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GLOBAL CHANGE AND RIVER ECOSYSTEMS

A multi-modeling approach to evaluating climate and land use change impacts in a Great Lakes River Basin

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Abstract River ecosystems are driven by linked physical, chemical, and biological subsystems, which operate over different temporal and spatial domains. This complexity increases uncertainty in ecological forecasts, and impedes preparation for the ecological consequences of climate change. We describe a recently developed “multi-modeling” system for ecological forecasting in a 7600 km^2 watershed in the North American Great Lakes Basin. Using a series of linked land cover, climate, hydrologic, hydraulic, thermal, loading, and biological response models, we examined how changes in both land cover and climate may interact to shape the habitat suitability of river segments for common sport fishes and alter patterns of biological integrity. In scenario-based modeling, both climate and land use change altered multiple ecosystem properties. Because water temperature has a controlling influence on species distributions, sport fishes were overall more sensitive to climate change than to land cover change. However, community-based biological integrity metrics were more sensitive to land use change than climate change; as were nutrient export rates. We discuss the implications of this result for regional preparations for climate change adaptation, and the extent to which the result may be constrained by our modeling methodology.

Keywords Climate change · Land use · Land cover · Rivers · Modeling · Fisheries · Salmon · Trout

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Introduction

River ecosystems consist of complex linkages between dynamic physical, chemical, and biological subsystems; each operating at different characteristic spatial scales and frequencies (Maxwell et al., 1995). This complexity makes ecological forecasting difficult; the ensuing methodological uncertainty being one of the obstacles slowing regional preparation for anticipated ecological impacts of climate change (NRC, 2007). Climate forecasters frequently employ "ensemble" modeling approaches (e.g., Murphy et al., 2004) in which multiple models of the same endpoint, each with its own characteristic strengths and weaknesses, are used together to generate more robust forecasts and to quantitatively evaluate model specification-related errors. In control systems engineering "multi-modeling" systems link a series of separately optimized models that describe distinct aspects (parameter domains) of a single problem in order to represent and control complex dynamic, nonlinear system processes (Johansen & Murray-Smith, 1997). In contrast, most water quality, hydrologic and fisheries forecasting typically involves single model simulations that are designed for the detailed representation of a single endpoint or suite of related parameters of interest. Examples of this "one-at-a time" approach in the river management field are legion. Even widely used water quality models which conceptually link hydrologic, hydraulic, and load generation processes (e.g., SPARROW Schwarz et al., 2001; SWAT Santhi et al., 2005) still are largely single purpose constructions which significantly abstract hydrologic/hydraulic process detail in the service of efficient water quality endpoint predictions.

In real-world management settings groups of stakeholders representing diverse interests (e.g., water quality, fisheries, farming, and forestry) are forced to understand and make decisions about whole systems and not constituent parts. For watershed stakeholders single focus, stand alone modeling often leads to large collections of partial and sometimes competing analyses; leaving unanswered the critical question of how models of different components should be integrated to evaluate the overall impact of alternate management strategies and choices. Nor do they typically provide much sense of forecast uncertainty with respect to the parameters that are predicted. The utility of a "multi-modeling" approach is that it can provide integrated forecasts over a wide range of ecological components and ecosystem services. The need for such forecast capacity is growing with the urgency of linking large-scale climate change modeling to local hydrologic, water quality, and ultimately biological consequences (e.g., Christensen & Lettenmaier, 2006; Moore et al., 2009, Nelson et al., 2009). Furthermore, ensemble modeling capability (multiple representations of single process domains) is quite easily implemented inside of a multi-modeling system (multiple models across multiple process domains), and this seems a promising approach to evaluating uncertainty in complex ecological forecasting. Explicit multi-modeling applications in ecological forecasting are at present rare; but they are now emerging in the context of global change preparation (e.g., see Nelson et al., 2009). Here we describe an analysis employing this approach to explore land use and climate change impacts in the Muskegon River watershed, a major tributary system of Lake Michigan in the USA.

The North American Laurentian Great Lakes (GL) and tributary watersheds support a $4.3 billion per year fishery, and the water needs of over 40 million inhabitants including five class one urban centers (Chicago, Detroit, Toledo, Cleveland, Buffalo, and Toronto). The water rich GL basin is likely to be particularly vulnerable ecologically to anticipated climate change (Kling et al., 2003), but like many parts of the U.S. has been the subject of only limited climate change planning to date (NRC, 2007; Dinse et al., 2009). In this paper, we briefly describe an ecological "multi-modeling" system developed for integrated assessment and ecological forecasting on the Muskegon River, a major watershed in the GL basin (Stevenson et al., 2008; Wiley et al., 2008). Using a series of linked land cover, climate, hydrologic, hydraulic, loading, and biological response models we examined the potential influence of land management practices and climate change on the ecological future of this important tributary of Lake Michigan. Specifically, we discuss the potential impacts of changes in climate and land use on water quality, channel stability, fisheries-relevant habitat, and biological integrity as reflected in its fish and macroinvertebrate communities.

Methods

Study area

The Muskegon River drains 7600 km^2 of Michigan's Lower Peninsula (Fig. 1). It is the second longest (~353 km) river in the Lake Michigan watershed and provides key spawning habitat for the region's economically important anadromous (adfluvial) fisheries. Included in its headwaters are Higgins (3,885 ha), Houghton (8,112 ha), and Mitchell-Cadillac (1,510 ha) lakes, and along its lower main stem a series of hydropower reservoirs. The river terminates in an extensive freshwater wetland that drains to Muskegon Lake, a drowned river mouth basin connected to Lake Michigan. The river drops a total of 175 m from its headwaters to Lake Michigan and has approximately 94 perennial tributaries comprised of over 2500 km of stream channel (at a scale of 1:100,000).

Over 47% of the watershed is forest. Between 1978 and 1998, the amount of urban in the watershed nearly doubled from 4% total coverage to over 7%. Approximately 22% of the agriculture in 1978 was lost by 1998, largely replaced by forest, which increased from 44% to 47% during the same 20 year period. According to the US Census Bureau, 358,184 people live in cities, villages, and townships that were wholly or partially located within the watershed; this represents approximately 3.6% of Michigan's population. The largest cities (and year 2000 population) include Muskegon (40,105), North Shores (22,527), and Cadillac (10,000). The watershed is located within a humid, temperature climate zone, receiving approximately 83 cm of precipitation annually from 1980 to 2005. The basin is dominated by coarse textured soils atop largely glacial drift deposits. This combination of climate, topography, and sediment types produce relatively stable flows in the Muskegon River that are primarily derived from groundwater sources (Kendall & Hyndman, in review). At these latitudes (43–45 N) groundwater dominated rivers support primarily cold and cool-water fish assemblages (Wiley et al., 1997; Zorn et al., 2002; Wehrly et al., 2003). The Muskegon River supports regionally important trout, salmon, and walleye sport fisheries (O'Neal, 1997).

Modeling approach

The Muskegon River Ecological Modeling System (MREMS) is a "multi-model" in the sense of Johansen & Murray-Smith (1997). It consists of a set of independent component models targeted toward various aspects of the Muskegon River ecosystem, using different spatial and temporal domains as appropriate. Models are synchronized by shared inputs from climate, land cover, and GIS river network models, and also by inter-model data exchange as required. Data geo-referencing protocols help models operating at different spatial scales to communicate and integrate outputs. Model execution mimics the hierarchical organization of real river ecosystems (Fig. 2) by routing all model calculations

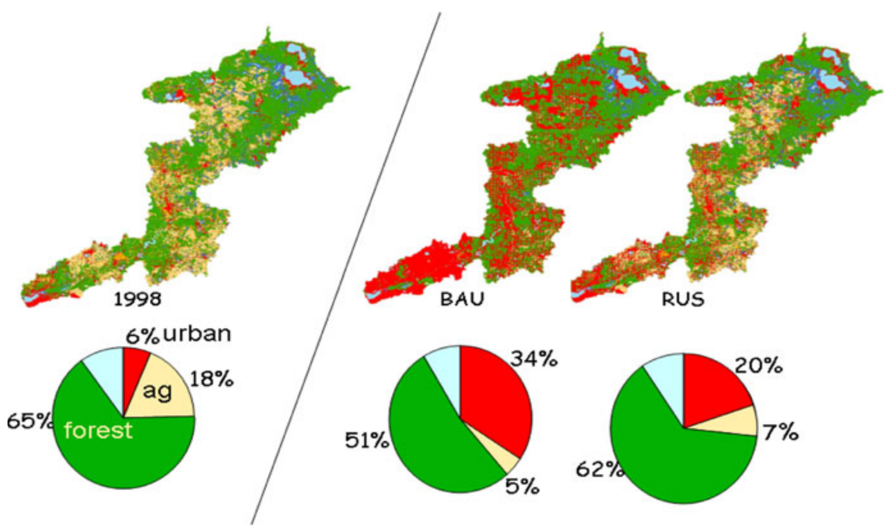

Fig. 1 Muskegon River watershed. Current and future forecast land cover maps used in the land management scenarios. Pie diagrams report corresponding land cover proportions for entire basin. Current scenario (1998 baseline) was derived from hand digitized aerial photography. BAU and RUS scenario land covers generated by LTM2 (Pijanowski et al. 2000, 2002a, b, 2005). The Muskegon River is tributary to the Eastern shore of Lake Michigan (inset)

from upstream to downstream elements and by organizing data flows from climate and landscape structure (land use) models to reach-referenced distributed hydrologic and physical models. The output of these in turn are used as input to a series of biological response models. We developed MREMS as an open modeling system to which any type of model could in theory be added. For the simulations described below, however, the specific suite of hydrologic, loading, and biological models are detailed in Table 1. Models were run by researchers at separate collaborating universities, and assembled and shared on a central web-accessible server and data execution directory (http://mwrp.net).

In the simulations reported below, we used the MREMS system to explore the potential impacts on the Muskegon River of two climate change scenarios along with two future land management trajectories. This study was a part of a larger, long-term, integrated planning exercise involving 16 watershed stakeholder organizations, a collaborating group of university and agency scientists, and a consortium of regional funders (Wiley et al., 2004, 2008; Stevenson et al., 2008).

The MREMS framework

The spatial framework of MREMS was adapted from the MRI-VSEC v1.0 system of Seelbach et al. (2006) by correcting local mapping errors and transferring it to the 1:24,000 scale. The VSEC system is a GIS representation of the drainage net itself, with longitudinal units defined "ecologically"; each VSEC unit is a contiguous channel segment, delimited to represent a relatively homogenous environment in terms of parameters meaningful to biological organisms (e.g., temperature, hydraulics, chemistry; Seelbach et al., 2002; Seelbach & Wiley, 2005). Higgins et al. (1999) referred to units of this type as fish macrohabitats. Ecological valley segments combine elements of local valley and channel geomorphology with catchment hydrology, the two dominant forces shaping riverine habitats. This approach is conceptually similar to the hydrogeomorphic 'HGM' concept used in wetland assessment (Hauer & Smith, 1998). The MREMS system identifies 138 distinct channel units in the Muskegon River, ranging from first to fifth order. Major reservoirs and Muskegon, Houghton, Mitchell-Cadillac, and Higgins lakes are included as separate VSEC units. In MREMS simulations, while basic computational resolution of constituent models varies, each directly or indirectly (via a post-processing) provides output for all 138 segments. The VSEC unit map then serves as the underlying skeleton on which model input and output is organized. Models communicate by placing spatially referenced outputs into a structured directory system that is organized by specific timeframe (simulation year) and problem context (scenario). A complete MREMS run for a specific scenario involves the serial execution of the set of component models (Table 1, Fig. 2) for each time frame, using links to scenario-specific inputs and outputs. In many cases, the output written by one model may be used as input by the next. Model execution order is determined by data dependency, thus execution order would typically start with the generation of a land cover map, followed by hydrologic, chemical and sediment loading, reach hydraulics (for key fisheries habitats) and finally biological models.

Overview of component models

Two climate scenarios were used in the simulations described below. A *standard climate scenario* was based on observed weather across the Muskegon watershed from 1980 to 2005 (Andresen, 2007; MAWN, 2008; NCDC, 2008) along with NEXRAD distributed precipitation (Fulton et al., 1998), along with a solar radiation model prior to the availability of such data (Yang & Koike, 2005). Hourly measured and simulated values from each gauge were distributed across the basin into 425 m grids using an inverse distance weighted interpolation. Beginning in 1996, NEXRAD data, at 4 km resolution, replaced interpolated gauge values provided that air temperatures are not below 0°C due to calibration issues with the radar-derived frozen precipitation data (Jayawickreme & Hyndman, 2007). A *climate change scenario* for the end of this century was then constructed from the standard climate scenario using A1B scenario model results from the Fourth IPCC Assessment (Meehl et al., 2007). A1B is a "conservative" forecast and assumes a peak of greenhouse gas emissions near mid-century, followed by modest reduction in emissions through 2100 (Nakicenovic, 2000). The IPCC regional model provided predicted anomalies by month for average daily temperature

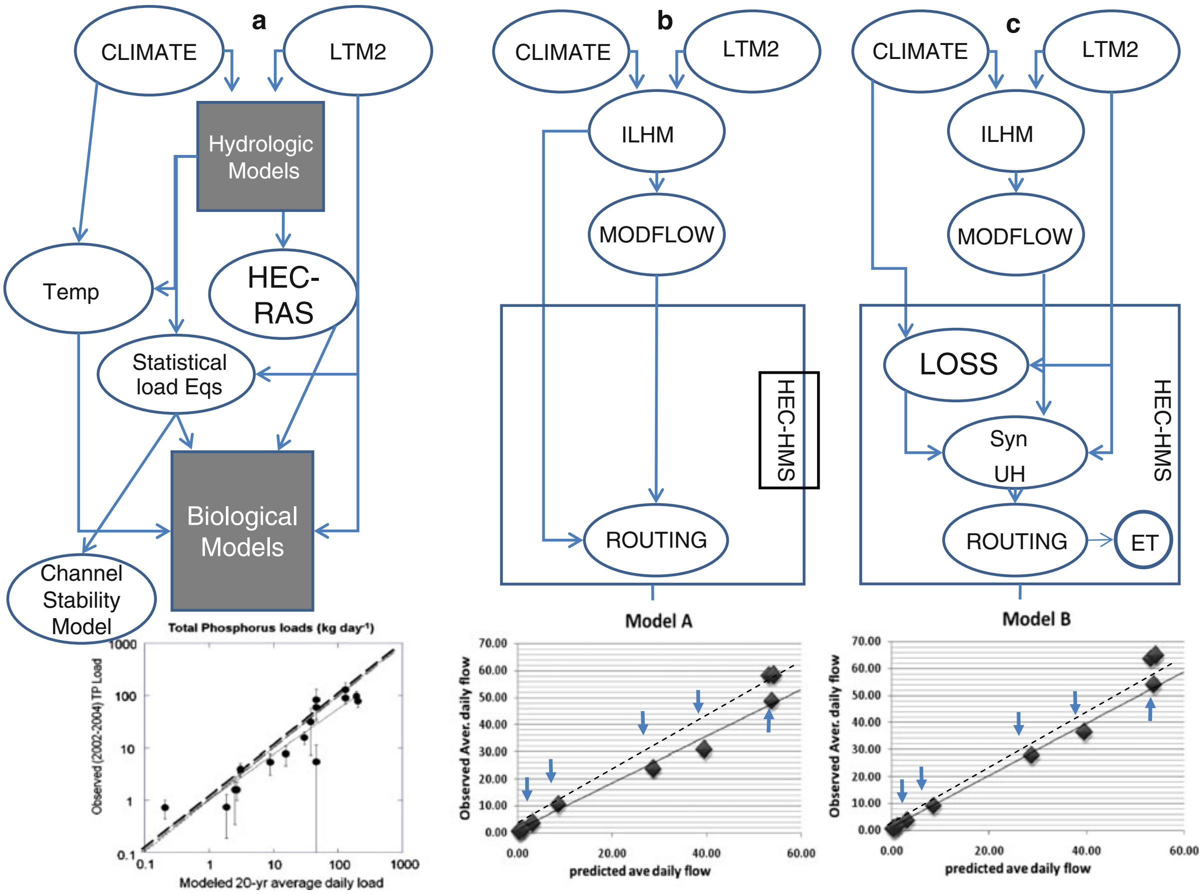

Fig. 2 MREMS multi-model organization. **a** Overall model structure. Climate and Land cover models drove multiple (shaded box) distributed hydrologic model variants to produce a series of 20-year basin-wide flow estimates. These in turn were used to model temperature, hydraulics, material loading, channel stability, and a suite of biological responses (*shaded box*) using models listed in Table 1. Data below show predicted and observed annual average TP loads for 14 Muskegon River sites sampled during 2002–2004; dashed line is the one-to-one ratio, verticals represent sample variance as ±2 standard errors. Predicted values are from model runs using hydrologic variant 2c (below) and are computed from linked outputs of seven sub component models. **b** Example of one of the simpler hydrologic simulation variants ("cr0") based on a linked ILHM and MODFLOW implementation with channel routing managed by HEC-HMS. Of the four variants, this was the most mechanistically tractable, carefully preserving hydrologic mass-balance in every computational step. Data plotted below it show predicted and observed annual average daily discharge (cms) at five permanent (*arrows*) and several other short-term gauging stations; *dashed line* is the one-to-one ratio. **c** Hydrologic simulation variant ("m×4") which linked ILHM recharge and MODFLOW groundwater estimates with surface water models managed by HEC-HMS. Data below show predicted and observed annual average daily discharge (cms) at five permanent (*arrows*) and short-term gauging stations; *dashed line* is the one-to-one ratio. This was the best performing of the variants and was used in all of the physical and biological response estimates reported here

and total daily precipitation. The regional model was downscaled for our runs by using its' predicted anomalies to "offset" our higher resolution "standard climate model" values. The resulting climate change scenario model is on average both warmer and wetter than our standard climate model. It retains, however, the substantial east–west spatial variability of the standard model reflecting strong attenuation of lake-effect thermal buffering and precipitation.

In MREMS modeling, land use/land cover estimates are based on 1:24,000 air photo mapping for 1978 and 1998, and on projections of future land cover developed for this study using the neural-net based Land Transformation Model v.3 (LTM:

Table 1 Component models linked in MREMS and used in analyses reported here

Model	Predicts	Type	References
LTM v.3	Land use change over time	Suite of linked neural net and linear models	Pijanowski et al. (2002a, 2005)
ILHM	Evapo-transpiration, recharge, runoff, soil moisture storage, snow dynamics	Process-based distributed, high resolution (120 m^2 grids) simulation	Hyndman et al. (2007) and Kendall & Hyndman (in review)
MODFLOW	Water table elevation, Groundwater flows	Standard FORTRAN codes	Harbaugh et al. (2000)
MRI_VSEC 1.0	Basic channel segment and contributing basin physical attributes	National hydrography-based GIS layer with empirical and model-based attribution	Seelbach et al. (1997, 2006), Seelbach & Wiley (2005)
HEC-HMS	Surface water routing	Hydrologic simulation system	USACE (2009a, b)
HEC-RAS	Surface water hydraulics	1D hydraulic simulation system	USACE (2009a, b)
MRI_LOADS, DOMQ	Flow-dependent dissolved, suspended, and bed loads and channel stability	Regional regression models	Baker et al. (2001), Ladewig (2006), Benson & Thomas (1966)
RPSTM	Daily water temperature statistics by reach	Reduced –parameter energy balance with channel routing	Cheng (unpublished)
GLGAP-SFM	Reach suitability for key fish species	Regional CART classification model for river segments	Steen et al. (2006, 2010)
MRI bioassessment models	Probability of ecological impairment by reach	CART reach classification model based on regionally normalized assessment	Wiley et al. (2002) and Riseng et al. (2006)
DWUA	Life-stage specific weighted useable area analyses	HSI analysis from HEC-RAS output	Raleigh et al. (1984) and Tyler (unpublished)

Pijanowski et al., 2000, 2002a, b, 2005). LTM has been widely used in the United States, Africa, and Europe for forecasting and backcasting land cover distributions in ecological planning contexts (Pijanowski et al., 2006, 2007). LTM spatially distributes prescribed county-level rates of land use transitions using neural networks to train on the relationship of surrogates to drivers of land use change. The model was calibrated using standard land change goodness of fit statistics (Pontius et al., 2008). Working with a group of regional stakeholders, we explored a series of different land management scenarios as a part of the Muskegon watershed integrated assessment (Stevenson et al., 2008). Joint stakeholder-modeler workshops developed a series of land management scenarios to evaluate potential management strategies of particular interest to the watershed stakeholders (including urban sprawl containment, riparian set-back rules, and agricultural land preservation). For each scenario, a series of land cover projections was developed covering the period 2000 to 2090 by constraining LTM runs with scenario-appropriate land transformation rules. Of the 13 primary management scenarios produced, four have been evaluated for sensitivity to climate change to date.

Here we report some of the results from the first two land management scenario analyses (Fig. 1). In our Business as Usual (BAU) scenario, a baseline future landscape reflects a continuation of the average rates of urban and forest growth observed from 1978 to 1998. In the BAU Scenario urban and forest land expansions occur at the expense of agriculture, and farming in this version of the future continues to decline steadily across the watershed, a pattern observed in this basin since the 1920s. In our Reduced Urban Sprawl (RUS) scenario, the LTM halved the region's historic rate of urban sprawl, and allowed forest re-growth to continue at a relatively high rate. The reduced rate of urban sprawl led to reduced extent of urbanization which in turn left more agriculture in place at the end of the 21st century.

Hydrologic forecasting was based on an ensemble of four variant simulations that linked a series of existing simulation modules including ILHM, MODFLOW, a regional synthetic hydrograph model, and HEC-HMS channel routing (examples in Fig. 2b and c). The Integrated Landscape Hydrology Model (ILHM; Hyndman et al., 2007; Kendall & Hyndman, in review), is a high resolution, distributed model developed to evaluate influences of both land use and climate on hydrology at scales pertinent to land managers. ILHM simulates all major surface and near-surface hydrologic processes including evapotranspiration (ET), snowmelt, groundwater recharge, overland flow, and stream discharge. Moisture is redistributed from precipitation to various subsurface and surface pathways, including canopy interception, snowmelt, surface depression storage, infiltration, evapotranspiration, throughflow, recharge, and stream routing. Input for the model consists of gridded topographic, climate, land cover, leaf area index (LAI), and other available information about the distribution of soils and glacial sediments. In the simulations, ILHM recharge estimates were linked to MODFLOW codes (Harbaugh et al., 2000) to estimate groundwater flux and accruals to tributary sub-basins. In two ensemble variants runoff estimates from ILHM were combined with MODFLOW estimates for each model sub-basin and then routed through the channel system. These variants represented the most mechanistically realistic of the four hydrologic simulations and included a version (Fig. 2b) which maintained a strict hydrologic mass-balance throughout all calculations. In the other two ensemble variants MODFLOW groundwater flux was combined with calibrated estimates of runoff from a regional synthetic unit hydrograph model (Fig. 2c) for downstream routing after corrections for calibrated estimates of riparian wetland and reservoir ET losses. Channel routing, data summary, and output management in all four model variants was handled in HEC-HMS v3.1.0 (USACE, 1998). Each model variant provided daily channel flows at each of the 138 VSEC river segments throughout the basin. Validation tests indicated that the most accurate ensemble variant ("mx4", Fig. 2c) predicted historical water balances for the five USGS gauged locations in the Muskegon basin within 5% of measured values over the 10-year simulation period (1996–2005). All four of the model variants frequently over-predicted flows in the lowest zone of freshwater estuary where backwater effects were common. In this paper, we used the most accurate of the hydrologic ensemble simulations to drive all subsequent loading and biological models as reported here. We used the entire ensemble of hydrologic forecasts to explore model variance and error bounds around modeled hydrologic and loading responses (see "Discussion" section).

Sediment and nutrient loads were estimated by linking hydrologic and land cover simulation outputs to a series of empirical "instantaneous" load regression models developed from state-wide data sets as part of the Michigan Rivers Inventory program (Seelbach & Wiley, 1997). Similar in general approach to the USGS SPARROW model (Schwarz et al., 2001), the loading regressions typically explained 85–90% of the N and P flux from sample catchments; and simulated load estimates for the Muskegon were well correlated (e.g., Fig. 2a) with observed fluxes measured during 2002–2004. Daily average concentrations were estimated as the ratio of daily loads to daily discharges. Changes in river channel stability were assessed for each river segment in terms of relative deviations from baseline (1980–2005) dominant discharge (Knighton, 1984) magnitudes. When deviations above or below baseline values exceeded 20%, stream segments were flagged as unstable and therefore likely to respond geomorphically. Increasing dominant discharge is associated with more channel and bank erosion, and sediment transport. Decreasing dominant discharge is typically associated with channel aggradation, and local bed sediment accumulation. Both conditions can initiate complex responses in terms of meander re-configuration, slope adjustment, and changes in bed material composition and structure (Schumm, 1977; Knighton, 1984).

Daily water temperatures for each VSEC unit were estimated using a new reduced parameter energy balance and channel routing model (RPSTM; Cheng & Wiley, 2007; Cheng, unpublished). Linked to HEC-HMS the model uses sub-basin groundwater flux from ILHM and runoff routing from HMS to estimate daily minimum, maximum, and mean temperature at the beginning and end of each HMS hydrologic routing unit.

We modeled the responses of the Muskegon River invertebrate and fish community to changing climate and land management trajectories by linking an ensemble of biological models to output from the physical modeling portions of MREMS. Building on earlier work in which simple summer air temperature offsets were added to regional habitat models (Steen et al., 2010) we linked these and other models with spatially explicit predictions of water temperature, stream flow, and water quality driven by statistically downscaled changes in precipitation and temperature. Biological response models used in these simulations include: multiple linear regression-based normalized assessment models for fish and macroinvertebrate communities (Wiley et al., 2002; Riseng et al., 2006) forecast for individual river segments using Bayesian probabilities from a CART (De'ath and Fabricius, 2000) analyses of a large sample of observed assessment scores ($n = 2000$; Riseng et al., 2006), Classification and Regression Tree (CART) models of sport fish habitat (Steen et al., 2006, 2010), dynamic weighted usable area models (DWUA) of sport fish habitat (e.g., Gouraud et al., 2001) and an agent-based model of steelhead (Oncorhyncus mykiss) recruitment dynamics (e.g., Tyler and Rutherford, 2007).

For the DWUA model and individual-based steelhead modeling, we focused on the approximately 40 km section of the lower Muskegon River immediately downstream of Croton Dam, a key fishery resource, and divided the section into cells for hydrological analysis (depth, flow velocity) by a one-dimensional channel routing model (HEC-RAS). A GIS model of river substrate was paired to the HEC-RAS grid of the river segments so that each cell of the river model included water depth, water velocity, and substrate characteristics that could be used to determine cell-by-cell habitat preferences for life stages of selected sport fishes. For the DWUA model, fish life stage habitat preferences were computed for each river cell based on habitat suitability indices (HSI) (e.g., Raleigh et al., 1984), which use known information on habitat preferences for a particular species-life stage combination to predict the amount of suitable habitat available in an aquatic environment for that life stage (USFWS, 1980). Species preference values for habitat variables range 0.0–1.0 for each variable. To compute the WUA for a cell, we multiplied the preference value (P) assigned for each environmental characteristic in the cell times the area of the cell. In results reported here integration with MREMS climate change scenario outputs for these two models included mean monthly temperature but not the hydrologic responses. Fully integrated runs of the DWUA and the steelhead IBM are currently underway.

Results

Both climate change and land management scenarios altered modeled hydrologic, water quality, geomorphic, and biological conditions across the Muskegon River watershed compared to current conditions. Pairwise contrasts (alternate climate change scenarios × alternate land management scenarios) suggest that the impact of climate change on this river system will not only be large, but also that response will vary significantly depending upon future land use trajectory.

Land use change scenarios under current climate

Projected changes in land cover had significant effects on the distribution of predicted flows in the watershed (Tables 2 and 3) and as a result over many other ecologically important characteristics of the modeled river ecosystem. Under the current climate regime, the BAU scenario led to future reductions in agriculture and forested land cover, reduced ET losses and increased both rates of groundwater recharge and storm runoff. As a result base flow, storm flow, and median discharge all increased in the lower main stem by 15–20% (Table 2) and across most of the rest of the watershed as well (Table 3); flow variability across the basin increased by 30%. Increases in the dominant discharge exceeded 20% in the lower main stem and in many other VSEC units suggesting wide spread channel destabilization would occur. Consistent with this, the loading model projected large increases in sediment loads for almost all sites (26% and 57% for mean and standard error, respectively). Increases in urban cover and associated flows, appear to cause an even larger increase in nutrient loads. Daily mean total phosphorus (TP) loads increased on average by 53% and daily total inorganic nitrogen (TIN) loads increased by 31% (Table 3). Nutrient concentrations (Table 4), however, appear to be somewhat buffered by the increasing flows and on average increased by only 32% and 12% for TP and TIN, respectively. Water temperature changes were minimal, tending to slightly lower driven by increases in groundwater flux to the river, but this assumes constant a groundwater temperature.

The RUS scenario also resulted in major losses of agricultural land cover, but in contrast to the BAU scenario it also had increases in forest cover

Table 2 Modeled flow statistics for the lower main stem Muskegon River (terminal VSEC unit) at its confluence with Muskegon Lake

Climate scenario:	Current	Current				IPCC A1B adjusted			
Land use scenario:	Current	BAU		RUS		BAU		RUS	
Parameter:	(cms)	(cms)	(%Δ)	(cms)	(%Δ)	(cms)	(%Δ)	(cms)	(%Δ)
Q05	105	124	18.1%	105	0.0%	128	21.9%	112	6.7%
Q10	88	101	14.8%	87	−1.1%	108	22.7%	95	8.0%
Q50	53	63	18.9%	58	9.4%	70	32.1%	65	22.6%
Q90	37	45	21.6%	41	10.8%	48	29.7%	46	24.3%
Qmin	23	26	13.0%	25	8.7%	29	26.1%	31	34.8%
Qmax	808	851	5.3%	793	−1.9%	957	18.4%	896	10.9%
DomQ	52	63	21.2%	60	15.4%	71	36.5%	61	17.3%
Basin land cover (%)									
Urban	6	34	466%	23	283%	34	466%	34	283%
Agricultural	18	5	−72%	5	−72%	5	−72%	5	−72%
Forested	56	52	−7%	61	9%	52	−7%	52	9%
Water and wetlands	8	8	0%	9	12%	8	0%	8	12%
Other	12	1	−92%	2	−83%	1	−92%	1	−83%

Summaries are over the modeled 25 year period (nominally 1980–2005). Current climate scenario coupled with current land use scenario provide baseline conditions. %Δ = percent change from baseline. Land use scenarios as described in the text and Fig. 1 (Current = 1998, BAU = end of century with business as usual land management; RUS = end of century with reduced urban sprawl rate). Q05-Q90 are daily flow exceeded values for indicated percentiles. DomQ = estimated dominant discharge for the period

(Table 2). Reductions in agricultural land cover again led to increases in recharge and base flow, but these were less than half the magnitude observed in the BAU scenario. However, high flows changed little and were even reduced relative to simulations based on current land cover; resulting on average in a more seasonally stable flow regime (Tables 2 and 3). Despite this general increase in flow stability, future dominant discharge still increased for many stream segments because of increasing base flows; but, increments in sediment load transported were about half those estimated for the BAU scenario. TP loads and concentrations changed little from current values, and were much reduced relative to the BAU forecasts. However, the projections based on the RUS scenario show marginally larger TIN loads than in the in BAU scenario (Table 4) reflecting more agricultural land use in the basin.

Landuse change scenarios under the A1B climate change scenario

Adding climate change to the Muskegon ecosystem forecasts dramatically altered most modeling results. Increasing air temperatures resulted in increased ET estimates across the basin. However, increasing precipitation, particularly during winter months led to even larger increases in recharge rates; the overall result being that water yields and flows in the river generally increased (Tables 2 and 3). The hydrologic impact was largest on the BAU land use scenario (roughly doubling % change in median and lower frequency water yields), but flow increases were also observed in the RUS case. Under the RUS × Climate Change scenario, average annual flows were essentially equivalent to the BAU scenario flows under the Current Climate scenario. For both land use scenarios, dominant discharge increased with respect to baseline, compared to land use change scenarios alone. Consistent with that result, sediment concentrations generally declined slightly (−7.8 ± 5.8%), but sediment loads and yields increased by about 50% for the BAU scenario and doubled for the RUS scenario. Nutrient concentrations changed little from the current climate scenario runs, but nutrient loads and yields increased for both TIN and TP. The relative impact of the A1B climate was higher on nutrients in the RUS scenario, with the change in

Table 3 Summary of modeled average daily load statistics for 138 VSEC channel units of the Muskegon River ecosystem

Climate scenario:	Current	Current				IPCC A1B adjusted			
Land use scenario:	Current	BAU		RUS		BAU		RUS	
Parameter:			(%Δ)		(%Δ)		(%Δ)		(%Δ)
Channel flow, ave. daily flow (cms/km^2)									
Median	0.0089	0.0108	21.3%	0.0098	10.1%	0.0116	30.3%	0.0108	21.3%
Mean	0.0094	0.0113	20.2%	0.0102	8.5%	0.0123	30.9%	0.0111	18.1%
SE	0.0002	0.0003	50.0%	0.0002	0.0%	0.0003	50.0%	0.0002	0.0%
Min	0.0006	0.0017	183.3%	0.0016	166.7%	0.0019	216.7%	0.0017	183.3%
Max	0.0519	0.0586	12.9%	0.0496	−4.4%	0.0600	21.4%	0.0530	2.1%
Total phosphorus flux, ave. daily load (kg/km^2)									
Median	26	36	38.5%	27	3.8%	39	50.0%	30	15.4%
Mean	30	46	53.3%	32	6.7%	50	66.7%	35	16.7%
SE	2	1	−50.0%	1	−50.0%	2	0.0%	1	−50.0%
Min	1	4	300.0%	3	200.0%	4	300.0%	4	300.0%
Max	457	197	−56.9%	152	−66.7%	214	−53.2%	164	−64.1%
Total inorg. nitrogen flux, ave. daily load (kg/km^2)									
Median	350	568	62.3%	447	27.7%	613	75.1%	532	52.0%
Mean	409	534	30.6%	491	20.0%	575	40.6%	529	29.3%
SE	14	11	−21.4%	11	−21.4%	12	−14.3%	12	−14.3%
Min	17	86	405.9%	77	352.9%	93	447.1%	84	394.1%
Max	2762	2175	−21.3%	1901	−31.2%	2324	−15.9%	2024	−26.7%
Total sediment flux, ave. daily load [kg/km^2]									
Median	72	88	22.2%	81	12.5%	98	36.1%	86	19.4%
Mean	183	230	25.7%	200	9.3%	251	37.2%	219	19.7%
SE	23	36	56.5%	30	30.4%	40	73.9%	33	43.5%
Min	4	5	25.0%	4	0.0%	5	25.0%	5	25.0%
Max	4974	8060	62.0%	6030	21.2%	9064	82.2%	6864	38.0%

Current climate scenario coupled with current land use scenario provide baseline conditions. %Δ = percent change from baseline. Summaries are over a modeled 25 year period (nominally 1980–2005), land use scenarios as described in the text and Fig. 1 (Current = 1998, BAU = end of century with business as usual land management; RUS = end of century with reduced urban sprawl rate)

median TP flux increasing from 3.5% to 15.4%, and TIN from 28% to 52%. This contrasts with the BUA scenario results that changed from 38% to 50%, and from 62% to 75% for TP and TIN, respectively (Table 3). Impacts of the climate change scenario on water temperature were large and pervasive. Although increased recharge drove somewhat higher rates of groundwater accrual and baseflow in the river (normally associated with lower temperature; Wiley et al., 1997), groundwater temperatures at this latitude strongly reflect annual average air temperature. The net effect was a 15–16% and 13–14% increase in mid-summer (July) daily average and daily maximum water temperatures, respectively. Perhaps most importantly, these changes occurred across the range of temperatures, 21–25°C, that generally define habitat transitions for Michigan's cold, cool, and warm-water fish guilds (Wehrly et al., 2003).

Modeled impacts of the climate change scenario on biological parameters varied substantially (Table 5). Community-based (fish and macroinvertebrate) assessment metrics, which responded strongly to land use scenarios, were relatively insensitive to the climate scenario. Under the BAU scenario, the invertebrate metric results suggested a slight improvement basin-wide. Under the RUS scenario, the reach impairment rate for invertebrates worsened

Table 4 Summary of modeled water quality statistics (mean annual concentration values) for 138 VSEC channel units in the Muskegon River ecosystem

Climate scenario:	Current	Current				IPCC A1B adjusted			
Land use scenario:	Current	BAU		RUS		BAU		RUS	
Parameter:			(%Δ)		(%Δ)		(%Δ)		(%Δ)
July water temp (°C)									
Mean	22.6	22.2	−1.8%	22.1	−2.2%	26.2	15.9%	26.1	15.5%
Max	25.7	25	−2.7%	24.9	−3.1%	29.2	13.6%	29	12.8%
SE	0.193	0.190	−1.6%	0.186	−3.6%	0.200	3.6%	0.193	0.0%
Total phosphorus ave. daily concentration (ppm)									
Median	0.025	0.036	44.0%	0.027	8.0%	0.034	36.0%	0.027	8.0%
Mean	0.028	0.037	32.1%	0.029	3.6%	0.037	32.1%	0.029	3.6%
SE	0.000574	0.000829	44.4%	0.000639	11.3%	0.000828	44.3%	0.000645	12.4%
Min	0.002	0.005	150.0%	0.001	50.0%	0.005	150.0%	0.004	100.0%
Max	0.083	0.094	13.3%	0.063	24.1%	0.094	13.3%	0.062	−25.3%
Total inorg. nitrogen ave. daily concentration (ppm)									
Median	0.396	0.454	14.6%	0.457	15.4%	0.43	8.6%	0.443	11.9%
Mean	0.401	0.448	11.7%	0.463	15.5%	0.438	9.2%	0.454	13.2%
SE	0.007489	0.003295	−56.0%	0.000761	89.8%	0.00268	−64.2%	0.005071	−32.3%
Min	0.09	0.195	116.7%	0.17	88.9%	0.192	113.3%	0.163	81.1%
Max	1.174	0.651	−44.5%	0.879	25.1%	0.633	-46.1%	0.863	−26.5%
Total sediment ave. daily concentration (ppm)									
Median	96	95	−1.0%	95	−1.0%	96	0.0%	95	−1.0%
Mean	218	202	−7.3%	201	−7.8%	203	−6.9%	201	−7.8%
SE	34	34	0.0%	33	−2.9%	34	0.0%	33	−2.9%
Min	8	8	0.0%	8	0.0%	8	0.0%	8	0.0%
Max	9029	8957	−0.8%	8763	−2.9%	8933	−1.1%	8747	−3.1%

Current climate scenario coupled with current land use scenario provide baseline conditions. %Δ = percent change from baseline. Summaries are over a modeled 25 year period (nominally 1980–2005). Land use scenarios as described in the text and Fig. 1 (Current = 1998, BAU = end of century with business as usual land management; RUS = end of century with reduced urban sprawl rate)

slightly. The fish community metric likewise indicated a small worsening of basin conditions for both land use scenarios (increasing by only about 4% in both cases). Impacts on individual fish taxa, however, were substantial and variable (Table 5, Fig. 3). Brook trout (*Salvelnis fontinalis*) were most negatively affected losing >60% of their currently available channel habitat. Resident (nonanadromous "steelhead") rainbow trout (*Orchorynchus mikus*) lost more than 30% of their habitat and brown tout (Salmo trutta) more than 15%. Lower river habitat supporting Lake Michigan and Muskegon-run salmonines were substantially impacted, although individually the extent varied depending largely on life cycle timing. Coho salmon were most negatively affected (climate-related reductions were >70%). Chinook salmon (*Onchorynchus tshawytscha*) and steelhead were relatively less sensitive but still were forecast to experience greater than 50% reductions in habitat availability. The species most sensitive to this climate change scenario was the northern pike (*Esox lucius*) which the CART models projected would experience close to a doubling of habitat in the Muskegon river. Smallmouth bass (*Micropterus dolomeiui*) also were predicted to benefit substantially (+24%). Walleye pike (*Sander vitreus*), an important sport fish in the larger lakes and lower main stem, were relatively insensitive to the climate change scenario. In almost

Table 5 Summary of GLGAP-SFM modeled sport fish habitat responses (km of useable habitat) in the entire Muskegon River basin

Climate scenario:	Current	Current				IPCC A1B adjusted				Average climate sensitivity
Land use scenario:	Current	BAU		RUS		BAU		RUS		
Taxa	(km)	(km)	(%Δ)	(km)	(%Δ)	(km)	(%Δ)	(km)	(%Δ)	(%Δ)
Smallmouth	501	515	3%	497	−1%	627	25%	622	24%	24
Brook_trout	1030	984	−4%	1038	1%	348	−66%	410	−60%	−61
Brown_trout	1516	1586	5%	1549	2%	1263	−17%	1277	−16%	−20
Rainbow_trout	1656	1612	−3%	1630	−2%	1067	−36%	1080	−35%	−33
Steelhead	315	438	39%	438	39%	270	−14%	261	−17%	−55
Chinook	112	223	99%	228	103%	165	47%	171	52%	−51
Coho	120	143	19%	141	18%	55	−54%	53	−55%	−74
Walleye	216	167	−23%	218	1%	179	−17%	201	−7%	−1
GLwalleye	55	35	−36%	64	18%	41	−24%	51	−6%	−6
Northern_pike	548	578	5%	551	1%	1026	87%	995	81%	27
	(proportion)	(proportion)		(proportion)		(proportion)		(proportion)		
Adfl.salmonines	0.064	0.094	47%	0.094	48%	0.057	−10%	0.057	−0.11	−58
All coldwater	0.278	0.292	5%	0.294	6%	0.185	−33%	0.190	−0.32	−38
All warmwater	0.116	0.114	−2%	0.117	1%	0.164	42%	0.164	0.416	42
All trouts*	0.491	0.489	0%	0.493	0%	0.313	−36%	0.324	−0.34	−35
All walleye	0.106	0.035	−67%	0.049	−53%	0.039	−63%	0.044	−0.58	−1
Fish comm'ty impaired	0.185	0.416	125%	0.324	75%	0.423	129%	0.330	0.784	4
inv. comm'ty impaired	0.111	0.293	163%	0.189	70%	0.291	161%	0.196	0.758	2

Current climate scenario coupled with current land use scenario provides baseline conditions. %Δ = percent change from baseline. Summaries are over a modeled 25-year period (nominally 1980–2005), Land use scenarios as described in the text and Fig. 1 (Current = 1998, BAU = end of century with business as usual land management; RUS = end of century with reduced urban sprawl rate). Smallmouth bass = *Micropterus dolomieui*; brook trout = *Salvelinus fontinalus*; brown trout = *Salmo trutta*; rainbow trout = stream-resident *Oncorhynchus mykiss*; steelhead = adfluvial *O.mykiss*; Chinook = *O. tshawytscha*; coho = *Oncorynchus kisutch*; walleye = all *Sander vitreus*; GLwalleye = Lake Michigan/Muskegon Lake resident *Sander vitreus*; northern pike = *Esox lucious*; adfluv. Salmonines = all spp of *Oncorhynchus* spp.

all cases, biological responses to the climate change scenario were less severe under the RUS than the BAU land management scenario which was associated with more severely reduced forest and agriculture. The BUA land use provided some thermal buffering due to increases in groundwater flows. This effect was, however, quite modest (preserving 6–9 km of otherwise lost main stem habitat).

Results of the dynamic weighted useable area modeling (DWUA) in the lower mainstem river were similar to the CART modeling results but did show some striking differences between juvenile and adult habitat. Useable habitat for juvenile and adults life stages of smallmouth bass, walleye, Chinook salmon and steelhead declined from 10% to 34% under the BAU scenario, and slightly less (0–33%) under the RUS (Table 6). In contrast, under the climate change scenarios habitat for warmwater and coolwater fishes was dramatically increased (+124 to 252% for smallmouth bass; 41–427% for walleye) and decreased for adult stages of coldwater species (Chinook salmon, steelhead) and juvenile steelhead. Useable habitat for juvenile Chinook salmon was predicted to increase under climate change due to an increase in spring temperatures (Table 6).

Discussion

MREMS scenario simulations indicated that climate change impacts on the Muskegon river ecosystem

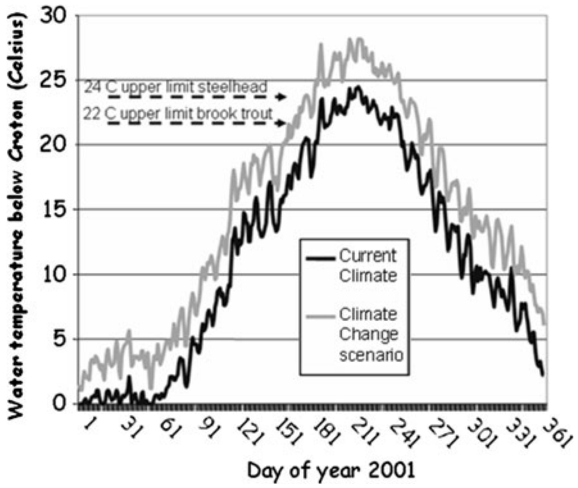

Fig. 3 The IPCC A1B-modified scenario raised groundwater and temperatures in our models by several degrees shifting water temperatures in many channel segments across critical thermal thresholds for coldwater species. The example here is for channel unit VSEC 18, a critical spawning reach for adfluvial steelhead trout below a major hydropower dam in the lower part of the Muskegon main stem. With late summer temperatures currently too high for brook and marginal for steelhead trout due to reservoir warming, climate change scenarios pushed summer temperatures above levels tolerated by either species and removed much of the lower mainstem as useable summer habitat

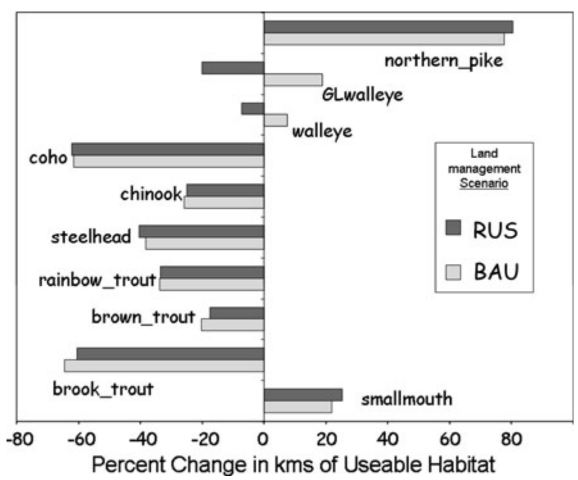

Fig. 4 Basin-wide changes in habitat availability (kms of channel) for key sport fishes based on the BAU and RUS × IPCC A1B adjusted climate scenarios

will likely be pervasive, but also variable depending upon future land use trajectories. Significant reductions in negative impacts on hydrology, water quality, and biological communities were associated with the highly forested future landscape produced in the RUS management scenario. This result suggests that traditional watershed management tools like land use planning could play an important role in developing climate adaptation strategies of the kind being promoted by IPCC and national governments (NRC, 2007; IPCC, 2007). However, even with the clearly preferable outcomes associated with the RUS scenario, the scale of ecological change projected was dramatic. Under the best-case RUS scenario, 57% of the Muskegon channel system would be destabilized by the end of this century; the BAU scenario modeling estimate was 76%. The same increase in river flows that lead to large-scale destabilization also drove 20–30% increases in sediment and nutrient loading (40–60% for the BAU scenario). The magnitude of these responses reflects the potency of climate impacts on river hydrology. Discharge rate is the principal organizing variable in fluvial systems (Schumm, 1977; Knighton, 1984); in rivers, ecological responses to future climate change will be necessarily linked to hydrologic response, and to the local details of basin geography, land use, and surficial geology that control hydrologic routing.

The Muskegon River, and most of the upper Great Lakes Basin, lies just south of the snow fall dominated northern latitudinal zone (50–80 N) where most GCMs predict increasing rainfall and net gains in annual river runoff (Palmer et al., 2008; Arnell, 2005; Nohara et al., 2006). The Great Lakes themselves complicate climate forecasting in this region and local anomalies associated with lake-effect dynamics are poorly represented in currently available GCMs (Lofgren et al., 2002; Croley, 2005). What is already clear is that the Muskegon basin has historically been strongly influenced by lake-effect precipitation (Kendall & Hyndman, in review), and that long-term gauging records for the region indicate increasing trends in rainfall and river discharge since the turn of the last century (Arnet, 2005; Dore, 2005). Relatively high annual rates of precipitation (up to 93 cm) on a landscape dominated by highly permeable glacial drift supports efficient recharge dynamics (Holtschlag, 1994; Boutt et al., 2001; Hyndman et al., 2007), high base flows and a characteristically cold and cool-water ecology for which the rivers of the northern lower Michigan Peninsula are well known (Wiley et al., 1997; Seelbach et al., 2006).

Table 6 Summary of dynamic weighted usable area habitat model (DWUA) and individual-based model (IBM) of sportfish in the lower Muskegon River, below Croton Dam

Climate scenario:	Current	Current				IPCC A1B adjusted			
Land use scenario:	Current	BAU		RUS		BAU		RUS	
Taxa/life stage:	(ha)	(ha)	(%Δ)	(ha)	(%Δ)	(ha)	(%Δ)	(ha)	(%Δ)
Juvenile WUA									
Smallmouth	4.10	3.55	−14%	3.88	−5%	7.96	94%	8.88	116%
Chinook	1.44	0.95	−34%	0.97	−33%	1.34	−07%	1.43	−01%
Steelhead	6.97	7.69	10%	6.93	−1%	3.80	−45%	3.27	−53%
Adult WUA									
Smallmouth	1.09	0.89	−18%	1.00	−9%	3.14	188%	3.62	232%
Chinook	4.74	5.36	13%	4.35	−8%	1.35	−72%	1.16	−76%
Steelhead	51.93	48.95	−6%	52.07	0%	45.70	−12%	44.4	−15%
Walleye	0.33	0.28	−17%	0.27	−18%	1.31	336%	1.44	336%

Current climate scenario coupled with current land use scenario provides baseline conditions. %Δ = percent change from baseline. Summaries are over a modeled 25-year period (nominally 1980–2005). Land use scenarios as described in the text and Fig. 1 (Current = 1998, BAU = end of century with business as usual land management; RUS = end of century with reduced urban sprawl rate). Smallmouth bass = *Micropterus dolomieui*; steelhead *Oncorhynchus mykiss*; Chinook salmon = *O. tshawytscha*; walleye = Lake Michigan/Muskegon Lake resident *Sander vitreus*. The steelhead IBM outputs are in number (No.) and mean length (mm TL) of age-0 individuals surviving to Oct 31 in a model year

In this largely groundwater driven river, our hydrologic models predicted both increasing groundwater and increasing runoff deliveries to the channel system under the IPCC A1B scenario. Other modeling studies for the region have variably reported annual mean flow increases (Lofgren, 2004, Palmer et al., 2008), decreases (Croley, 2005), or both depending on specifics of the climate change modeling (Lofgren et al., 2002). Uncertainties associated with variously designed GCMs, parameterizations particularly in the GL region remain large at the present time (Kling, et al., 2003; Palmer et al., 2008; Lofgren, 2006). Our purpose in this analysis was not to explore implications of that climate uncertainty but instead to examine in more local detail the implications of a typical climate change scenario on the local river ecosystem characteristics. The hydrologic responses we observed from our models (∼ 20–30% increases) were roughly consistent with the regionally comparable analyses of Palmer et al., (2008) and Lofgren (2004) who estimated river flow increases in this region of up to 0-40%, and 15%, respectively. What our analysis adds is the clear implication that (1) land use patterns can modulate hydrologic and related loading responses to climate change, and (2) that, as a result, the ecological consequences of climate change in river systems will be inextricably linked to ongoing decisions about the management of landscapes and fisheries, as well as dams (Palmer et al., 2008) and consumptive water use (Croley & Luukkonen, 2003).

Sources of variation and uncertainty

Forecasting ecosystem responses to future change is necessarily risky business. Uncertainty about the magnitude and even direction of modeled system response to land use or climate change could arise from errors in model representation (specification error, parameterization error, or computational error) and from patterns in propagation of those errors including their statistical inflation through the series of sequential estimations inherent in a multi-modeling system. Furthermore, there is substantial "real" spatial and temporal variability in the dynamic responses of river systems which reflects underlying geographic differences in geology, land cover, drainage history, antecedent moisture conditions, etc.; these too add substantial uncertainty to any overall interpretation of system response. We have not to date carried out any formal study of error propagation characteristics in the MREMS system. Validation studies comparing predicted and observed values from the 2002–2004 field seasons generally (as in Fig. 2) indicate the system does an adequate job (correlations typically > 0.9 for physical parameters, >0.6 for biological parameters) representing spatial variability over the watershed. A detailed comparison of MREMS hydrologic variants with a Muskegon River implementation NOAA's DLBRM (Kao et al. unpublished; for model description see Croley, 2005) showed that the MREM' "mixed" model variants more accurately captured long-term average flows and basin water-balance characteristics, but were more prone to peak flow timing errors than the NOAA model which was heavily calibrated to the downstream-most gauge. Peak arrival delays in the lower river of 1–2 days are not uncommon in our hydrology models; particularly during winter months when the different snow-melt modules in our simulation variants greatly affect flow timing. We know also that all of the Muskegon River hydrologic models have periodic large errors at the downstream-most sites associated with Lake Michigan seiche activity, and with flooding due to high flow constraints imposed by bridges and channel engineering. These result in occasional large but temporary backwater effects near the mouth that reduce river discharge rates and increase local wetland storage. Inclusion of a hydrodynamic model at the estuary mouth will be required to correct this problem.

The ensemble of hydrologic model variants does provide some sense of the forecast variability in MREMS although we are still in the process of completing more detailed analyses. Ensemble mean and variance plots for the lower river (Fig. 5) suggest that overall the hydrologic models are in good agreement that the impact of climate on flow will be consistently larger than that of land use. Inter-ensemble variation in predicted magnitude of the land use response reflects the fact that the "mixed" variant models (including the $m \times 4$ variant used throughout this paper) were consistently more responsive to land use change than the variants with ILHM generated runoff (Fig. 2b in contrast to Fig. 2c). There was also a large spatial variability (see Table 3) across the watershed in the direction and magnitude of response, so site-specific behavior can deviate substantially

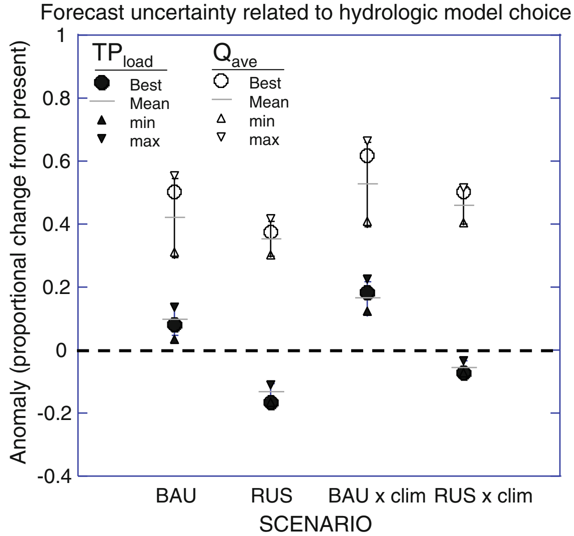

Fig. 5 Hydrologic ensemble variation in anomaly forecasts for river reach VSEC 18. Results from four hydrologic simulation variants (see "Methods" section) were pooled to estimate mean (±)1 standard deviation responses for MREMS forecasts of average daily discharge (*open symbols*) and average total phosphorus concentration (*closed symbols*). Range in response represented as minimum and maximum values. The large circle symbols represent the forecast from our "m×4" variant (see Fig. 2c) which had the best overall performance in hydrologic validation tests and was used to estimate ecological responses reported in Tables 2–6

from downstream integrated response, and from system average response.

So far in our analysis it appears that variability in flow estimates due to (hydrologic) model choice is much smaller than spatial variability across the watershed; coefficients of variation between models ranging from 4% to 9% (across scenarios) compared to 227–288% between sites. When comparing uncertainty in estimates due to hydrologic model choice further down the computational chain of the multi-model (e.g., TP load in Fig. 5) coefficients of variation change little; ranging from 4% to 11% and showing no evidence of problematic error propagation. As this multi-modeling system matures, we hope to add ensemble modeling capability to more levels of the multi-modeling system. We currently do have multiple model representations for certain sport fishes in the biological ensemble but have not yet tried to analyze their coherence or variability. In the case of these biological models, differences in life history representation and habitat scale substantially complicate comparisons.

Climate change and biological assessment

Linking hydrologic and loading model output to CART and MLR-based biological models led to forecasts of significant changes for a number of regionally important fish species. The Muskegon River is the single largest natural source of Chinook salmon reproduction in Lake Michigan and supports a regionally well known and economically valuable multi-species riverine sport fishery (O'Neal, 1997). In our simulations, cold water fishes in general were particularly sensitive to the climate change scenario and adfluvial salmonines most notably so. These model responses were driven principally by changes in summer water temperature (Fig. 2) which in this river system are controlled by largely by groundwater temperatures. Fish community composition is particularly sensitive to temperature changes in the 18–23°C range (July mean temperature; Wehrly et al., 2003) with a critical upper thresholds for many cold water species laying between 22 and 24°C (Eaton & Scheller, 1996), While the climate change scenario produced an average 3°C rise in annual air temperature and an average 4°C rise in mean July water temperature, these changes occurred across an extremely sensitive physiological range for local fishes (Fig. 2). The result was that modeled habitat availability dramatically and disproportionately declined for some important species, and expanded for others (Fig. 3, Tables 5 and 6). It is interesting to note, however, the independently derived assessment models for both invertebrate and fish communities were much more conservative in response to climate change than to land use change. Their pattern of sensitivity was almost the reverse of the observed in the individual fish models. Taken together, these results could be interpreted as implying that species distributions and community composition may be dramatically altered, but the underlying biological integrity of the community (*sensu* Karr, 1991) may be relatively unchanged (Fig. 4).

Indeed, in our forecasts the biological assessment metrics were impacted much more severely by land use scenarios than by the climate change. This response is in general consistent with the water quality modeling results which forecast relatively stable and decreasing concentrations of TP and sediment (respectively) under the climate change forecasts, but large increases in concentrations of both with land use change. This occurred despite significant increases in total load transport under the climate change scenario, which in the modeling was offset by dilution from higher flows. The assessment models we used were based on regionally normalized assessments of community composition data which estimate reference condition statistically (Wiley et al., 2002; Riseng et al., 2006). It is possible that the underlying empirical models were insufficiently sensitive to proximate physical variables forecast by MREMS and overly influenced by basin land use metrics. The fish assessment model did, however, explicitly evaluate base flow yield changes. The invertebrate model evaluated both changes in base flow yields and in summer water temperature. Furthermore, same kind of statistical over-fitting concern could also apply to the CART habitat models' relatively high sensitivity to the climate change scenario. But in this case, completed runs of the more mechanistic simulation models (DWUA and IBM recruitment modeling) to date agree with and confirm their predictions.

Whether or not wholesale shifts in species distributions related to global warming should be interpreted as indicating ecological impairment, is in itself, an interesting question (cf. Parmesan, 2006). We should hope that assessment metrics designed to reflect proximal insults on ecological integrity might indeed be relatively insensitive to regional shifts in climate. Ecological assessments are traditionally referenced in terms of either historical condition or by minimally disturbed regional baseline conditions. In either case, wholesale change in climate which affects underlying basin hydrology and temperature regimes are likely to disrupt current empirical relationships between community composition and traditional watershed stressors associated with land use, pollution, and local hydraulic modification. Even if baseline conditions themselves are changing, we will still need assessment protocols and metrics to manage and protect river ecosystems. If our current assessment methodologies are not in fact relatively neutral to direct climate impacts then we risk a growing probability that river assessment studies will be swamped by the effects changing climate. If so, then they will become relatively useless for evaluating the effects of the more common (and less "global") ecological insults that originate in the watershed.

Land use as an adaptation strategy

Comparisons of our modeling results from land use management scenarios with and without the climate change scenario clearly illustrate the extent to which the impacts of climate on rivers can be modified and filtered by landscape condition. Reductions in flow, sediment loading, nutrient loading, and even biological impacts were achieved in the RUS scenario relative to the BAU scenario, with the difference between the two often magnified under the climate change scenario. This occurred because land cover related differences in hydrologic routing and ET losses modified the consequences of changing climate signals. At a time when many are concerned over the lack of institutional preparation for the ecological impacts of climate change, linking climate change preparation to land use change may be a way to engage more traditional watershed managers and institutions. Land use planning is already a central, widely accepted, and in many areas institutionalized feature of both academic and practical watershed management. Linking land use management with climate change may provide both a new rationale and a new opportunity to take action on what we already know is often an effective river management strategy.

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