COMBINING VALLEY SEGMENT CLASSIFICATION WITH NEURAL NET MODELING OF LANDSCAPE CHANGE: A NEW APPROACH TO INTEGRATED RISK ASSESSMENT FOR RIVER ECOSYSTEMS

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ABSTRACT

The rapid pace and pervasiveness of landscape modification has made predicting watershed vulnerability to landscape change a key challenge for the twenty-first century. River ecosystems are, in particular, directly dependent on landscape structure and composition for their characteristic water and material budgets. Although it is widely acknowledged that landscape change poses serious risks to river ecosystems, quantification of past effects and future risks is problematic. Important issues of scale, hierarchy, and public investment intervene to complicate both assessment of current condition and the prediction of riverine responses to changes in landscape structure. In this paper we demonstrate how neural net approaches to landscape change prediction can be coupled with river valley segment classification to provide a framework for integrated modeling and risk assessment across large-scale river ecosystems. Specifically we report on progress and techniques being employed in a collaborative risk assessment for the Muskegon River watershed and its ecological interactions with Lake Michigan.

The Muskegon River Ecological Modeling System (MREMS) links the Landscape Transformation Model (LTM) to a series of standard hydrologic, loading, and biological models via a GIS-based valley segment classification framework. Models currently linked in MREMS include MODFLOW, HEC-HMS, GWLF, and a number of regional biological assessment models. The MRI-VSEC river reach classification system, a GIS-product developed for the Fisheries Division of the Michigan Department of Natural Resources, is used to define spatial rules for the parameterization and spatial integration of component models. The result is an open modeling system capable of predicting future (and past) states of the landscape, and then evaluating likely changes in hydrology, chemistry, and biological integrity/productivity in a spatially explicit framework. Integrated modeling of the Muskegon has already identified areas of the Muskegon

watershed most at risk from future development. These results are already being used by investigators and regional stakeholders to both target monitoring/restoration activities, and to refine basin-wide modeling goals and queries for future MREMS analyses. Stakeholder workshops were used to develop a final set of modeling scenarios to be evaluated by the MREMS system when component model development is completed.

INTRODUCTION

Regional scale assessment and planning for management of aquatic resources has been a rising priority of governmental resource agencies and other groups interested in rapid and effective targeting of limited conservation resources (EPA 2003). Given the number of river systems and density of tributaries of interest at a regional scale, and their inherent variability, resource managers need tractable tools to assess ecological character (status), and estimate the risk of future impairment associated with various land planning scenarios. Both watershed based modeling and river classification have been proposed as methods of simplifying analysis in order to more efficiently protect river ecosystems (Hawkes 1975; Hudson et al. 1992; Maxwell et al. 1995). Linking typical status and risk assessment models (e.g. bio-assessment protocols or predictive models) to explicit classification systems, however, remains a key methodological problem. Ideally, a solution would provide both a spatially explicit classification system that simplifies the natural complexity of our rivers, and a method for coordinating suites of physical and biological models capable of predicting current and future conditions across a region and over time.

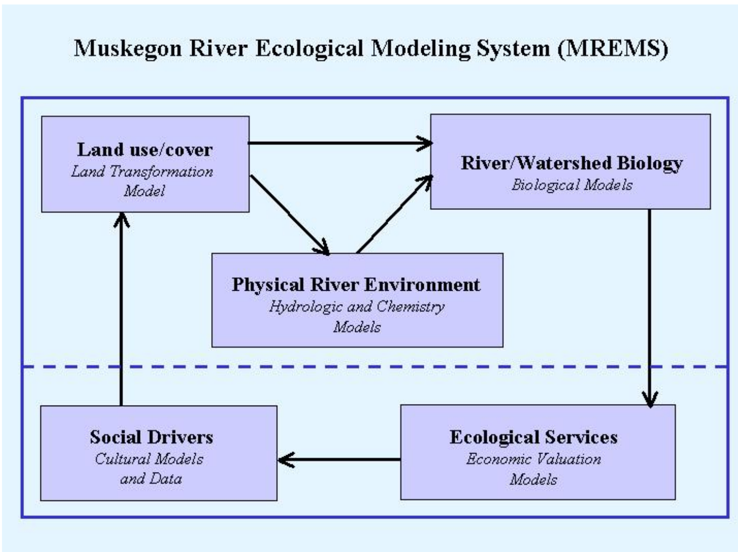
As a part of a large collaborative study of the 2600 square mile Muskegon River watershed, we have recently developed a GIS-based approach using ecologically defined valley segment units to integrate a state-of-the-art neural net model (Landscape Transformation Model: LTM; Pijanowski 2000, 2002a; 2002b, 2004) with a variety of hydrologic and other models for the purpose of conducting rigorous integrated risk assessments at a watershed scale. The result is a modeling system, the Muskegon River Ecological Modeling System [MREMS], in which a variety of types of models can be used together to estimate risks to key watershed resources arising from various landscape change scenarios. Valley segment scale ecological units (VSEC; Seelbach et al. 2001) are used as an efficient and ecologically meaningful physical framework for organizing data exchanges between interacting models and stratifying model predictions. Output is re-mapped onto classification units to summarize and visually integrate spatially explicit forecasts of ecological status and future risk.

In this paper we provide a basic description of the structure of the MREMS system and detail the model linkage strategy we are employing. In addition we provide preliminary examples of integrated assessment modeling based on the coupled execution of a series of land use change, hydrologic, loading, and biological response models from our Muskegon River studies.

METHODOLOGY

MREMS is a distributed modeling environment in which we are linking many different kinds of models to build a comprehensive picture of how the Muskegon River Ecosystem functions. In most cases we are using several models of the same general phenomenon because often they employ different approaches, scales, or generate different types of useful output. Philosophically, our approach is to recognize the inherent inaccuracies associated with all modeling and so we favor redundancy by including many types of models, and modeling at multiple spatial scales. Therefore, MREMS can be best visualized as consisting of a suite of interacting sets of models, each focused on a particular aspect of the Muskegon River Watershed environment (Figure 1).

Figure 1 - Schematic representation of the structure of MREMS components and execution order



Apart from its component models, MREMS is essentially an explicit protocol and directory structure which facilitates the linked execution of component models in a spatially explicit manner. The MRI-VSEC v1.1 (Seelbach et al.1997), a GIS product, provides the spatial framework for coordinating all input, output, and display of the component models in MREMS.

MREMS Component Models

We have developed MREMS as an open system in which any model type can, in theory, be used. At the present time we are working with suites of hydrologic, loading, and biological models (Figure 1; Table 3). These models represent much of the range in types of models used in natural resource planning contexts. Some are simple GIS models; some linear statistical models that produce point estimates; some are complex linear structural models that describe both physical and biological processes. Several are large-scale dynamic simulation models (e.g. Hec-HMS; MODFLOW, several fisheries bioenergetic growth models). Beyond the neural net LTM, the most complex component models are the hydrologic simulations implemented using HEC-HMS, GWLF, and MODFLOW. A basin-wide 15-minute time step version of the HEC-HMS is now being refined. In MREMS it uses a 2-layer custom groundwater recharge routine to generate baseflow components, which are then added to and routed through the HEC-HMS surface water network. A scenario execution (see below) results in 20-year hydrographs being estimated for each of the 56 model elements. These in turn are used to interpolate the 20-year hydrographs for each of the 138 VSEC units in the Muskegon. HEC-HMS uses the SCS unit hydrograph approach to interpret LTM projected landcover changes and produce resulting hydrographic predictions for the river system. The hydrographic projections in turn are used to drive a variety of other component models in MREMS.

TABLE 1. Component models being linked in MREMS

Model	Predicts	Type
MODFLOW	Groundwater flow	Sim
MRI_DARY	Groundwater inputs	GIS
HEC-HMS	Surface water flows	Sim
MRI_FDUR	Surface water flow frequencies	Linear
HEC-RAS	Surface water hydraulics	Sim
GWLF	Surface dissolved loads	Sim
MRI_LOADS	Surface dissolved loads	Regress
M0C3D	Groundwater dissolved loads	Sim
MRI_JTEMP	July water temp	Regress
<u>Regional Assessment Models</u> All taxa Sensitive taxa EPT Index Algal Index	 Fish/insect diversity Fish/insect diversity EPT taxa Agal status	 Regress Regress Regress Regress

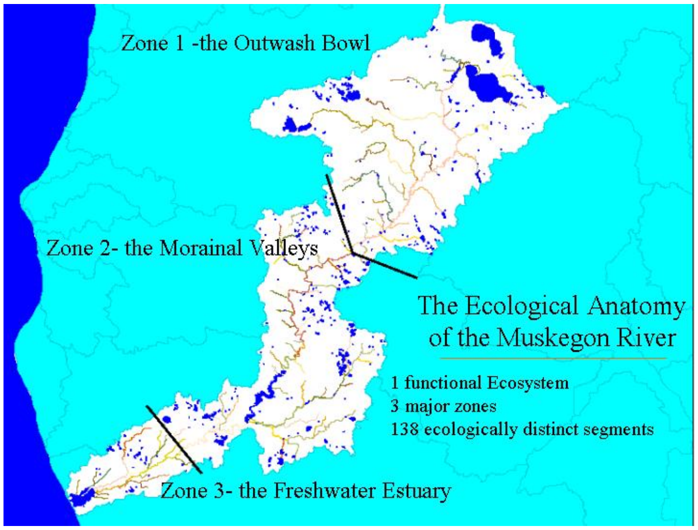
Bioenergetic IBM Steelhead Salmon Walleye	Growth rate and survivorship	Sim Sim Sim
Mass Composition Sport fishes Total fishes Sensitive fishes Total Algae Filter-feeders Grazing inverts	 Kg/hec total mass Kg/hec total mass Kg/hec total mass g/m^2 g/m^2 g/m^2	 SEM,Regress SEM SEM SEM SEM SEM

The most critical model for running risk assessment scenarios in MREMS is the Land Transformation Model (Pijanowski et al. 2002a; Pijanowski et al., 2002b), which provides us with changing land use distributions upon which many other component models react. LTM v.3 is a data intensive neural net model, which predicts land use change at the level of 30m pixels across the landscape. Neural net "imagined" landscapes, coupled a standard 20-year climate scenario (1970-1990 observed temperatures and precipitation), and best available DEM and geology covers provide the physical template from which input parameters for constituent models are prepared. The Muskegon River drainage net itself (in the form of the VSEC framework) is then used to identify appropriate spatial strata for model parameterization and execution.

The MRI-VSEC Framework

For our model of the Muskegon Watershed we have adapted the MRI-VSEC v1.0 system of Seelbach et al. (1999) by correcting some minor mapping errors and transferring it to a 1:24000 scale channel cover based on 1978 (MDNR, MIRIS) air photos. We define ecological valley segments (VSEC units) as (variably) large sections of river channel that contain distinct, relatively homogeneous habitat conditions and biological assemblages. Higgins et al. (1999) referred to units of this type ands scale as fish macrohabitats. Ecological valley segments combine elements of local valley and channel geomorphology with catchment hydrology, the two dominant forces shaping riverine habitat. In general, this approach is conceptually similar to the hydrogeomorphic 'HGM' concept used in wetland assessment (Hauer and Smith 1998). The system identifies 138 distinct (contiguous) channel units in the Muskegon River ranging from first to fifth order channel segments (Figure 2). Major reservoirs and Muskegon, Houghton, Cadillac and Higgins Lakes are included as separate VSEC units. In MREMS, all models are required to provide model estimates and output for each of the 138 segments. The resolution of the output (e.g. a single site or multiple sites in the segment) is left to the individual model and modeler. Basic parameters for many landscape features (e.g. land cover, surficial geology, elevation, basin size) are provided by the MREMS system for upper, mid-point, and lower segment nodes.

Figure 2 - The Muskegon VSEC Map which provides the spatial framework for MREMS model linkage.

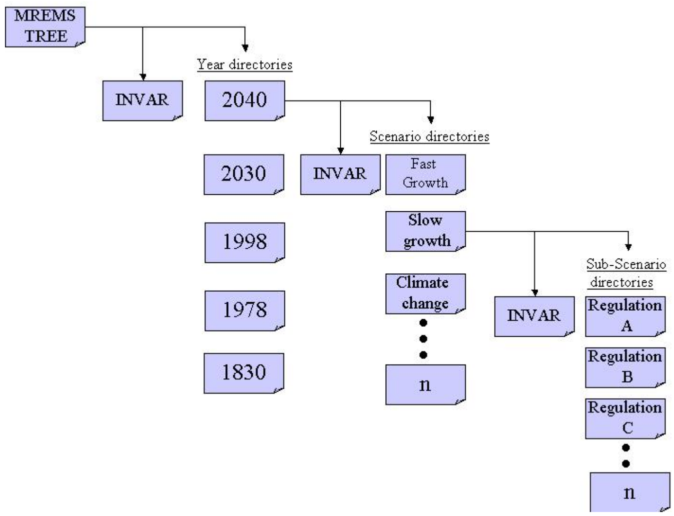


MREMS Linkage Protocols

Participating component models follow a set of communication protocols that require, among other things, all output files be explicitly referenced to the GIS-mapped spatial framework. The spatial framework is a GIS representation of the drainage net itself, with longitudinal units defined “ecologically”. That is, each unit of the spatial framework is a contiguous channel segment, delimited so that it is likely to represent a relatively homogenous environment in terms of parameters meaningful to biological organisms (e.g. temperature, hydraulics, chemistry). This unit map then serves as the underlying skeleton on which model input and output are organized.

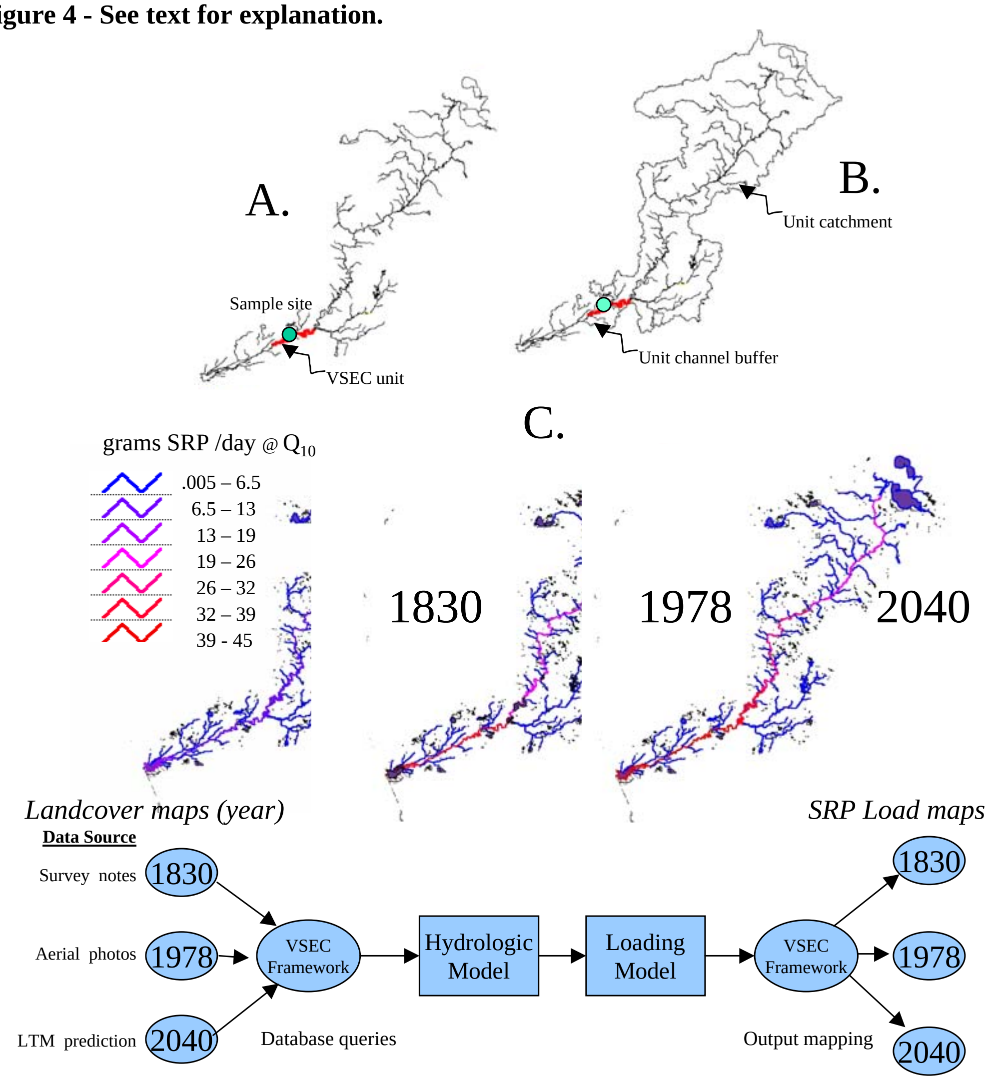
Models communicate by placing appropriate identifiable output (*.txt or *.dbf) into a structured directory system that is organized into specific timeframe (land cover sample year), problem context (scenario) and management option (sub-scenario) levels. At every level an INVAR (invariant) directory hold data sets, which are also true for that and all lower levels of the directory space, as well as a subdirectory index, log, and other ancillary files (Figure 3). An MREMS run for a specific scenario involves the serial execution of a set of component models for each time frame, using scenario-specific, and sub-scenario specific inputs and outputs. In many cases the output written by one model may be used as input by the next. Execution order is determined by data dependency. Typically execution order would start with the generation of a land cover map (produced by LTM), followed by hydrologic, chemical loading, and ecological models in that order (Figure 1).

Figure 3. MREMS Directory Structure



To illustrate the general MREMS methodology Figure 4 shows data paths through MREMS used in a relatively simple coupling of 3 models (LTM, MRI_FDUR, and MRI_LOADS) used in proof-of-concept tests in 2002. Sample sites are used to represent the entire VSEC unit they occur in based on the mapping criteria of ecological homogeneity (Panel A, Figure 4). VSEC unit ID is used to geo-reference and query associated catchment, riparian buffer, and site scale databases to generate input parameters for component models (Panel B). Once output is generated by MREMS' component models, they are linked back to the VSEC unit ID and onto the VSEC spatial framework to produce channel maps with explicit model predictions for each of 138 VSEC channel segments. Panel C shows the Muskegon VSEC unit map with predicted phosphate loading over time. The illustrated 2040 scenario gives expected loads at the 10% annual exceedence discharge if high rates of urbanization observed in the 1990's were to continue to the year 2040.

Figure 4 - See text for explanation.



PRELIMINARY RESULTS FOR A RAPID DEVELOPMENT SCENARIO

Full implementation and parameterization of the MREMS modeling system is not scheduled to be complete until late 2005; awaiting the completion of field studies across the Muskegon basin. Nevertheless a number of preliminary runs have already been made, both to calibrate and evaluate component models and to refine linkage protocols. These early runs use LTM projections assuming a 1990's rate of growth and therefore provide a kind of "worst likely case" development scenario for the basin. These runs are already proving useful in focusing current conservation and restoration activities. The spatially explicit nature of the MREMS system identifies those segments of the rivers that are most at risk from rapid development and likely patterns of land use change.

Regional LTM projections for the year 2040 using a fast growth scenario suggest that most of the additional urbanization in the basin will occur along the Lake Michigan-US131 corridor, and secondarily along other major transportation corridors across the Muskegon watershed (Figure 5 below).

Figure 5 - Sequence of land cover scenarios used to drive preliminary MREMS executions. 1820 source is MDNR digitized GLO notes; 1998 through 2040 are LTM neural net projections from base 1978 MIRIS air photo interpretation and trailng data sets.

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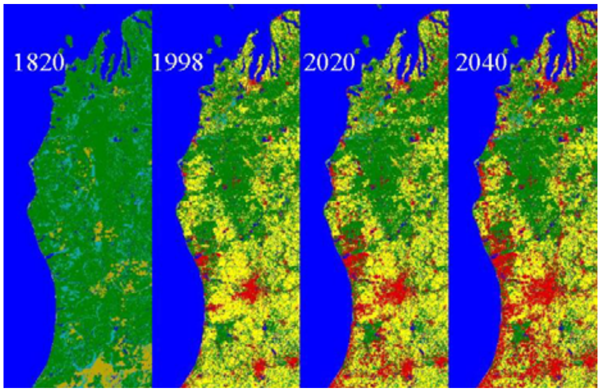


LTM coupled HEC-HMS and GWLF runs provide a basis for examining both direct hydrologic responses and then indirect hydrologic effects by driving other models' impacts on water quality, sediment transport, potential channel geometry, and ultimately the response of biological communities. For example, in Figure 5 HEC-HMS output for Cedar Creek shows the change in basin response to identical precipitation forcing for the 1998 versus 2040 landscape configuration. Even though Cedar Creek is predominantly driven by groundwater inputs, this MREMS run suggests anticipated increases in impervious surface will increase event peak discharge rates in the channel by nearly 100%. Using the modeled hydrographic data in dominant discharge analyses indicates that sediment transport in Cedar Creek is likely to increase by 32 % on an annual basis. Further, that resulting changes in the transport regime are likely to lead to channel aggradation and loss of important fish habitat (Table 2). Coupled biological models suggest extirpation of 2-3 of the 10 or so species currently found in this tributary. Similar but somewhat more dramatic impacts were predicted for Brooks Creek, an adjacent and more agriculturally developed watershed. Nutrient loading models likewise indicate large increases in nitrogen and phosphorus export from these tributaries (Figure 4, above).

Regression models predicting biological community response (see Wiley et al. 2002) required as input parameters estimates of TDS concentrations, baseflow yield, catchment area, and percent of the catchment in urban and agricultural land cover. Adjusting inputs based on LTM, hydrologic, and loading model predictions, total diversity and number of intolerant species were predicted for each VSEC unit in the river system. Mapping the change in diversity across the basin provides a spatially explicit map of the risk of species loss due to predicted landscape development (Figure 6). Since combining historical data, aerial-based GIS coverages and LTM predictions yields a series of land cover maps. MREMS can be used to produce a sequence of hindcasts and forecasts that model the trajectory of biodiversity in any VSEC unit of interest.

For example in our early MREMS runs the fast development scenario described above affects biological diversity principally in the main stem and lower river tributaries. Most of the main stem downstream of Evart is predicted to lose 1-2 species. The segment immediately below Cedar Creek (N. Branch lower Muskegon River) and Cedar Creek itself were the most seriously threatened. Cedar Creek is predicted to lose 3-4 species and the N. Branch Muskegon (in the Fish and Game Area) 4-6 species. These declines are relative to modeled diversity using the 1998 land cover configuration. As can be seen in the insets in Figure 6, this decline is a part of a trend in declining diversity. Both aquatic insects and fish diversity decline over time with intolerant taxa.

Figure 6 - Modeled hydrographs for Cedar Creek using observed 1998 and LTM projected 2040 landcover scenarios. Precipitation, temperature and all other variables held constant.

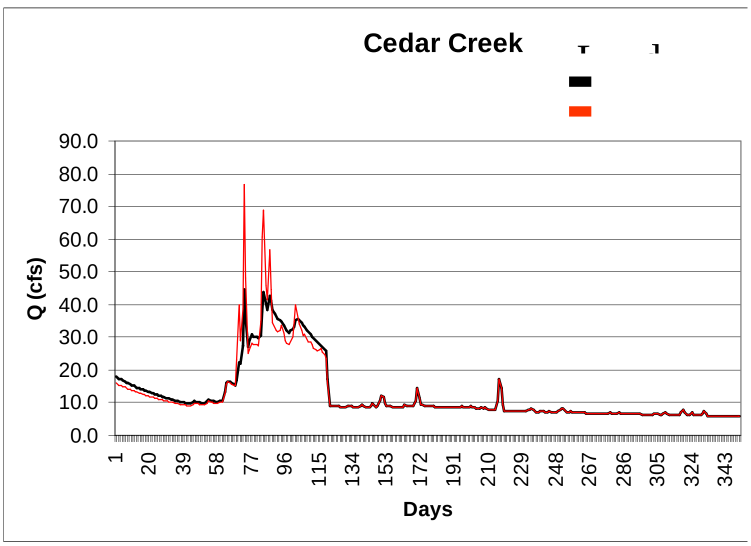
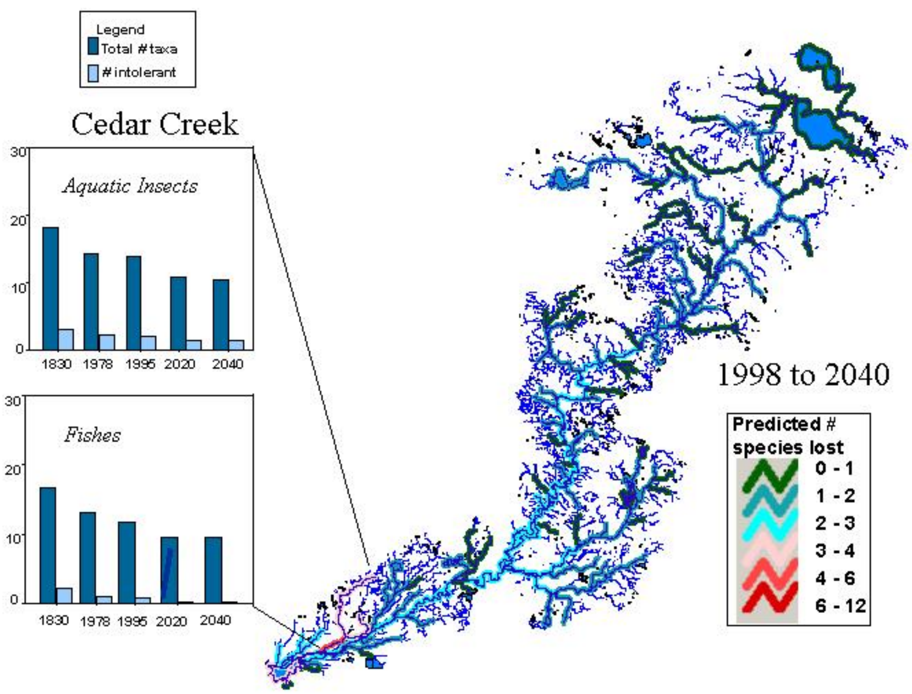


Table 2 - Example of multiple ecological responses predicted by MREMS run for a “Fast Growth” scenario. Change rates for 1998 to 2040 time frame comparison.

Site	% DQ[1]	Channel[2] Response	% SL[3]	%TDS[4]	Fish spp. loss
Cedar Creek	-13 %	aggrade	+26 %	+32%	3-4
Brooks Creek	-22 %	aggrade	+72 %	+20%	1-2
Main River @ Evart	0 %	No change	+1%	+20%	2-3
Main River @ Reedsburg	0 %	No change	+6 %	+3%	0-1

[1] %DQ: Percent change in Dominant Discharge (determines the size of the equilibrium channel)
[2] Channel response: expected response based on %DQ
[3] %SL: Percent increase in average daily sediment load [tonnes/day]
[4] %TDS: Percent change in median Total Dissolved Solids concentration (ppm)

Figure 7 - Changes in biological diversity predicted in response to land cover change predicted in the “fast growth” LTM scenario.



DISCUSSION

Although final implementation and risk assessment modeling with MREMS lies ahead, limited runs to date are already proving useful in both watershed restoration planning and study design contexts. The spatially explicit nature of the modeling system facilitates visualization and communication about potential risks to this important river resource. In particular, Cedar Creek in Muskegon County has repeatedly emerged as a tributary system clearly at risk from development. These results have already led to increased attention and conservation planning efforts for Cedar Creek. These include a fisheries habitat inventory being directed by NRCS; a volunteer-university collaboration to develop sediment loading functions for Cedar Creek; a new MDNR-MDEQ collaborative modeling effort aimed at identifying potential hydrologic storage and baseflow protection BMPs; and, due to our MREMS calibration work, we have increased the density of automated gauging installations in an effort to improve the precisions of our hydrologic predictions.

Our early experiences with Cedar Creek arose out of early proof-of-concept modeling runs completed in 2003. Ultimately, when we run the final basin-wide risk assessments for which MREMS is designed we will be evaluating various management scenarios developed by a focus group of collaborating Muskegon watershed stakeholders. At a stakeholders workshop in August 2002 they identified three major types of scenarios that they would like to evaluate using the MREMS system. These categories include land management scenarios (e.g. evaluating different sized riparian set-backs; evaluating effects of alternate rates and sites of development); hydrologic management scenarios (e.g. evaluating dam and lake level control effects, examining the effect of wetland losses and protection on river hydrology); and sediment/erosion management scenarios (e.g. investigation where the bank erosion and aggradation is being affected by development, and where bank stabilization is a useful strategy). A full list of the MREMS risk assessment scenarios developed at the stakeholder workshop are available at http://mwrp.net/mrems/. The component model selection and parameterization is actively being adjusted with these stakeholder identified evaluation goals in mind. For example a new dominant discharge module was developed over the last year to help address several of the sediment/erosion scenarios addressed (e.g. Table 2 above).

Unresolved Issues and Challenges

Several implementation issues remain to be resolved. In preliminary MREMS runs, the system directory structure was small enough that it was simply passed back and forth between machines and modelers via an FTP. LTM projections were run on dedicated WNNT platforms, output was then converted to grid files, summarized in an Arc/Info environment by VSEC, and placed manually into the MREMS directories. Other models copied the directory structure into their local disk space, executed and wrote output to the copy, and then updated the relevant portions of the MREMS directory. Now as the full complement of models come online, especially HEC-HMS and MODFLOW, which produce 20-year daily hydrographs for each VSEC unit, the scale and complexity of data exchange has grown. MREMS (VSEC-indexed) output files are now running several hundred megabytes in size per scenario and time frame combination. Errors in naming, calculation sequence, and updating of revisions with on-going model calibrations have begun to make an FTP based file exchange difficult to manage. We are now exploring a web-based MREMS directory with an XML client to provide standardized indexing and metadata records for models writing to the MREMS directory structure.

Future Plans and Benchmarks

Modern GIS systems provide the appropriate technology for blending bottom-up attribute-based modeling (and sampling) with top-down regionalization and mapping approaches (see review by Seelbach et al. 2001). Advanced landscape-transformation models can be systematically linked to a landscape-cognizant, an ecologically interpreted river segment classification system, to provide an effective spatial framework for both sampling inventory and site-specific modeling of river status and risk with respect to landscape alterations. The value of this approach lies principally in (1) the orchestration of integrated model-based assessments by standardizing the scales of parameterization and analysis; and (2) the resulting spatially explicit visualization of the complex products of landscape and other environmental change. Beginning and ending with maps, while maintaining the rigor of process-based and site-specific modeling, our approach brings the capability of detailed technical information processing to the public in a fashion that is relative easy to comprehend. Its value can in part be measured by the almost immediate utility of early output in identifying threatened sub-catchments like Cedar Creek in the Muskegon Watershed. Even though based on preliminary versions of MREMS, this identification has helped local stakeholders (principally the Muskegon River Watershed Assembly, MDNR, and MDEQ) justify additional investments in restoration and conservation planning activities.

The overall MREMS system itself will not be ready for a complete basin wide analysis until 2005, pending completion of field studies and model development work now underway in the lower river and Muskegon Lake Estuary. Nevertheless, the approach developed for MREMS is already being used in larger regional studies. At present, segment-based modeling systems are being built for state resource agencies in Wisconsin, Michigan, and Illinois as part of a collaborative risk assessment project funded by the USEPA (STAR Program). In that project VSEC-type mapping frameworks are being developed for each state, and coupled with landscape sensitive statistical models of hydrology and biology. LTM neural-net modeling is then used to forecast future landscape change that in turn drives predictions by channel segment unit, following the basic MREMS approach. Similar analyses are also being included in the USGS Aquatic Gap program for the Great Lakes. Since all of the programs, including the MREMS project, are still in active development it is difficult to predict how successful valley segment stratified risk assessment will prove to be. Early indications are that the marriage of neural net models and stream classification networks may be a valuable conservation tool indeed.

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