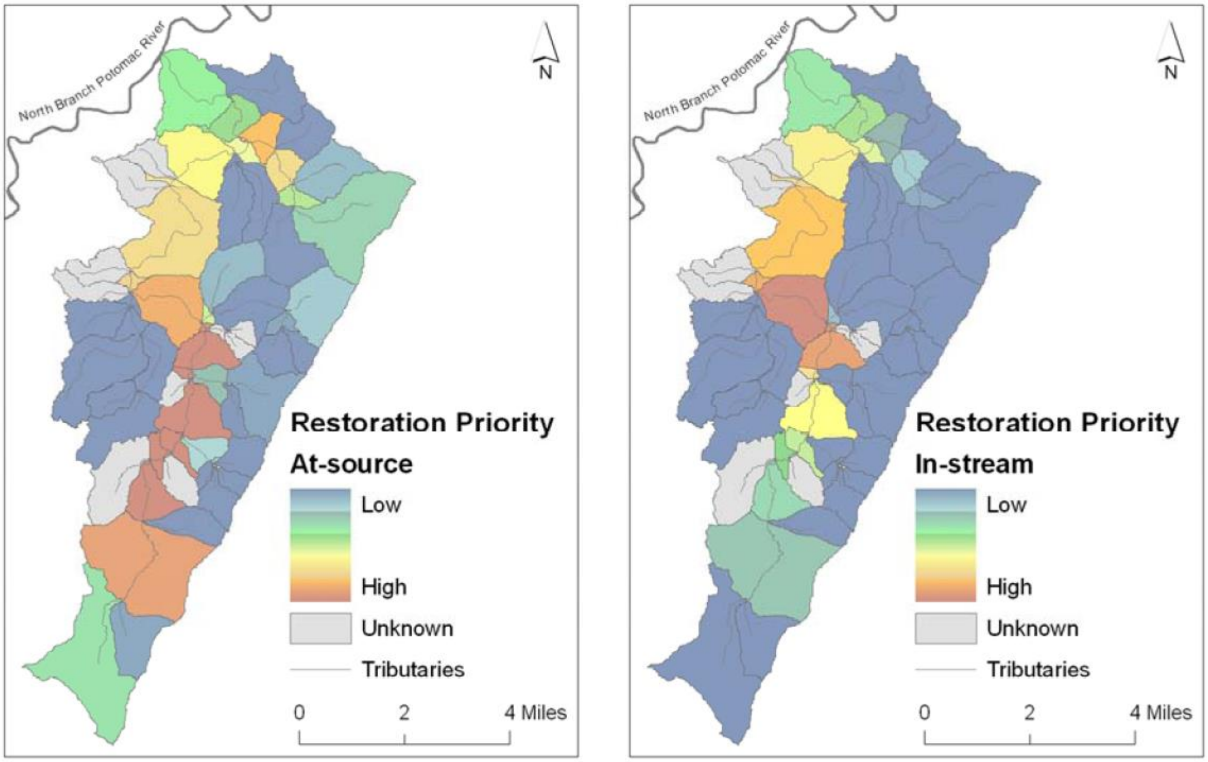


Figure 9. Restoration outputs from the MB Accumulator

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