Final Report

Jointly Changing Climate and Land Use in the Mid-Atlantic: Modeling Drivers and Consequences in Economics, Hydrology, Geomorphology, and Ecology

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Summary:
This project included research along an interdisciplinary track between economics, hydrology, geomorphology, and stream ecology. A summary of key findings in each area follows under these headings. In addition, there were two other key events in which our group participated: a "Stakeholder meeting" held at the outset of our project, and a case study comparison meeting held in January 2005. A summary document from the case study comparison meeting and a list of stakeholder meeting attendees are attached as appendices to this report.

Economics:

***Task 1E:* Produce a series of long term land use change scenarios (20 to 50 years) by refining and extending existing models.**

Task 1E(a): Improve the explanatory model of land use change upon which the forecasts are based
The work reported in this section was partially funded by this project and also funded by other projects and by the University of Maryland. This work is part of a larger research agenda on land use modeling. The coherent nature of the research makes it impossible to allocate specific results to individual funding sources, but the research findings reported in this section are fundamental to the completion of the subsequent tasks.

The ultimate task is to generate predictions of changes in land use and land use pattern for the watersheds of interest to the scientists (i.e. the ecologists, hydrologists and geomorphologists) involved in the major part of this climate change project. This can be accomplished only by addressing the broader task of improving models of land use change at the rural urban fringe. The pattern of development outside of urban areas, including fragmented forms of development often called 'sprawl', are regional-level phenomenon driven by individual choices over location and land use and are influenced by a myriad of factors, including land features, infrastructure, policies, and individual characteristics. Because it is the cumulative result of individual actions, an understanding of development requires an understanding of individual decision-making and how these decisions "aggregate up" over time and space. However, because of a lack of spatial data on individual-level land use and location choices, most empirical studies have attempted to analyze land use change using data at a more aggregate level, e.g. census tract or county level. At this scale, empirical analysis of development decisions is limited to identifying characteristics that are associated with, but do not necessarily cause, development.

The research agenda of which this project is a portion combines economic theory with parcel-level data on land conversion and a Geographical Information System (GIS). Because development is an economic decision constrained by regulation, the pattern of development emerges as the result of several types of influences: (1) spatially varying policy variables, including several "smart growth" policies and a clustering regulation that requires developers to preserve varying amounts of open space by clustering development on a parcel; (2) other spatially heterogeneous features of land parcels, including accessibility to urban centers, soil quality, and size; and (3) interactions among neighboring landowners' land use decisions due to land use externalities. Analysis is built on continuously improving models of the optimal timing of development, which incorporate the effects of land use externalities and are estimated using hazard (often called duration or survival) models. Specifically the work incorporates an extensive set of policy variables, including a variety of "smart growth" variables, clustering policies, and agricultural preservation program elements that are hypothesized to influence development timing, and focuses on how the presence of land use externalities may enhance or moderate the effectiveness of these policies. Both direct and indirect policy effects are considered. What follows is a summary of findings from four related pieces of analysis undertaken to improve the spatial model of development decisions and to test hypotheses about the direct and indirect effects of policies.

Irwin, Elena and Nancy Bockstael, "Endogenous Spatial Externalities: Empirical Evidence and Implications for Exurban Residential Land Use Patterns." In *Advances in Spatial Econometrics, Methodology, Tools and Applications*. L. Anselin, R. Florax and S. Rey (eds.). Springer Publishing, 2004, pg 359-380.

The basic thesis proposed in this paper is that neighboring land uses generate spatial externalities, and that consideration of these externalities generates interdependencies among neighboring agents' land use decisions. This is in contrast to the long-standing hypothesis that the major influence on land use pattern is distance to exogenous elements of the landscape – such as city centers. That interdependencies matter means that the land conversion process is driven partially by endogenous change. An individual's land use decision is a partial result of the cumulative outcome of neighboring agents' individual conversion decisions and ultimately becomes part of this cumulative outcome affecting future changes in land use. Thus the process of land use change is path dependent. This paper tests for interaction effects and explores whether the interacting agent hypothesis can explain residential land use pattern changes in rural-urban fringe areas - areas which have experienced the highest rates of land conversion over the last two decades.

In attempting to determine the existence of interaction effects we show the existence of a statistical identification problem, not widely recognized in the literature. Omitted variables embedded in the stochastic term of any analysis of development decisions arise due to unobserved heterogeneity in landowners and land parcels. The unobserved heterogeneity associated with parcels is likely to be strongly correlated in space as attributes associated with nearby locations are almost certain to be positively correlated. The presence of unobserved but spatially correlated heterogeneous features that influence the conversion decision complicates the identification of endogenous interaction effects. If omitted variables are invariant over time and spatially correlated over space, then it will be difficult to distinguish between the influence of such unobserved spatial effects and those of true spatial externalities from surrounding land uses. Even in the absence of true spatial externalities, a positive interaction effect among neighboring parcels will *appear* to exist. This type of identification problem has arisen in other contexts outside the land use modeling literature and econometricians have attempted to developed strategies for untangling the confounding elements. However, most of these strategies do not work in the context of land use change because of complicating factors.

A bounding strategy by Heckman and Singer is possible, however, and is adopted in this paper to reveal the existence of a *negative* interaction effect between neighboring developments. Thus, it appears that parcels that are developed into residential developments in the urban-rural fringe exert a negative effect on the likelihood of development of neighboring parcels. The intuitive argument in support of this analytical finding is that residents who seek housing in the urban-rural fringe value neighboring open space and seek to avoid congestion and other factors associated with large tracts of continuous development.

The over-riding conclusion of the paper is that the land use state of a parcel exacts an influence over subsequent land use decisions of neighboring undeveloped parcels. Once the importance of interaction effects is realized and one admits that development patterns are not solely driven by distance to exogenously determined features of the landscape, then forecasting future land use pattern becomes potentially more complex. Additionally the evaluation of policies aimed at affecting land use change also becomes more difficult. Past and current decisions influence future decisions and future changes in land use pattern. Policies will figure into current decisions and in so doing affect how land use change plays out over space and time.

Irwin, E. and N. Bockstael, "Land Use Externalities, Open Space Preservation, and Urban Sprawl," ***Regional Science and Urban Economics*****, vol 34(6), Nov 2004.**

Cluster development policies have gained popularity as local governments attempt to reduce the fragmented, low-density development that is occurring in the urban-rural fringe. Cluster policies allow higher densities of development in some portions of a parcel as long as other portions of a developable parcel are protected in open space. These policies would appear to protect critical natural resource areas and promote a more efficient use of land, but this view assumes that the clustering policy itself does not alter the rate or amount of growth in the regulated and immediately surrounding areas. This paper attempts to test for both direct and indirect effects of the policy on the likelihood of development.

In this empirical paper we find that parcels subject to clustering regulations that either allow or require small to moderate amounts of open space set-asides are more likely, other things equal, to be developed. Costs of compact development are lower and this offsets the lower valued smaller lots. However, large open space set-aside requirements depress the likelihood of development. What is potentially more interesting is that we find an indirect effect on neighboring parcels. The existence of preserved open space generated by the clustering requirement actually appears to hasten the timing of development for neighboring parcels due to positive amenities from the preserved open space.

This paper provides additional empirical evidence of interdependencies among neighboring landowners that influence the timing and pattern of land development. We find evidence that parcels with greater amounts of preserved open space nearby are more likely to have larger hazard rates of development (relative to those with more low-density development nearby), while more neighboring commercial and industrial development has a depressing effect on the hazard rate. This suggests that interaction effects tend to push new development away from areas with existing high-density urban development and pull new development towards areas with yet undeveloped land. If such effects are sufficiently strong, they will foster an increasing leapfrog or sprawled pattern of development. The positive amenity value associated with preserved open space created by the clustering policy suggests that open space preservation policies can alter the evolution of development patterns not only because they create an area in which development cannot occur, but also because they may create areas that attract neighboring development. The pattern of development that emerges across space and time is one that is clustered at the micro-scale (within a parcel), but potentially fragmented at a neighborhood or more regional scale. While these results are hampered by potential problems of econometric identification, they provide some evidence of the nature of land use interdependencies that exist among neighboring agents and the manner in which these effects interact with policies and aggregate up over time and space to influence regional patterns of development. They also provide a cautionary tale for policymakers concerned with promoting a smart growth agenda: policies that seek to promote smart growth by preserving open space may actually lead to more sprawled patterns of development.

Towe, C., C. Nickerson, and N. Bockstael. "An Empirical Examination of Real Options and the Timing of Land Conversions", Paper to be presented at the AAEA meetings, August 2005, being prepared for journal submission.

Purchase of Development Rights (PDR) programs have become a popular land use control instrument. Under these mechanisms, landowners voluntarily receive payment for agreeing to forego development of their land and accept easements placed on their land.

Since the first 'purchase of development rights' (PDR) program was implemented in 1974, over 53 state and local governments in the U.S. have collectively spent over $2.6 billion in public funds to preserve 1.6 million acres. The few studies that have attempted to test whether these programs slow development have provided mixed results. In this paper we ask the question: does the existence of a PDR program (and eligibility to participate in it), in and of itself, have an effect on the timing of development.

The context in which this question is asked is one of real options. Specifically, this paper diverges from past optimal timing of development papers in attempting one of the first empirical applications of real options theory. For some time, theoretical papers on the topic, such as those by Capozza and Li, have recognized that land development is equivalent to the exercise of an option. The conditions that describe a real options fit the development decision well, as these conditions require that the investment is irreversible, that returns are uncertain, and that the decision to convert can be postponed. In contrast to real options theory, more traditional models such as the net present value (NPV) rule for characterizing land conversion decisions are deterministic in the sense that land is expected to be developed as soon as the net present value in development, net of conversion costs, exceeds the present value of the current use.

Our empirical model investigates a more complex real options problem – one in which land use conversion occurs in the presence of more than one 'investment' option. Specifically, landowners can 'invest' by developing their parcel or by selling their rights to develop. The question of interest is whether the existence of this option affects the nature of the development decision – in particular whether it alters the optimal time to develop. Theoreticians have derived the result that the existence of multiple options should delay development and that the more similarly valued the options, the more the development is delayed. However, empirical tests of this are non-existent.

This study is one of the first to empirically estimate several predictions of real options theory in a land use context, including whether price uncertainty impacts decisions to convert farmland to developed uses and whether the presence of multiple land use options – specifically, an option to preserve farmland in a PDR program – delays development decisions. It does so using a duration modeling which captures the conditional dependence of the conversion decision. One element of real options theory suggests that price uncertainty, measured by the variance in development returns, slows the speed of development. We find significant empirical evidence that variance in returns has a delaying effect on the timing of development. We also find significant evidence that having the option to sell a PDR easement delays development with a mean delay of about 3 years. This finding is also in line with real options theory predictions, which imply that the addition of an option to the choice set will increase the value of waiting to the landowner.

Towe, C. and N. Bockstael. "Testing the Effect of Neighboring Open Space on Development using a Real Options Model", Workshop on The role of open space and green amenities in the residential decentralisation hosted by INRA at Dijon, France, December 2005.

In this paper we return to the analysis of interaction effects and policy implications, but here we consider the indirect effects of Purchase of Development Rights programs. We are specifically interested in the effect preservation of a parcel has on neighboring development decisions. If interactions exist among these neighboring parcels then, depending on the sign of the interaction, preservation of a parcel may have indirect effects on neighbors, either reinforcing the protection of land or encouraging fragmented development. If the former, then typical evaluations of preservation programs will understate their effect. If the latter, then preservation programs may have unintended consequences. Because preservation programs can legally target whatever types of land desired, they provide the public sector with an instrument that can affect long term land use patterns, but the ultimate effect may or may not be as expected.

As already noted, testing a hypothesis about interaction effects is surprisingly difficult. Conventional regression-type analyses of land use interactions suffer from the sorts of identification problems described earlier. Because many of the factors that make development more or less profitable are spatially correlated, the empirical finding of more development adjacent to existing development is not evidence of a positive interaction effect. Such an outcome could easily arise simply because both parcels are characterized by similar levels of the factors that affect development profitability. Likewise, finding empirical evidence of a negative relationship between preservation and neighboring development decisions might simply be a different manifestation of this same spatial correlation in exogenous attributes: spatial correlation in factors that induce development, as well as spatial correlation in factors that induce preservation, suggest that we are likely to find empirical evidence of a negative relationship between development decisions and neighboring preservation. Only if strong positive interaction effects exist between preservation and development – generated, for example, by the positive externalities open space provides to residential use – would we expect to find a positive empirical effect of preservation on development decisions.

In this paper we use two approaches to test for interaction effects between preservation and the land use outcome of neighboring parcels. The first builds on the hazard analysis of the previous paper, basing the model on real options theory. The hazard model is useful because it embodies the inherent dynamic nature of the decision process. However, it does not provide a means of handling the identification problem conclusively. The second is a quasi-controlled experiment (using propensity score matching) that recasts the problem in the context of a non-random selection problem. In this framework, we test for a treatment effect where the observation of interest is a developable parcel, the *treatment* is the preservation of a neighbor and the *outcome* of interest is whether the developable parcel is developed or not over a specified time period following the preservation action. The usual task set out by propensity score matching procedures is to estimate the mean 'treatment effect on the treated'. For our problem, this is the effect on the likelihood of development of having a preserved neighbor, averaged over all parcels that were treated in this way. Matching estimators pair each treated observation with one or more observationally similar non-treated observation, using conditioning variables to identify the similarity. This quasi-controlled experimental approach follows the recent surge in this type of analysis of policy outcomes.

From the hazard model we find statistically significant evidence of a positive interaction effect between preservation and the likelihood of development of neighboring parcels. Having a preserved neighboring appears, in this model, to increase the ‘hazard’ of development. Results from the quasi-controlled experiments support the sign of this interaction. The estimated ‘treatment effect’ on the ‘treated’ is positive and significantly different from zero for all versions of the model. Over two designs and two matching estimators, the treatment effect on the treated is estimated to range from approximately 11% to 14%.

All of this evidence provides support for the contention that preserved open space is likely to induce more neighboring development, holding other things equal. Thus preservation programs, if not designed carefully, may actually encourage landscape fragmentation by setting in motion a path dependent process that encourages a checkerboard pattern of preservation and development. Knowing of the existence of this interaction effect may help the public sector design land use policies with a higher probability of achieving their stated goals.

Task 1E(b): Develop reasonable forecast scenarios for the 20-50 year horizon

The findings from the above papers are important in constructing forecasts for the scientists because the provide evidence of a) the importance of policies that preserve open space and b) the importance of interaction effects among parcels. The role the latter plays in the construction of forecasts will be explained in more detail under Task 2Ea. The role the former plays is in determining the types of scenarios chosen.

Our findings suggest that the removal of development rights from targeted land (either through open space set-asides, direct acquisition of the land, or purchase of development rights) is arguably the most effective ‘smart growth’ policy being considered. The effects of Priority Funding Areas designation has yet to be proven and, in any event, has little impact on the watersheds of interest to the scientists on this project. The only other policies that have had an appreciable effect are not ‘Smart Growth’ policies, per se. For example, Adequate Public Facilities Moratorium (APFM) is a growth control instrument that pre-dates Smart Growth and played a moderate role in the mid to late 1990’s by temporarily slowing development in some areas where school capacities were exceeded. We have a research endeavor underway to test more conclusively whether the early APFM’s (put into place in the 1990’s) had more than a transient effect on the timing and location of development. One important factor affects any scenario predictions we put forth. As of the early 2000’s, new features of the APFM’s have become the governing force in determining *how much* land will be developed each year.

The scenarios discussed in the proposal included a baseline scenario based on business as usual given current zoning, a smart growth scenario, and a climate change scenario. To address the first two needs we provided the scientists with two types of scenarios. The initial set of forecasts from our models included ones in which current zoning and no aggressive land acquisition programs (including no further preservation (PDR) activity) was assumed and one which assumed an aggressive policy in which the public sector purchased the development rights for all rural legacy land (under the Smart Growth program) that had not, by 2010, already been forecasted by our model to be developed. In a second set of forecasts (December, 2005), we included purchases of development rights on land designated as ‘hubs’ under the new Greenprint program, as well as the rural legacy land.

The specification of one or more climate change scenarios is far more difficult. There are several reasons for this. First, climate change is unlikely to have a direct effect on land development patterns at the spatial scale we are dealing with. The counties targeted by the scientists in this project are not coastal counties, and so are not expected to be affected by sea level rise. In addition, neither agriculture nor forestry in these counties is regionally competitive. The types of commercial agriculture that seem competitive are those that serve the residential community directly – e.g. horticulture activities that provide landscape plants, pick-your-own operations, and organics and speciality crops. Climate change will probably not alter the viability of these operations, because they depend on proximity to buyers and not competitiveness in regional or national markets.

The proposal suggested that policies in response to climate change may have an effect on land use change. However, there would seem to be no pending policies that are likely to have an immediate impact on the spatial distribution of development within the region. California and some northeastern states are trying to implement their own CO_2 reduction programs. The policies that are being talked about most are emissions trading by power generating plants and subsidies for hybrid cars (and for non-fossil fuel technologies). The first may, in the long run, have an effect on the spatial pattern of migration at the national scale, if power generation in the Northeast (for heating) and Southwest (for cooling) becomes much more expensive. But effects at the scale of this study (a few watersheds in Howard and Montgomery Counties) are impossible to imagine. The hybrid car subsidy, all other things equal, might be expected to encourage more sprawl, but current and expected gas price increases would have the reverse effect.

Finally, unless a policy has an immediate impact, it is unlikely to affect development as Howard County is projected to be fully built-out by about 2020. Montgomery County is not far behind. Both these counties are fast growing and, given current zoning regulations and currently protected land, most available land is projected to be developed within 20 years. For all these reasons, land use change in these study watersheds is either unlikely to be sensitive to climate change or will be sensitive in ways that at this point in time are not easily predicted.

***Task 2E:* Develop a means of translating probability mappings into forecasted landscapes for use by the other scientists on the team.**

The tasks of this section relate to the technical details of using the modeling results described above, together with scenario definitions, to produce output usable by the scientists. As such, there is no publishable papers that outline these tasks. However, the methods developed under these tasks are being employed in related work that compares economic models of land use change with cellular automata models for forecasting land use change.

Task 2E(a): Incorporate into forecasts interaction effects among neighboring land uses, making forecasts path-dependent.

The creation of land use forecasts for the scientists involves taking the land use as of about 2002 and forecasting which parcels will be developed in each subsequent year until developable parcels are exhausted. The basis of the simulation is the estimated models described under Task 1E(a). Application of the estimated model to hither-to undeveloped parcels generates predicted probabilities of development. A key element of the simulations is the incorporation of interaction effects. With each round of development, the subsequent year's probabilities of development are altered because the probability that any parcel will be developed is a function of the land use states of its neighbors. As of the most recent set of forecasts, we have incorporated into the simulations an updating module that takes account of the previous period's change in surrounding land use and recalculates the predicted probability of development each year for each parcel on the basis of the changing landscape. New parameter estimates from the work described in Task 1E(a) are now used to reflect the effect of different types of surrounding land use on the probabilities of development.

Task 2E(b): Translate the model's output which comes in the form of predicted probabilities into realizations useful as input into others' models.

The early scenarios implemented the preliminary version of the Monte Carlo simulations and the more recent scenarios used a more refined version. In the last few weeks, we have revamped these routines yet again to incorporate the more sophisticated models estimated in the Towe, Nickerson, and Bockstael paper and the Towe and Bockstael paper. It is also possible to supply multiple realizations of any scenario, but realize that this just adds confusion to the multiple alternatives added by each of the science layers in the simulation runs.

The nature of the process is the following: The parameterized land use change model is used to produce forecasted probabilities of development for every developable parcel in the first forecast year, under a given scenario description. The forecasted realization is derived by making random draws (without replacement) from a uniform distribution in which each developable parcel has a representation proportional to its predicted probability of development that year. Given the realizations for the first year, the probabilities of development for all remaining parcels at risk of development are then updated for the next year. Realizations for year two of the forecast are then defined using the same random draw process. This goes on until the set of developable parcels is exhausted. We can then reset the seed and run as many full forecast realizations as we want. Multiple realizations can be compared.

Task 3E(c): Improve the model's ability to predict the amount of development each period.

This is a difficult conceptual issue and one that we are still struggling with. The model best describes which parcels are likely to be developed first, but the total amount of land developed each year is much more difficult to explain. We have made some progress using regional economic indicators embedded in the hazard model, but there are interesting and complex issues of duration dependence that arise in the context of the particular hazard model we are using. These are issues that no one, to my knowledge, has thought about in the context of land use.

In any event, this is somewhat irrelevant for projections into the future – at least for Howard County. As of the beginning of the 2000's, Howard revamped their Adequate Public Facilities Moratoria, putting what are clearly binding constraints on housing allocations in each broad planning area. So the total amount of land (but not the precise location of that land) being developed each year in Howard County is actually now set by regulation. the only question is whether these constraints continue to be binding until developable land is used up – in about 2020.

There are some ways in which the landscape may change further, but these are difficult to predict because they involve structural shifts in policy. For example, if the current maximum density zoning regulations are relaxed, existing developed land may be more densely developed. This would have an enormous effect on northwestern Montgomery County, where zoning prevents anything but extremely low density development. If open space requirements in previously developed subdivisions are returned to the development pool, then preserved pockets of open space in subdivisions will disappear. Finally, if development rights on previously preserved agricultural land are released at low cost and returned to property owners, then massive amounts of open space in the western part of Howard County in particular could be available for development. Any of these scenarios could be considered, but would require major revamping of our forecasting model and some very bold assumptions about when/how the structural policy change takes place.

Hydrology:

The hydrologic elements of this project will continue along three lines of inquiry: 1) continued model development, 2) examination of spatial variability in climate-based drivers, and 3) production of continuous and event-based streamflow estimates for both historical and predicted future climate.

Task 1H: **Develop a method to calibrate the parameters of the continuous streamflow model as a function of land use.** We have developed a technique that is documented in Hejazi and Moglen (in review in *ASCE Journal of Water Resources Planning and Management*). We summarize that technique here:

The calibration of the model is performed using observed temperature and precipitation time series as input and the observed daily time series. The continuous streamflow model also requires the input of several other hydrologic input variables.

The continuous streamflow model is embedded within a numerical optimization routine in an effort to reduce subjectivity in the calibration process. This allows the optimization routine to handle the job of the modeler to modify the input variables until the optimum simulated streamflow times series is produced. The optimization routine is based on an objective function that minimizes the summation of errors squared. This would lead to minimizing the standard error value. However, this did not necessarily produce the best visual fit because it tends to minimize peak flow errors at the expense of larger errors on a percent basis for smaller flows. Thus, a weighted average of two different objectives was incorporated in the optimization routine program.

While the visual assessment of a calibration is important, it is often necessary to quantitatively assert the quality of a given simulation in its approximation of observed streamflow. Better goodness-of-fit statistics between two hydrographs can generally be achieved by minimizing the summation of errors squared, minimizing the standard error, or maximizing the correlation coefficient. Another measure of goodness-of-fit is the modified correlation coefficient, R_m, which is equivalent to the correlation coefficient multiplied by a factor, *a/b*, that incorporates the water budget balance (McCuen and Snyder, 1975).

$$R_m = R \cdot a/b \tag{3}$$

$$a = \left[\frac{\sum Q_{sim}^2 - \sum (Q_{sim})^2 / n}{n} \right]^{0.5} \tag{4}$$

$$b = \left[\frac{\sum Q_{obs}^2 - \sum (Q_{obs})^2 / n}{n} \right]^{0.5} \tag{5}$$

where R is the correlation coefficient, Q_{sim} is the simulated streamflow in cm, Q_{obs} is observed streamflow in cm, and n is the number of observations in the streamflow time series. Optimizing on the modified correlation coefficient is not adequate in itself because the optimization routine tends to maximize the (*a/b*) ratio component at the cost of the correlation coefficient component.

To optimize simulated discharges to closely match both flood and baseflow conditions we employed a weighted objective function. We used a weighted average of two criteria: summation of errors squared and the (*a/b*) ratio. The objective function minimizes the quantity, *S*, which minimizes the summation of errors squared (and thus minimizing the standard error), and maximizes the ratio of *a/b*. The variable *w*, which may range between 0 and 1, indicates the weight given to each component of the criterion variable. After some experimentation with various values for *w*, calibrations were performed with a *w* of 0.2, which gave 80 percent weight to minimizing the sum of errors squared and 20 percent to maximizing the (*a/b*) ratio:

$$S = w \cdot \sum (\hat{Q}_{sim} - Q_{obs})^2 + (1-w) \cdot \left| 1 - \frac{a}{b} \right| \tag{6}$$

This value for *w* appeared to achieve the best balance between matching flows across both flood and base flow conditions.

Task 2H: **Modify the existing streamflow model to accept an input time series of land use from which the parameters mentioned in Task 1H can be estimated.** This was successfully carried out as part of the work documented in Hejazi and Moglen (in review in *ASCE Journal of Water Resources Planning and Management*).

Task 3H: **Develop a method to meaningfully employ the spatially distributed grid of precipitation and temperature time series within the streamflow model.** We were not successful in developing this method.

***Task 4H:* Use the methods developed in Tasks 2H and 3H to determine changes in the hydrologic budget (surface runoff, sub-surface runoff, baseflow, and evaporation) and distribution of streamflow (magnitudes of Q_1, Q_{10}, Q_{50}, Q_{90}, Q_{99}) as a function of differing future land use scenarios and climate model inputs.** This work was carried out and is documented in Hejazi and Moglen (in review in *ASCE Journal of Water Resources Planning and Management*). **Key findings:** Under jointly changing climate and land use we observed very clear reductions in simulated low flows and increases in simulated peak flows. On the question of which driver: climate or land use plays a greater role in influencing flow durations, our specific findings for an already urbanized watershed in the Maryland Piedmont region suggest that climate is more important. However, care should be exercised by the reader when generalizing these results to other locations. Results may vary depending watershed size, the specific climate model being used to provide future climate projections, and the current degree of urbanization within the watershed. The value of this research is the presentation of a method to forecast possible changes. The general finding of amplified impacts on flow duration from the synergistic effects of jointly changing climate and land use is important given the forecasted likelihood of changes in both drivers over the foreseeable future.

Additional findings: We also investigated a regression-based approach to estimating the annual 7-day low flow. This work resulted in the paper Hejazi and Moglen (in press in *Hydrological Prcesses*). **Key findings:** Historically observed data of the 7-day low flow in six urbanizing watersheds in the Maryland Piedmont region, along with climatic and land use data were utilized to develop a regional regression equation. The regional regression model predicts the annual 7-day low flow based on four indices: the total 270-day antecedent precipitation, the average 60-day antecedent average temperature, the level of imperviousness in the watershed, and the drainage area of the watershed. Precipitation then temperature emerged as the strongest predictor variables followed by imperviousness. The imperviousness predictor was calibrated based on only two of the six watersheds, which had experienced the largest change in land use. This enabled us to better capture the potential impact of urbanization on low flow, which was not evident when using the data from all six watersheds.

The regional regression equation developed in this study was employed to predict trends in low flows considering the effects of both climate change and urbanization. The Cox-Stuart trend test indicated a significant decreasing trend in future low flows under the CCC climate predictions with both climate and land use change. On the other hand, a significant increasing trend in future low flows was observed using the Hadley climate predictions. Comparing the CCC and Hadley predictions of low flows under constant land use shows that the climatic inputs of temperature and precipitation have contradicting effects on low flows. These findings are explained by two arguments. First, the CCC model predicted a drier and warmer climate than the Hadley model. Second, low flows have a stronger dependency on precipitation than on urbanization or temperature. This is in agreement with the magnitude and signs of the exponents of the calibrated low flow model developed in this study, where precipitation has an exponent that is approximately two times greater in magnitude than the exponents of the temperature predictor and the imperviousness predictor.

Our findings were in contrary to a past study by Wilby et al. (1994) who found that urbanization has a greater influence on low flows than climate change. Furthermore, Querrner et al. (1997) concluded that temperature along with precipitation greatly impact low flows. However, we found that precipitation is the more pronounced driver of the direction of future low flow trends. Although both Hadley and CCC projected significant increases in temperature, they were not capable of offsetting the effect of precipitation. And each of the two climate models produced a different direction of change in low flows. This implies the need to improve the uncertainty associated with climate models, and more specifically on precipitation.

Geomorphology:

***Task 1G:* Develop watershed scale models to predict changes in channel morphology, sediment character, and sediment budgets caused by changing land use and climate**

We have developed a comprehensive model that predicts changes in streambed grain size distribution, elevation, and slope as functions of changing land use and climate (Pizzuto et al., 2005, 2006). The model derives inputs of water from hydrologic modeling results described above. Inputs of sediment have been determined in two ways. We calibrated the Water Erosion Prediction Project (WEPP) model for our urbanized study area using data obtained from a 12 year period between 1962 and 1974 (Schnick, 2005). This effort produced interesting and useful results. However, the WEPP model proved cumbersome to use in tandem with our hydrologic and geomorphic models, and therefore we also developed an empirical approach to predicting sediment inputs using the available data for our study area. Independent variables used in this empirical method include water discharge and the percentage of the watershed under construction.

In order to be useful for ecological prediction, the geomorphic model is unusually comprehensive, and several novel features are included that have not been quantified before. A very wide range of sediment grain sizes are “tracked” on the bed, including particles from sand (particles from 0.062 – 2 mm in diameter) to boulders (particles larger than 256 mm). Turbidity in the water column caused by suspended sediment is computed on a daily basis. The amount of mud in gravel pores is also tracked using a novel approach. Bed disturbance, as indicated by the areal extent of bed movement during hydrologic events, is also tracked on a daily basis. Finally, the geomorphic model also includes the effects of local bedrock exposures in mediating erosion and deposition in our study area, an effect that has been noted in several studies, but which has never been included in a numerical model before.

***Task 2G:* Calibrate and test these models using data obtained from related ongoing research in the study area.**

Several different approaches have been used for model testing and validation. We have completed a detailed sediment budget for part of our study area that documents patterns of sediment production and storage from 1952-1996 (Allmendinger et al, in review, 2004). These results provide an empirical framework for model testing. Additionally, we have applied our geomorphic models to the same watershed over the same time period to verify that model predictions are consistent with our observational data (Lewicki, 2004).

Task 3G: **Using the hydrologic modeling as the primary driver of geomorphic change, perform modeling scenarios to evaluate geomorphic consequences of climate change. Evaluate the interactions between changing climate and land use. Identify significant areas of uncertainty and evaluate how uncertainty influences ecological forecasts.**

The geomorphic models have been applied to a variety of multidecadal time periods that serve as useful scenarios to evaluate the relative effects of land use and climate change. One of the most revealing set of scenarios involved a comparison between present conditions and a future condition of global warming and surburban development (Pizzuto et al., 2005). The results of this comparison indicated that global warming and surburban development will result in 1) increased magnitude of storm flows, 2) increased bed mobility and disturbance, 3) increased transport of bed material, and 4) increased turbidity. In addition, the mud content on the bed and the fraction of bedrock in the active bed layer both exhibit dramatic variability under the future scenario of climate change and suburban development. Variability in both parameters is extreme, ranging from near 0 to almost 100% as flashy storm flows cause bed deposition and flushing during rising and falling stages.

Applying the geomorphic model to these scenarios has also highlighted the need for additional studies in key areas. These include 1) developing better methods to predict the supply of suspended and bed material from the watershed, 2) creating improved algorithms for mud storage on the streambed, and 3) enhancing our understanding of how bedrock exposures influence stream sedimentation on decadal timescales**.**

Stream Ecology:

Task 1SE: **Develop and test method to predict water temperature based on land use and climate change drivers**. Based on empirical data, we found that temperature surges were much more likely in small watersheds with high impervious surface. Given these conditions, summer temperature surges occurred (in the empirical data) on up to 10% of summer days, causing increases of up to 7^{o}C lasting for 1 to 3 hours. We modified an existing model of water temperature as a function of lagged air temperature. We added terms to this model for watershed size and temperature surge following a summer thunderstorm. This model, currently in press at JAWRA, predicts that temperatures will exceed those conducive to positive growth for cold-water game fish (brown trout) under urbanization scenarios, but not under climate change alone.

Task 2SE: **Develop and test method to predict entry of nutrients into stream, based on land use and climate change drivers.** We did not develop this model.

Task 3SE: **Develop rules/functions for species responses to physical habitat.** We proposed to identify a suite of 3 focal fish species, each of which is sensitive to a different stressor. Instead, we parameterized our ecological model for all 39 species present in the 4 watersheds. We conduct literature searches and solicited expert opinion to parameterize a matrix on characteristics for each of these species. This matrix of species-specific characteristics relating to stressor vulnerability will be in itself a valuable contribution to the literature.

As we predicted, the model was constrained to use as predictors only those variables that could be forecasted at appropriate scales and resolutions by the hydrologic and geomorphic models being developed in this project. However, this constraint pushed us to develop a highly practical and predictive model, using only readily available data, and also to interact extensively with our colleagues to develop novel models, e.g., predicting siltation.

Task 4SE: **Develop and preliminarily test a spatially and temporally explicit habitat suitability model which takes into account complex spatial relationships within the watershed and possibly within the channel, and produces predictions about habitat availability (along with measurements of uncertainty) for at least one of our focal species.** We proposed to build a relatively simple habitat model for at least one of our focal species, using the information gathered in Task 3SE as well as our initial predictions from economics, hydrology, and geomorphology. We did develop this model (FISSh, currently in review), which integrates input from hydrology, geomorphology, and stream temperature.

Initially we intended to develop a spatially explicit (GIS) model incorporating movement at different scales. However, it soon became clear that this model was intractable within the timeperiod available. Instead, we focussed on modelling the responses of all 39 species in the watershed. In this way, we were able to consider a variety of combinations of traits, and how these combinations affected vulnerability of the species.

Our model (FISSh) integrates five submodels (downscaled climate projections, stream hydrology, geomorphology, water temperature, and biotic responses), to predict biotic responses (fish growth and reproduction) to land use and climate change in Piedmont headwater streams of the eastern U.S. Our hybrid of population dynamics and habitat suitability modelling models entire fish assemblages based on readily available biotic information (including requirements for temperature, food, spawning) and day-to-day variability in stream conditions. The model takes into account such disparate processes as stream warming due to impervious surface and/or increased air temperatures; increased productivity and decomposition; flashier flow regimes; and higher siltation rates. We illustrate the use of our model by comparing predictions for two scenarios, a baseline scenario (low level of urbanization and present-day climate) and an urban sprawl / climate change scenario (‘stressed’ scenario; heavy urbanization and climate projections for the end of the century as simulated by the HadCM3 model). This model is currently in review at Ecological Applications.

Currently we are preparing a third manuscript comparing the effects of urbanization alone, climate change alone, and the two stressors simultaneously. Our results suggest that over ¾ of the species in the watershed will be highly stressed future scenarios, and that urbanization is a more immediate threat than climate change. On the other hand, climate change may selectively disadvantage native species by increasing the number of days on which non-native (mostly warmwater) species can reproduce and grow. Interestingly, in some cases where the average effect of urbanization is negative and the average effect of climate change is positive, the combination of the two stressors is disproportionately negative – i.e., more negative than would be expected from simply adding the two effects. This suggests that while climate change alone may benefit some species, it does not ‘mitigate’ the effects of urbanization. Where both climate change and urbanization have negative effects, the effect of combining the two stressors is additive.

As noted in the original proposal, we do not have the resources to validate the model. However, we designed the model to work as a series of comparisons between baseline conditions and future stressors. In addition, as proposed, our current manuscript is exploring multiple realizations of future climate.

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Relevant Web Sites: www.watersheds.umd.edu

Responses to Case Study Assessment Questions

Nancy Bockstael, Glenn Moglen, Margaret Palmer, and Jim Pizzuto

December 16, 2004

This set of responses is in reply to the "Case Study Assessment Questions" sent to our group by Betsy Anderson at ICF Consulting with regards to our group's involvement in studies of several urbanizing and urbanized watersheds draining to the Chesapeake Bay. Our group is comprised of four Principal Investigators spanning the disciplines of economics (Bockstael), hydrology (Moglen), geomorphology (Pizzuto), and stream ecology (Palmer). Before addressing the assessment questions, it's helpful to first include a brief overview of each of the components of the study we are undertaking:

Economics Component:

The economic component of this project focuses on forecasting land use change, where land use change includes both development of land previously in agriculture or natural vegetation and preservation of land (which entails the purchase of development rights by some government agency thereby preventing future development). It is unlikely that climate change will directly affect the development process in the study area, as the study area includes no coastal counties, there is no commercial forestry, and the agricultural activities are aimed at local markets. However, the focus of the project is the interaction of climate change and land use change over a time horizon of 50 years or more. As a consequence, it is important to consider how land use change may play out over the coming decades.

Using micro-level models of development decisions we are able to forecast year-by-year changes in the landscape. However, under current policies and regulations (specifically regulation on density of development), together with forecasts of changing population and incomes, complete "build out" occurs within 20 to 25 years. Complete build-out is defined as the state in which all land available for development is developed according to existing zoning regulations. While complete build-out may not come about within this specified period due to changing markets and regulations, anticipating such structural changes at a micro-level of analysis is not possible.

Hydrology Component:

The hydrology component of this project uses inputs from two drivers: land use change (from the economics component) and climate forecasts from two different GCM's. This gives rise to three different simulation scenarios:

1. Future land use change only
2. Future climate change only
3. Future changes in both land use and climate

The hydrologic component combines two different types of hydrologic models to estimates of streamflow at any location along the drainage network of each of the study watersheds. A spatially explicit version of the NRCS-TR55 model is used to estimate peak flows throughout the watershed as a function of the 1.5 year storm event (the storm that generally causes bankfull flow). A continuous streamflow model is used to estimate flows on a daily basis at the outlet of each of the study watersheds using current or future climate (temperature and precipitation) as drivers. Results from the continuous streamflow model may then be interpolated in space to any location in the watershed as a function of the NRCS-TR55 predictions for bankfull conditions. This combination of models provides a unique streamflow time series for any location in the watershed as a function of any of the scenarios enumerated above.

Geomorphology Component:

During the study, we completed field work and we also developed three types of models for geomorphology and sediment transport in urbanizing watersheds. Field work resulted in a suite of data useful for model calibration, as well as a detailed sediment budget for the Good Hope Tributary, a small subwatershed of Paint Branch. The three numerical models we developed included models predicting 1) changes in stream channel width, 2) sediment yield and the evolution of the bed material grain size distribution of the Good Hope Tributary for 1952-2045, and 3) the morphology and bed sediment characteristics of a reach subjected to changes in discharge and sediment supply caused by varying land use and climate. A model has also been developed that provides comprehensive predictions of the morphology, texture, and elevation of a reach. After considerable experimentation, we have found that the Watershed Erosion Prediction Program (WEPP) is not well suited for predicting the supply of suspended mud from the watershed, and so we have developed empirical relationships for this purpose. Our empirical equations predict both the volume and concentration of mud supplied to the reach as functions of discharge and the percentage of construction in the watershed. We have also included empirical relationships for estimating changes in pool depth and riffle frequency as functions of land use. These relationships are based on extensive field observation. These variables are particularly important for evaluating fish habitat, and therefore it has proven useful to include them in the model. In summary, this rather comprehensive model includes predictions of the state of the bed at a single location in a watershed under conditions of changing discharge and land use.

Stream Ecology Component:

As part of our ecological work, we completed extensive sampling on all 68 stream reaches within our four study. The urbanized streams had incised channels, lower baseflow, more extreme peakflows, and low levels of invertebrate diversity compared to the agricultural streams. However, the agricultural streams had extremely high nutrient levels and very low ammonia uptake compared to the urbanizing streams. Whole stream metabolism was also evaluated and data are being analyzed. Invertebrate diversity was strongly related to land use, showing a linear decline as the % of development increased (Moore et al. *submitted*). We found no threshold in the relationship between impervious cover and invertebrate species richness (Fig. 2) – the relationship was strictly linear and our close evaluation of data from other published work indicates little to no evidence for thresholds despite this commonly held belief. Of particular interest was the high diversity in agricultural watersheds – we attribute to pro-active conservation management and bmp's in our study regions (Moore and Palmer *in press)*. We also found a very strong relationship between invertebrate species richness in our most urban sites and the percent of the riparian buffer that is in forest (Fig. 3). To our knowledge, this is the first time anyone has demonstrated that despite high levels of impervious cover (up to 60%), if the riparian forest is intact then stream invertebrate diversity appears to be somewhat protected. This is not necessarily the case for nutrients – we believe high nutrient levels at some urban sites that have intact riparian zones may be the result of leaky sewer pipes and run-off from roads (we speculate some of this is from automobile emissions and from atmospheric deposition). Nutrient uptake (NH_4) was influenced by the presence of the riparian buffer but also depended on levels of nitrogen in the stream. The results have important implications for local-policy makers because the dominant goals for restoring the Chesapeake Bay are to reduce nutrient and sediment inputs yet the counties and states are using invertebrate biodiversity as a measure of watershed health. Our results suggest the need to not only consider how structure and function are linked in running-water ecosystems but to ask what benchmarks should be used to prioritize restoration and conservation efforts.

Assessment Questions and Responses:

Topic 1. Modeling frameworks/methods applied in each case study (including the drivers of modeling/method choices, difficulties encountered, whether and how geographic scale affected modeling/method choices)

1. ***What were the major factors that influenced your design or choice of a framework (e.g., familiarity with the model(s), technical aspects of problem and features of the model, existing data, consideration of scale, ability to incorporate ecosystem responses, generalizability of the framework to other watersheds). By "modeling framework" we mean the model or set of models and scenarios that together allowed you to project: (a) climate and land use change effects on watershed conditions; (b) consequent effects on ecosystem processes and functions, and; (c) changes in associated ecosystem services.***
2. ***How did you select the environment and ecosystem services that you are evaluating?***
3. ***How did you select the assessment endpoints used in the study?***
4. ***Which aspects of your process and results do you think can be extrapolated to watershed-scale research in your region or in general? Which processes must always be developed on a case-by-case basis?***
5. ***In retrospect, what are the strengths and weaknesses in your modeling framework for this type of analysis? Please describe them and any related suggestions you might have for future watershed case studies.***

Economics Response:

Question 1: The major factors influencing the choice of model were a) cutting edge theory of land use change from the real options literature in economics, b) the availability of previously developed parcel-level data over a period of 11 years for our study area, c) the need to incorporate the effect of policy instruments on outcomes, d) the need to reflect the path dependent nature of development and preservation decisions, and e) the need to capture the nature of the considerable uncertainty that exists in forecasting outcomes.

Real options theory views land use decisions as similar to financial options, in the sense that they are irreversible investments made under uncertainty. While real options approaches represent cutting edge theory in land use change, few empirical applications exist. We have framed both the development and preservation decisions in terms of this theoretical model and then made the model empirically operational using the parcel-level data over a period of 11 years. The first stage uses these historical data and incorporates factors that affect decisions to estimate the parameters of the land use change decision model. The estimated parameters together with forecasts of future populations and real incomes are then used to forecast future decisions.

This approach is desirable because it is 'process-based' modeling. It differs from 'pattern-based' modeling of land use change (e.g. using cellular automata models) in that it attempts to *explain* the development or preservation decision made by the landowner and it uses as the unit of analysis the parcel rather than a cell in the landscape. Only when the decision unit is the parcel can most regulations and land use policies be properly interpreted. The process-based model seeks to capture the decision environment of each landowner and explain in the context of a mathematical decision model why he chooses to take the action (either preservation, development, or status quo) that he takes in each time period. The decisions are affected by expectations (including mean and variance) of returns to different decisions, given current zoning and environmental regulations, site- specific characteristics, and demand for housing. Site specific characteristics include factors that make a particular parcel more profitable to develop, because of demand and cost considerations. They also include factors that make a parcel more desirable to preserve because of features of county/state purchase-of-development-rights programs. In both decisions what is going on around the parcel affects the decision. As a consequence, both estimation and forecasting requires continual updating of the landscape after each round of decisions is made. This is a particularly important feature of the modeling process which highlights the path dependent nature of land use change.

Even with a well-conceived model, there is a considerable amount of uncertainty generated by forecasts of future development and preservation decisions. This is true even in the immediate future. Uncertainty grows as the forecasts play out over time both because of the uncertainty about future policies and because of the path dependent nature of development and preservation decisions. Predicted probabilities of land use change are analyzed in terms of Monte Carlo simulations that produce multiple realizations of the future. This allows us to evaluate the likelihood of certain patterns of landscape change over time.

Question 2: Not applicable to Economics Component

Question 3: The endpoints of the economics analysis depend on what is required as inputs into the hydrology, geomorphology and ecology analyses. This is a projection of possible changes in land use/land cover in yearly time steps over the next several decades at the scale of the parcel. Using parcel boundary maps, it is possible to provide a complete vector coverage each year, with different annual realizations of this landscape provided by the Monte Carlo simulations.

Question 4: The modeling approach, specifically a) operationalizing the real options theoretical models, b) updating the landscape and c) describing multiple realizations of outcome, are all generalizable to other areas of the U.S. However, several important factors in formulating the specific decision models and parameterizing them are very site specific. Competing uses of land differ regionally as does the intensity of growth in the demand for housing. Most important, land use regulation takes place at the local level and must be incorporated differently for different regulatory environments.

Question 5: The strengths are embedded in the above discussions. The weaknesses are the data intensity of this approach. But with increasing reliance on geographic information systems to keep track of land parcels for tax and regulation purposes, such parcel-level data sets will be more readily available in the future. A second weakness is the inherent uncertainty described elsewhere.

Hydrology Response:

Question 1: Choices were made based on the needs of the geomorphology and stream ecology components of this project and on my own familiarity and expertise with existing models. With respect to the spatial explicit NRCS TR-55 model, the choice was driven by the sensitivity of this model to land use and by my own interests to generalize this point model into a model that could apply to any location along the drainage network. With respect to the continuous streamflow model, this choice was driven by the simplicity of the model (written in FORTRAN) and my ability to readily modify the code to accept time-dependent inputs. This model is similar in structure to the HSPF model but that model is unwieldy to use and does not allow for dynamic land use change.

Question 2: (N/A)

Question 3: (N/A)

Question 4: The general process undertaken in this study is fairly general. The results however are specific to these watersheds. The hydrologic impacts of land use change may vary greatly according to local conditions. Are agricultural areas being converted to urban areas (this is the general case near our study watersheds)? In this case, total runoff volumes are not substantially changed, but peak flows still increase owing to timing changes from urban structures like pavement and storm sewers. The result is enhanced peak flows. If the dominant land use change were from forest to urban the runoff volumes would increase substantially and the peak flow increases would be more dramatic. However, there are places where abandoned agricultural fields are reverting to forest – hear peak flows will be reduced. In more arid settings, urbanization may actually lead to reductions in flows because of the conversion of a desert landscape to lawns and other vegetation that might lead to runoff volume reductions and/or delays in runoff timing.

Question 5: The strengths in this approach are in its ease of application. Others with fair GIS skills and with very modest additional training could use the models developed in this work to make predictions for their location of interest.

The weaknesses include the model's dependency on good estimates of land use change and the consequences on runoff production from areas of changed land use. Further, estimates from this modeling approach give only daily averages. In locations where changes in streamflow response at less than a daily scale are needed the models will require either revision of models or expert interpretation of the daily flow estimates.

Geomorphology Response:

Question 1: The major factors were primarily my own personal assessment regarding what processes were important in the study area. Because these processes are not represented by any standard models, our group wrote our own. Models were written in FORTRAN and also using MATLAB.

Question 2: These were selected by the group, not by me.

Question 3: Assessment endpoints that I used were selected based on available data.

Question 4: The processes represented by my models are of regional, but not necessarily general (read: global) importance. All of the models will require calibration using site specific data.

Question 5: The strengths are related to the overall simplicity of an analytical models used. This simplicity is possible because detailed conceptual models exist for the relevant processes in the study area. The conceptual models are based on extensive fieldwork. This is both a strength and a weakness. The knowledge gained from the field work greatly improves the modeling framework, but the simplicity it leads to reduces the generality of the approach. Field work in other regions would lead to different methods for different regions.

Particular weaknesses of our models are related to 1) poor knowledge of boundary conditions, particularly sediment yield, and 2) lack of field measurements of sediment transport rates. The sediment supplied from the upland landscape must necessarily be specified for any geomorphic model, yet methods to perform this function are rudimentary or lacking entirely. In the present research, empirical equations were used that lack generality. Sediment transport functions were also not calibrated for local conditions, but were largely taken from recent laboratory and field studies performed elsewhere. This leads to considerable uncertainty in model predictions.

Stream Ecology Response:

Question 1: With respect to the (b) and (c):

We needed a model which would easily integrate input from land use, climate, hydrology and geomorphology, and we wanted to take advantage of the predictions from all of these inputs. This ruled out using an off-the-shelf model, although we did experiment with one in the beginning. We chose to write the model in Mathematica because of familiarity with this software. We ruled out a spatially explicit model in GIS because of writing process-based models in ArcView was too time- and resource-intensive.

We decided early on to model fish, because they integrate the multiple stressors, they provide a most readily communicable endpoint (e.g., most people care more about fish than about invertebrates), and they are relevant to the local structure and function of the stream (whereas nutrient concentrations are more relevant to the Bay itself).

We considered 3 major approaches to modelling: habitat suitability, population dynamics, and individual based models. We also considered using a focal species, a group of focal species, or the entire species pool. From these possibilities, we chose habitat suitability for the entire species pool. We chose the species pool because we wanted to look at more than game species, which are the best (only) studied species in the system, but are rare in headwater streams. We rejected individual based modelling because very little quantitative information is available to build process based models for most of the fish. This lack of information would also damage the credibility of any population dynamics model. By contrast, coarse resolution information necessary for a habitat suitability model is available for many species and can be inferred for the remaining species based on family or ecological similarities. In addition, this approach will allow us in the future to simulate “random” assemblages of species.

Question 2: Given the decision above to focus on habitat requirements for the species pool of fish, we developed (in conjunction with a fish expert) a list of the most important processes constraining habitat. These include temperature (for spawning; for survival of eggs and young of year; for dissolved oxygen, for growth of food resources); siltation (for clogging effects on eggs and gills, for decreasing feeding efficiency, for clogging hyporheic pores and hence reducing habitat space for invertebrate prey); flashiness (for washing away eggs, juveniles, and food resources); riparian zone loss (for decreasing allochthonous input and thus amount of invertebrates; for increasing light penetration); and amount of riffle vs pool habitat (for space for spawning, refuges, and habitat). Each of these processes is able to be evaluated within the model – that is, we have equations which predict, at least qualitatively and in some cases quantitatively, the necessary aspects of temperature, siltation, flashiness, riparian zone condition, and riffle vs. pool habitat.

Question 3: See #1 above. We model the suitability of habitat for various fish species. This does not mean we are predicting actual population levels or even persistence of populations within the reach, but we are predicting whether the reach is suitable for each species. In one sense this is a compromise required by the poor state of knowledge about small-bodied, non-game stream fish. However, it is also a strength of the model in that it allows us to look at large numbers of species, predict conditions for entire assemblages, and investigate the amount and direction of change that seems likely to occur in an assemblage.

Question 4: With regard to the ecological processes (e.g., not the hydrology and geomorphology drivers!), the models are written in a very general sense and should require only numerical changes in parameters to apply to streams throughout the Piedmont (although this may not hold if one wanted to compare streams with very different chemistry, requiring additional processes in the model to account for stream productivity and food supply). In addition, many of our processes are qualitative rather than quantitative. However, the stream temperature models would need to be recalibrated. In addition, our approach requires a matrix of coarse scale data on the various species, so a different species pool would require expanding/replacing this matrix. Finally, the model is temporally explicit, keyed to processes such as spawning times and leaffall, and these temporal relationships would have to be recalculated.

Question 5: Our main strength is ability to look at the entire assemblage and predict magnitude and direction of change in the assemblage, using the very sparse information available on many species in the streams. Our main weakness is that, as yet there is no “common currency” for the various stressors. For example, no one knows how to compare the stress of warmer water on eggs to the stress of siltation reducing habitat space for invertebrate (food) species. Since there is no common currency, we are left with reporting a collection of stress levels for each species, or the response of a set of species to a particular stressor. In the future, in order to predict the effects of anthropogenic stresses, we need more basic research on “uninteresting” species and better understanding of how to relate disparate kinds of stresses.

Topic 2. Processes used to establish and maintain stakeholder involvement (including choice of stakeholders, level of their engagement, the effect of geographic or political boundaries on choice of stakeholders and successful engagement)

1. ***How did you identify the stakeholders for your case study***
2. ***How did you engage them in the case study?***
3. ***What is the level of stakeholder involvement in your project? Please select one of the following categories and give a narrative description of their involvement:***
   - ***Minimal (briefed at the beginning and end of the project)***
   - ***Moderate (meetings or other communications at least quarterly per year, perhaps some involvement in the technical details of the project)***
   - ***Substantial (meetings and communications as often or more often than quarterly with stakeholders engaged in many of the technical details of the project)***
4. ***What were the ecosystem services that were priorities for your stakeholders?***
5. ***How did you determine the appropriate scale(s) for addressing the selected services, and what role did your stakeholders play in determining scale?***
6. ***Were stakeholders involved in refining the modeling framework for the study?***
7. ***Please describe lessons you learned in terms of the utility of stakeholder involvement and how to make the process useful and efficient.***

Economics Response:

The economics component did not interact with stakeholders except in giving a presentation in our meeting with stakeholders. However, largely because of this project (and the other EPA project) I developed a cooperative agreement with USDA on landowners decisions to enroll in agricultural preservation programs. It was this preservation decision that USDA was most interested in and I have worked closely last summer and this fall with a USDA economist to get the details right of the Howard County program.

Hydrology Response:

I would like to preface all responses below as preliminary since our project is still underway and these results indicate only past experience communicating with stakeholders and may not reflect future interactions. - GEM

Question 1: Stakeholders were identified three ways:

1. Montgomery County, Maryland, Department of Environmental Protection (DEP) served as a PI on our earlier Water and Watersheds grant. The group's relationship with DEP continues into this project.
2. Through invitation from among the PI's many professional relationships. All PI's are connected with the local and regional

“watershed-oriented” community. We simply brainstormed a list of those we thought would be interested in our project and invited them to a stakeholder meeting at the outset of our study.

3. Through consultation with EPA project manager, Catriona Rogers.

Question 2: Stakeholders were engaged through a large meeting at the outset of our project in November 2002. Conversations with Montgomery County DEP continue by phone, visits at their headquarters, and at PI meetings.

Question 3: Stakeholder involvement has been minimal for the large group invited at the outset of our project. It has and continues to be moderate for Montgomery DEP.

Question 4: Interests varied among our stakeholders. Many did not think in terms of “ecosystem services”. If you queried them further, the persistent responses would have centered on issues water quality, erosion and sedimentation, and habitat, among others.

Question 5: Scales were determined by data availability and model capabilities. Stakeholders had little input.

Question 6: No. The framework for the modeling approach was determined by the PI’s.

Question 7: The broad “net” we tossed in putting together our original stakeholder meeting attendee list led to attracting many who were probably interested in learning about our study, but I don’t think they really wanted to participate more actively than that. Everybody is busy with their own responsibilities and the stakeholder concept assumes that groups or individuals are willing to play an active role. This is rarely the case and many attendees seemed dumbfounded at the notion that we wanted to know what input/output they could provide or needed. Further the PI’s are busy and the scope of the project we outlined was ambitious without trying to satisfy additional requests from the stakeholder community. In an idealistic way, the stakeholder concept is wonderful. The reality is that both the PI’s and potential stakeholders are, in my experience, too limited by resources of time, money, and personnel to have stakeholder engagement lead to really substantial results. I think the EPA should re-think the stakeholder model.

Geomorphology Response:

(Not applicable to this question)

Stream Ecology Response:

Topic 3. Watershed management practices (including differences and underlying causes of differences in management practices, and the effect on the ability to respond to or incorporate case study results)

1. ***Prior to the start of your project, what management practices were being used to manage or protect ecosystem services?***
2. ***How did watershed managers (and other stakeholders) that you've dealt with initially think about climate change – as a linear and gradual process, as abrupt change, as something they're already dealing with? Did their involvement in your analyses change their perceptions?***
3. ***To what extent have the outputs of your project been designed specifically to help stakeholders improve their watershed management decisions?***
4. ***How might watershed management practices change as a result of the outputs of your project? If you suspect they won't, why not? What are the obstacles, if any?***

Economics Response:

Question 1: This topic does not apply directly to the economics component. However, environmental regulations exist that have an impact on development, and programs designed to preserve agricultural lands take some environmental considerations into account. For example, in Howard County, wetlands and other environmentally sensitive lands (e.g. steep slopes, certain soils, etc.) must be included in the open space portion of any development and cannot be built on. Also in Howard County, land in CREP easement programs, land that has wooded stream buffers, and land adjacent to environmentally sensitive areas is ranked higher in competition for land preservation funds.

Question 2: It is probably safe to say that government agencies involved with land use regulation do not see climate change as a pressing issue in our study area. The rapid and dramatic changes in the landscape due to development will likely overshadow any consequences of climate change over the next several decades.

Question 3: The analysis of land preservation decisions is aimed at helping in the design of agricultural preservation programs

Question 4: Except by providing a better understanding of the factors that affect preservation decisions (something which is not central to watershed management), the economics component does not address this issue.

Hydrology Response:

Question 1: Stormwater management regulations have been in place since the 1980's in an effort to mitigate the effects of urbanization on the landscape. Montgomery County DEP has been aggressive in seeking to actually retrofit stormwater facilities (detention ponds, wetland areas, etc.) to mitigate areas urbanized before the 1980's.

Question 2: To my knowledge, climate change is not yet a consideration of the watershed managers I'm aware of. These managers are more concerned with land development and other issues that have more clear-cut consequences at this time.

Question 3: (Not applicable to this question)

Question 4: I'm not speaking for hydrology in this response, but for this project as a whole. Ideally, our project will provide tools that should allow planners to forecast the possible range of impacts to their watersheds over time due to land use change, climate change, and any joint impacts of both. Managers might use these results to change policies that control how land is developed or otherwise used so as to avert negative changes in sensitive or susceptible areas.

There are at least two obstacles to this research being used in this way by managers:

1. The research needs to be communicated to them and they need to "buy-in" that this research is relevant and not just an academic exercise.
2. Uncertainty: if the error bars on impacts are too large managers may not place much confidence in this work or those that are limited in resources might actually use the uncertainty to justify non-response to this work

Geomorphology Response:

(Not applicable to this question)

Stream Ecology Response:

Topic 4. Methods for characterizing and communicating uncertainties and the receptivity of various stakeholder groups to the information

1. ***What information about risk and uncertainty do your stakeholders ask for, and is that information presently available or attainable? How have you communicated uncertainty to them?***
2. ***Is the magnitude of uncertainty in your results less than, in the same range, or greater than the uncertainty that they are accustomed to dealing with?***
3. ***Of the uncertainties you face in your case study, which are your results most sensitive to?***
4. ***What methods have you used thus far to characterize uncertainty?***
5. ***What is your communications strategy for delivering your results to current stakeholders (and other relevant stakeholders)?***

Economics Response:

Question 1: N/A

Question 2: N/A

Question 3: The results are most sensitive to broad brush assumptions we must make about future structural changes in land use regulations and future growth in population and real incomes. It is quite difficult to guess how the legislative process will respond to the continuing development pressures over the long run. Given current regulations, the developable land in our study area will be exhausted within a few decades, even assuming no land preservation. How society will address that challenge is difficult to predict. Also, forecasts of population and real income growth are subject to a number of uncertainties including future states of the economy, tax policies, immigration laws, gasoline shortages, etc.

The second source of uncertainty arises within the context of our model. We predict probabilities of development and preservation for each parcel, but owner idiosyncrasies will always play a major role in actual outcomes.

Question 4: Our methods for characterizing uncertainty are two-fold. At the broad brush level, we consider a few simplified but polar cases for how the long term may play out. At the micro-level, we include Monte Carlo simulations and evaluate the stability in the pattern of outcomes.

Question 5: We will communicate through papers, reports and presentations.

Hydrology Response:

Question 1: We haven't yet developed any final results so we have not yet been in the position of communicating uncertainty.

Question 2: I don't have any experience with how stakeholders deal with uncertainty so I can't address this question.

Question 3: This is a good question, but I don't know the answer. I believe as we play out the chain of information through each of the models we should get a better idea of where the sensitivities are greatest.

Question 4: Uncertainty is being characterized by examining the sensitivity of the hydrologic models to multiple realizations of the driver inputs. For instance, the economic models that drive the land use change are probabilistic and thus multiple realizations can be created that represent equal likelihoods of actual occurrence. We will propagate these equivalent realizations through the hydrology models and examine how streamflow estimates are affected. From the standpoint of climate change, we are examining projections from two different models (Hadley and PCM) so these estimates will, again, propagate through the hydrologic predictions as well. Further, by considering the three different scenarios outlined in the overview, we should be in a position to assert whether forecasts are more sensitive to land use or climate change and whether the two varying together have amplifying or compensating effects.

Question 5: As academics, the obvious outlet for communicating our results is through publications and presentations at conferences. Meetings, especially with Montgomery DEP have provided a good way to have an ongoing conversation with them about not just our final results, but intermediate results and difficulties.

Geomorphology Response:

(Not applicable to this question)

Stream Ecology Response:

Question 3:

- How stresses are combined – what is the "common currency"?
- Biology of understudied species (especially silt tolerance, temperature tolerance).
- Habitat suitability predicts only possibility. The possibility of a species surviving in a given location may not be realized if cannot reach the location (dispersal barriers) or is eliminated through interspecific interactions (competition, predation, etc).

Stakeholders Meeting – Attendee Information List

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> Expertise: Integrated assessment modeling and vulnerability to climate change with emphasis on both socio-economic and ecosystem aspects. Interested in alternative approaches to questions related to land use, pollution, development and policy.

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> Expertise: Public policy, education and regulation around urban stormwater and urban watershed issues, community and neighborhood-scale organizing.

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> Expertise: My background is in human-environment interactions. My current research is examining the environmental implications of population change in various metropolitan areas of the United States. I am attempting to project how population change … will impact air and water quality.

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> Expertise: I am a hydrogeologist with experience in surface and ground water modeling and monitoring, plus a bit of geomorphology work. I have developed temperature models and am happy to provide feedback for the water quantity and quality components of this project.

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Expertise: I monitor a site on Rock Creek for the Audubon Naturalist Society and am knowledgeable in macroinvertebrate identification. I am a member of the Executive Committee of the Montgomery Group of the Sierra Club

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Expertise: I work in the Chesapeake Bay Program to promote sound land use practices in order to reduce impacts of development on water quality.

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Expertise: Representing the Consortium for Atlantic Regional Assessment (CARA). The consortium is blending climate change models, land use change drivers, and decision science tools to aid in information delivery and decision making.

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> Expertise: I am interested in how land development influences the hydrology and geomorphology of stream basins. My interests include the effects of such development on runoff, recharge, base flow, and the geomorphic stability of stream channels.

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> Expertise: Non-academic, involved with Sierra Club and other green groups. Interested in the process of finding better solution to sprawl and development issues, reducing human impact on the local environment.

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