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Prediction of climate change effects on fish communities in the Mackinaw River watershed, Illinois, USA

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Abstract As part of an integrated assessment of multiple sector impacts produced by predicted changes in climate we have integrated a set of models, which provide predictions of fish populations under changing flow and temperature regimes. The core of the approach is the U. S. Fish and Wildlife Service Physical Habitat Simulation Model (PHABSIM). PHABSIM estimates habitat conditions based on flow, which are life stage specific. The output from PHABSIM is used to model fish populations, considering both flow and a temperature threshold, which affects spawning date. Water temperatures were modelled based on air temperature. The resulting assessment tool provides the means to evaluate the effect of multiple stressors produced by climate change scenarios. The model has been used to estimate smallmouth bass (*Micropterus dolomieui*) populations for representative reaches of the Mackinaw River, Illinois. The model has been used to illuminate population effects of changing flow and temperature under historical climate/weather conditions, as well as under climate change scenarios. The integrated models in the assessment tool have provided a useful addition to watershed management, improving our capacity to evaluate natural resources impact at temporal scales typical of climate change, and management response systems.

Keywords Fish populations; habitat modelling; multiple stressor response; smallmouth bass; temperature modelling

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Introduction

In its Third Assessment Report, the Intergovernmental Panel on Climate Change (IPCC, 2001a) found: “In light of new evidence and taking into account the remaining uncertainties, most of the observed warming over the last 50 years is likely to have been due to the increase in greenhouse gas concentrations…Future changes in climate are expected to include warming, changes in precipitation patterns and amounts, sea-level rise, and changes in the frequency and intensity of some extreme events.” Although a general sense of the impacts of climate change are provided by the modeling that supports the IPCC analysis, the prediction of impact at regional scales is problematic. The IPCC (2001b) notes “There is little agreement across climate scenarios regarding changes in total annual runoff across North America.” Further, IPCC (2001b) found “Varying impacts on ecosystems and human settlements will exacerbate subregional differences in climate sensitive resource production and vulnerability to extreme events.”

The challenges for watershed management, when considering climate change issues, include choice of climate change scenario, evaluation of climate change effects, integration of climate change effects with other mechanisms of change, and finally development of management programs that operate effectively for the changes produced, and over the time scales associated with climate change events. It is of concern that the assessment tools commonly used in watershed management may provide inadequate support for the management challenges associated with climate change. For example, the progressive environmental alteration associated with climate change will require process-based assessments that effectively track change in environmental conditions while illuminating mechanisms of alteration. Unfortunately, existing assessment tools fall short of meeting

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process-based criteria. For example, existing biomonitoring approaches provide an excellent means of assessing an existing condition or state, and compilations of past biomonitoring data do support trend analysis and provide limited support for prediction. In summary, traditional biomonitoring approaches are largely descriptive, applicable only to the time of collection, are often affected by an uncertain history, and often fail to define cause and effect when complex environmental settings are encountered (Herricks, 2001). What is needed is the development of biomonitoring tools that are process-based rather than descriptive. Tools that support analysis over time scales appropriate to climate change, considering both history and future performance. Tools that more adequately define cause and effect in complex and changing multiple stressor environments.

This paper reviews the development of a prototype tool, which is process-based, and provides a process-based assessment using accepted population modeling approaches. The tool described integrates two stressors, and has the capacity to address time-related change using both historical and predicted environmental conditions. The authors do not argue that the analysis/assessment tool they have developed necessarily meets all of the challenges of watershed management, but we feel the approach does provide a process-based assessment approach that considers long-term trends, identifies mechanisms of change, and provides insight into biological processes that better define cause and effect in complex, long-term, multiple stressor, assessment problems.

A climate change scenario

Although there is considerable uncertainty about the exact regional consequence of climate change, estimates of general regional effects have been developed from global scale modeling. IPCC (2001b) provides a sense of the consensus reached for North America. In the analysis of water resources and aquatic ecosystems the analysis found uncertain changes in precipitation and little agreement on changes in total annual runoff. The IPCC suggested that adaptive responses will include altered management of artificial storage capacity, coordination of surface and groundwater supply management, and voluntary transfers between water users. To provide an example of the implications of climate change on Illinois, Figure 1 provides the projected Illinois climate change in a geographic context. Walter Robinson, Department of Atmospheric Sciences at the University of Illinois produced this illustration based on results from the Hadley Centre greenhouse gas simulation. In this scenario, the general climate would become warmer and dryer. Accompanying this general shift in rainfall and temperature would be an expected shift in the number and kind of extreme events, such as tornados, heavy rainfall, and winter extremes that include snowfall and ice storms. Clearly, this scenario suggests a change in water resources, and a change in needed watershed management strategies to cope with climate change effects.

Impact assessment

To assess possible impacts of any climate change scenario, it is necessary to develop a method of quantifying change, and evaluation of those changes in terms of impact criteria. Impact criteria are developed from performance measures. For example, performance measures for watershed management might include regulatory effectiveness, economic efficiency, equity, administrative ease, and robustness/flexibility. Similar performance measures for natural resources, specifically ecosystem protection, would include population characteristics, community stability, or ecosystem processes. The relationship between the performance measures and the actual desired characteristics is the basis for an impact assessment.

We have found that developing performance measures of ecological systems in water resources management benefits from the adoption of a uniform set of definitions. The

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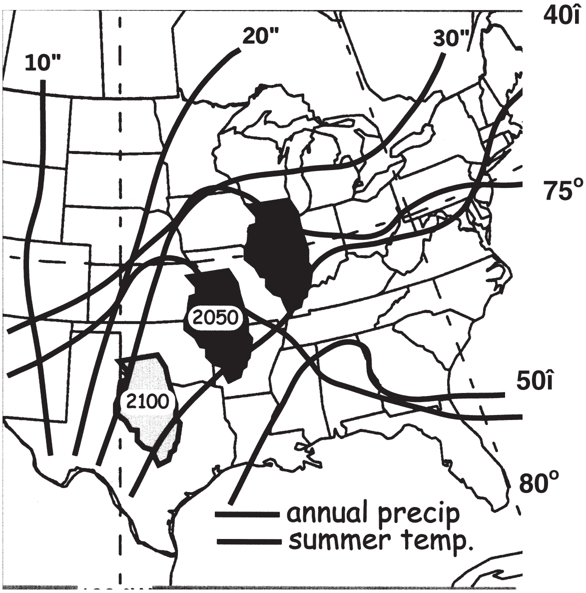

Figure 1 Illustration of a possible climate change scenario, tracking changes in rainfall and temperature in relation to existing conditions to illustrate change in terms of a geographical similarity in climate. (Modified from illustration produced by Walter Robinson, based on Hadley Centre simulations.)

following definitions, developed by Eheart and Tornil (1999), are generally consistent with accepted definitions for water resources (Hashimoto *et al.*, 1982 a and b; Fiering, 1982 a,b,c and d) and ecosystems (Westman 1978): **vulnerability** reflects the severity of failure; **resilience** reflects the ability of the system to "bounce back" from a failure event; **reliability** reflects the probability of meeting a standard; **robustness** reflects the insensitivity or satisfactoriness of the performance variable in the face of parameter uncertainty; and **recovery** reflects the time between failure events.

By using vulnerability, resilience, reliability, robustness, and recovery measures, it is possible to define impact criteria that are appropriate to climate change analysis. For example, vulnerability should be assessed both in terms of absolute change in an assessment parameter, and the time period over which that failure event extends. Resilience is similarly assessed in terms of an absolute change in the assessment parameter, and the speed (e.g. time related change) with which that parameter approaches pre-failure conditions. Reliability accepts the fact that there will be variation in assessment parameters and that it is essential to have both a measurable standard, and a reasonable expectation of what the standard should be. Robustness can be assessed in the lack of variation in an assessment parameter. Recovery can be determined both in an absolute sense by comparing pre- and post-event measurements, and the time-related issues of parameter change occurring between failure events.

Assessment tool development

The assessment tool developed to provide a basis for prediction of multiple stressor (hydrology/flow and water temperature) effects of climate change required the integration of several models. The core model is the Physical HABitat SIMulation (PHABSIM) procedures developed by the U. S. Fish and Wildlife Service and presently maintained by the United States Geological Survey (*http://www.mesc.usgs.gov/products/pubs/15000/15000.asp*). PHABISM uses discharge data with representative reach cross-section depth,

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velocity, and substrate data to provide stage specific estimates of channel hydraulic conditions. This hydraulic data is integrated with species and life stage specific habitat suitability information to produce an estimate of habitat quantity. This habitat quantity metric, the weighted usable area (WUA) is developed for a representative reach, which can be extrapolated to other reaches in the drainage net with similar channel characteristics. PHABSIM was applied to a reach of Panther Creek, a major tributary of the Mackinaw River in central Illinois. Flow data were developed from USGS gauging stations providing a 50 year flow record and habitat assessment period, Bergner (2002). This approach allows analysis of historical flow conditions for model testing, and the evaluation of modified flow regimes typical of climate change scenarios. Flows for climate change scenarios were developed using two methods. One method evaluated historical records and constructed a flow sequence typical of years that were hotter or drier. The second method used output from SWAT modelling (Wollmuth and Eheart, 2000) which was driven by rainfall inputs of expected climate change scenarios.

The WUA estimates from PHABSIM were then used in a fish population model. Food and space are considered as major factors/limits to population growth. In this tool, space is estimated from WUA values for each life stage, and changing space/area availability associated with flow is used in the prediction of populations over time. Food is assumed to be non-limiting in the model. The population model was implemented in STELLA, a dynamic modelling environment. For this prototype tool a smallmouth bass (*Micropterus dolomieui*) model was used, Figure 2. As illustrated in Figure 2, an optimum, weekly minimum and average WUA was determined. The optimum WUA was set at the highest WUA in the record, weekly minimum and average WUAs were determined from PHABSIM model output. The model was developed using life history data available from the literature, and species response data from Illinois, producing estimates of life stage specific population values.

A second input to the population model is water temperature. A nonlinear logistic stream-air temperature regression model was used to estimate water temperature from air temperature (Mohseni *et al.*, 1999). The air temperature data were developed from historical weather data compiled and analysed by Kunkel (personal communication). This historical analysis provided both actual historical temperature conditions, and an analysis that determined which years had temperature conditions that matched climate change scenarios (e.g. 1, 2, 5, 8 °F increase over average conditions). In the model application, daily temperature from years that provided scenario conditions were used to assemble a long term data set to drive the water temperature model. The temperature estimates were used as a threshold value, identifying the onset of spawning for smallmouth bass (e.g. the first 6-day period in which water temperature ranged between 57 and 72°F). Spawning then continued for two months. The temperature model thus affected onset of spawning, independent of the suitability of flow conditions for spawning success.

The integrated modelling system provides an assessment tool that addresses critical issues of a process-based climate change assessment. Using this tool, it is possible to use fish populations as an indication of the effect of changing climate conditions. In this example, the relatively long lived smallmouth bass is used, but other models have been developed for species with different life histories (Tompkins, 1998). In this prototype application, the life history of the smallmouth bass provides a basis for analysis of the cumulative effects of annual conditions. Further, it is possible to analyze life stage specific population responses to identify factors associated with population change. Through identification of factors required for population maintenance, it is possible to identify causal factors for population change, leading to identification of cause and effect relationships, critical in management practice selection. Although only two stressors were used in this

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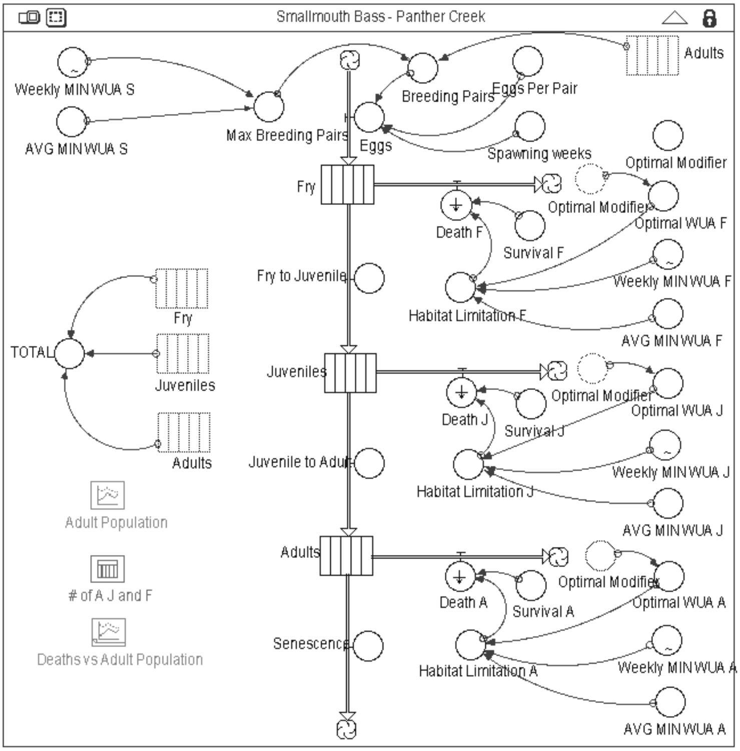

Figure 2 STELLA model of smallmouth bass population growth incorporating WUA and temperature limitations

prototype, the population model allows the evaluation of multiple stressors, when species response data are available.

Prototype model results

An example population model output is provided in Figure 3. In this figure it is possible to identify periods of spawning success and failure (second panel from top) and track adult population trends in relation to life state specific responses to flow (third panel from top). Using this prototype model, it has been possible to identify which historical flow conditions lead to predicted population change, and identify life stage specific characteristics associated with those changes.

It is also possible to develop new indices for population model analysis that provide insight into population responses. Practical sampling limitations would prevent determination of these indices from field data. For example, Figure 4 shows changing juvenile population estimates (upper panel) and juvenile WUA, spawning times, and a fry/juvenile ratio.

Climate change impact assessment

The prototype modelling tool provides a new approach to the measurement of vulnerability, resilience, reliability, robustness, and recovery. For example, it is possible to identify vulnerability in terms of absolute population values as well as predicted population change over time. Further, it is possible to develop vulnerability indices, such as the ratio of existing population size to a target value, and then plot a change in these indices. It is also possible to conduct these analyses with single or multiple stressors, and consider a wide range of future conditions in the assessment. A similar approach can be used to analyse resilience,

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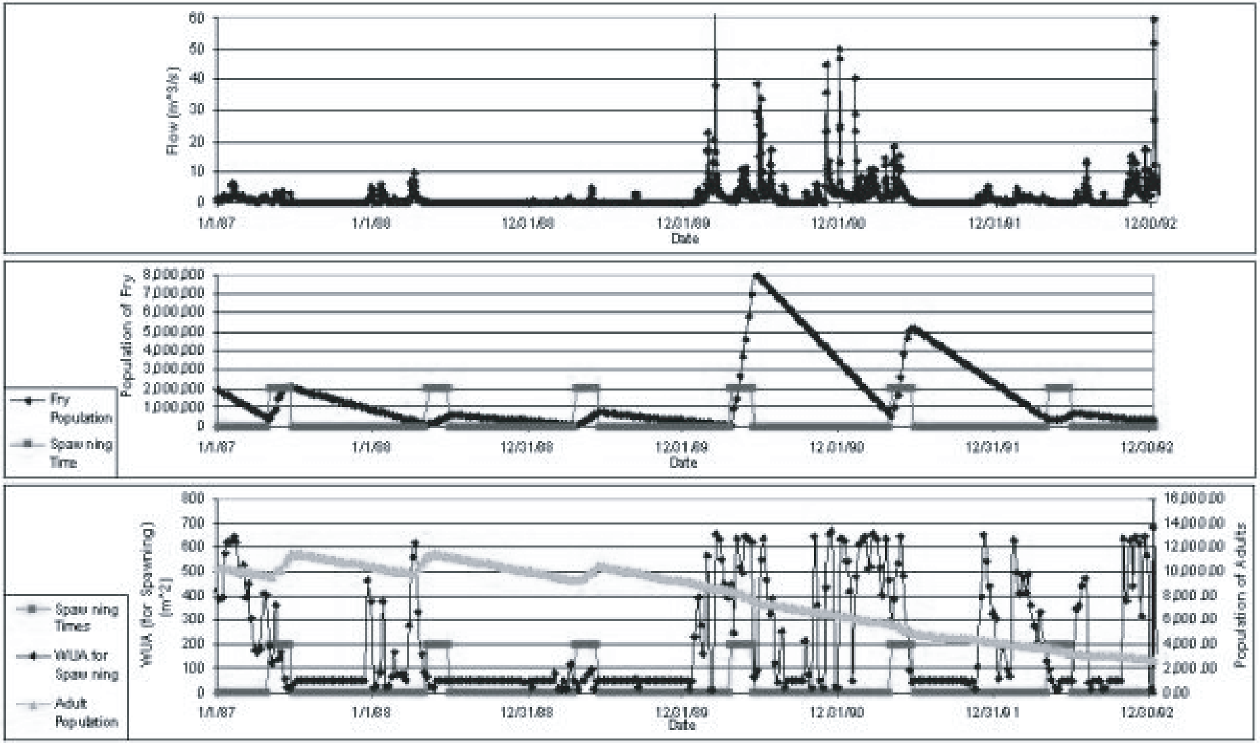

Figure 3 Population model output illustrating spawning time/fry production, spawning success and adult population relationships

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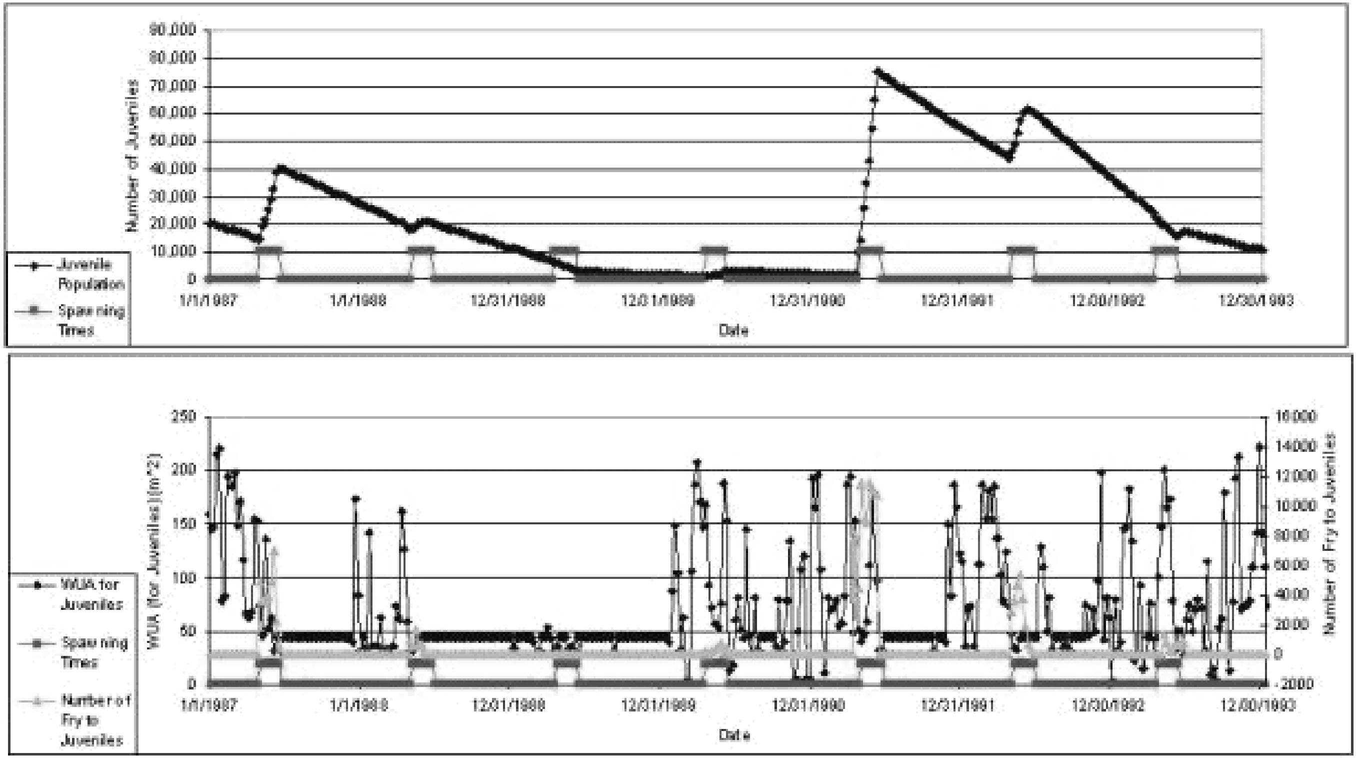

Figure 4 Juvenile population trend with fry/juvenile ratio values showing spawning success

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reliability, robustness, and recovery, develop new indices for these measures, and apply those indices in historical and/or predictive analysis.

Prototype tool assessment

An argument developed in this paper is that the future of water resources management will present challenges to scientists and natural historians that can only be met by developing process-based tools. Existing descriptive approaches used in biomonitoring and environmental analysis provide an essential foundation for assessment activity in watershed management, but the limits of descriptive approaches are becoming more apparent as management emphasizes performance and outcome.

The prototype tool identified in this paper is limited in its present application, but it suggests promise in many areas. The major limit to this tool is effective calibration and sensitivity analysis. To accurately calibrate the model, long term population information would be needed, information that is based on a response only to flow or temperature. Those data are not available, although population model characteristics were evaluated against a long term population record in the development of models for each species (Tompkins, 1998). The tool does have an advantage in that the modelling structure is transparent. Transparent in the sense that the integration of flow and temperature in the tool is achieved through a population model. Further, population model development has followed accepted population modelling theory that has been well described (Pielou, 1974; Nisbet and Gurney, 1982). The implementation in STELLA provides a practical, and transparent, model structure as well. The end result is the addition of a single tool to the array of tools that can potentially be used in watershed management. With an array of tools available, the watershed manager is challenged in both selection and proper use of tools, independent of concerns about accuracy, precision, or utility of any single tool.

Conclusion

The prototype tool described in this paper provides a process-based approach to the assessment of long term alterations in environmental conditions. The approach provides life stage specific population estimates, which supports the development of new indices of response, which can be tailored to impact characteristics such as vulnerability, resilience, reliability, robustness, and recovery.

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