Applying Multiple Models to Inform Watershed Management and Land Use Planning in a Coastal Community

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1. **Expanded Executive Summary and Key Findings** (three page limit)

In the Chesapeake Bay watershed, land planners are tasked with reducing impacts of development on surface water quality to meet the federally mandated Total Maximum Daily Loads to the Bay. Watershed modeling provides an essential tool for explicitly stating the dominant hydrologic mechanisms hypothesized to control interactions between human stressors and the landscape and for making predictions about land management impacts to flow and water quality. Although numerous watershed models have been developed for the region, it has been difficult to take advantage of the results as a decision support tool. For one, the model applications often focus on land units that are relatively large compared to the scale of land management. In addition, it has been difficult to communicate the reliability and significance of the model predictions to the general public.

To overcome these limitations, we proposed using two innovative approaches: ensemble model averaging and source prioritization. Briefly, ensemble model averaging derives point predictions from competing (multiple) models, based on an average over the set of model outcomes. Model average predictions tend to be more reliable than estimates from any single model, especially when multiple parameters are being evaluated across multiple ungauged outlets (Boomer et al. *in review*). The source prioritization analysis identifies the sub-watershed areas most sensitive to land management practices by comparing predicted changes in flow and nutrient discharge due to land use change (Kalin and Hantush 2009). Areas that generate the largest increases in nutrient discharge per unit area were identified as the most sensitive or highest impacts area.

The study focused on Queenstown, MD, a Chesapeake Bay coastal community under increasing development pressure because of its proximity to Washington, D.C. and Baltimore. The Queenstown Planning Commission wanted to identify a growth strategy that would minimize environmental impacts while promoting economic development. We proposed to assist them by comparing impacts from alternative future growth scenarios using an ensemble model approach. The model set included a nutrient assessment spreadsheet developed by Maryland for municipal land planners (MDP) and three watershed simulation models: the General Watershed Loading Functions (GWLF), the Soil and Water Assessment Tool (SWAT), and the Chesapeake Bay Program's Hydrologic Simulation Program-Fortran (HSPF) Phase 5 application. We compared changes in predicted flow, total nitrogen (TN), and total phosphorus (TP) associated with four land use and land cover configurations and also two climate scenarios.

We expected variation in the absolute magnitude of the model predictions but that the model responses to alternative scenarios would trend similarly. Instead, we found that predicted impacts from the different land use and climate scenarios also varied by model. GWLF indicated that conversion of croplands to low density development would have the least impact on water quality due to the reduced nutrient loads and limited groundwater infiltration. The HSPF model indicated that no-till croplands would have the least impact on water quality because of its higher soil infiltration rates (as opposed to flash flooding from impervious surfaces) and relatively low nutrient concentrations compared to pasture, which is assumed to incur high rates of nutrient applications derived from livestock operations.

Results from the SWAT indicated that pasture-based, low-impact farming would have the least impact on surface waters because of higher nutrient uptake and evapo-transpiration rates. More importantly, differences in predicted nutrient loads among the alternative land use scenarios were relatively small compared to the variation in the predicted loads among the models for any single scenario. The relatively small changes in nutrient loads associated with different land use scenarios and the large differences among the models for any given scenario highlighted the uncertainty in the model predictions and the difficulty of using the complex models to inform land management decisions at the local scale. Despite the inconsistencies in the model predictions, all of the models indicated that both development and agriculture are significant non-point sources of nutrient pollution.

Variation in the model structures became even more evident with the long-term climate impact analysis. We used two climate change scenarios: the Hadley Centre Climate Model (HADCM2) predicted, slightly warmer temperatures (+2°C), and much greater precipitation (approximately 15 cm per year); and the Canadian Climate Center model predicted much warmer temperatures (+5°C) but much less precipitation (-10 cm per year). The GWLF model was more sensitive to HADCM2 climate scenario because of the increased groundwater flux to streams predicted to occur with the additional precipitation. These results were consistent with model's strong response to increases in development. The loss of groundwater recharge due to increased impervious surface coverage resulted in larger changes to the annual stream flow and nutrient load estimates. The SWAT model predicted more significant impacts to surface waters under the drier climate due to the enhanced evapotranspiration. Again, these SWAT results were consistent with the land use change analysis which indicated a strong response to changes in plant cover. Using a single model would have obscured these core assumptions regarding the relative importance of different hydrologic processes (i.e., runoff, groundwater transfer, and evapotranspiration). Yet these differences represent major uncertainties likely limiting our ability to model our hydrologic systems and adequately assess management alternatives.

Although the results of the ensemble model were informative from a scientific perspective, the similarity in the predicted loads under alternative land use scenarios using any single model ultimately shifted the Planning Commission's attention away from water resources to other planning responsibilities. In contrast to the watershed analysis, the impact analyses for these additional objectives, including economic development and traffic safety, were based on simple spreadsheet calculations or even a simple ranking based on consensus of a round-table discussion. Although the basis for evaluating impacts from the alternative land use scenarios on these additional objectives was much simpler than the environmental analysis, results ultimately yielded a much greater influence on the management decisions. As a result of this project, we suggest that complex, simulation watershed models have limited utility at municipal or county scales. Instead, watershed models likely are most appropriate and useful at a regional-scale for developing landuse-based loading coefficients, similar to the tool developed by the Maryland Department of Planning. Rather than assigning a single number, the multiple-model framework could be used to develop a probabilistic range of loading coefficients that also would communicate the uncertainty in the model predictions.

Key Findings:

- ***Applicability to a priority coastal issue:*** Given the urgency to improve water quality conditions across the Chesapeake Bay and to meet Total Maximum Daily Loads, we believe the project provides important information about the utility of watershed models for local land planning and also guidance for improving the watershed models to support future management decisions. The ensemble modeling approach had limited influence on local land management, but the model comparison provided an efficient strategy for understanding key differences in the underlying conceptual frameworks of the models and identifying key scientific knowledge gaps.
- ***Cost:*** From the Planner's perspective, the cost of developing complex watershed models was excessive and disproportionate to the decision support tools used to evaluate management impacts on other planning objectives. The multiple-model framework seems essential, however, to efficiently improving our ability to assess land management alternatives over time. We conclude that the cost is more appropriate for regional regulatory agencies, such as the Chesapeake Bay Program, which can oversee large collaborative efforts. The multiple-model framework could provide a basis for improving the MDP source assessment tool by developing a probabilistic range for each land used-based loading coefficient. At the same time, evaluating differences in the model output would provide a strong basis for developing our conceptual understanding of watershed processes and improving model performance.
- ***Maintenance Requirements:*** The multiple-model framework would provide an ideal basis for implementing an adaptive management strategy, provided the models appropriately predict impacts from alternative management scenarios on defined objectives. Accordingly, this would require on-going support and significant investment.
- ***Accuracy:*** The range of predictions highlighted the limited precision of the model predictions. The lack of observation data, however, prevented us from evaluating the accuracy. Based on other studies, the model average provides the most reliable point estimate, while the range of predicted range values provides a basis for communicating the uncertainty in the model predictions.
- ***Speed:*** Relative to the tools used to evaluate other planning objectives, the watershed models were extremely complex and time intensive. This realization further highlighted the limited utility of complex simulation models for local land management.
- ***Ease of Use:*** The simulation models require extensive time for implementation, and therefore, are not viable tools for most land planning agencies. Fostering collaboration among experienced modelers from federal and state agencies, academic institutions, and private entities would be a more effective approach to using watershed models. Success will hinge on how closely the partnership engages land managers in defining management objectives and alternatives, and subsequently developing appropriate modeling tools.
- ***User capacity requirements:*** The watershed models require extensive time for preparing input data, initializing the model, and calibrating the model, as well as summarizing the output data. The time demands of the complex simulation models primarily limit the user capacity. The loading coefficient models were much more appropriate given the available staff resources. Time and cost represent the biggest constraint to managers interested in adopting these tools.

2. Project Development

Abstract: To help meet federal and state mandates to reduce nutrient loads, Maryland requires that all municipalities prepare a non-point source discharge assessment as part of a Comprehensive Growth Plan. This mandate presented an ideal opportunity to integrate watershed science and management. Although numerous watershed models have been developed for the Chesapeake Bay watershed, it has been difficult for land managers to take advantage of these decision support tools. For one, the model applications often focus on land units that are relatively large compared to the scale of land management. In addition, it has been difficult to communicate the reliability and significance of the model predictions. To overcome these limitations, we used two innovative approaches: ensemble model averaging and source prioritization. We used four watershed models to assess impacts from four future growth scenarios and two climate change scenarios on surface water resources in Queenstown, a small coastal community representative of the rural communities that oversee land management throughout most of the Chesapeake Bay watershed and its shoreline. The model set included the Maryland State Non-Point Source Assessment and Accounting spreadsheet, and three simulation models: GWLF, SWAT, and the CBP-HSPF5. The simulation models were calibrated with data from three stream gages located approximately 20 km away from the study area. The simulation models performed comparatively well in predicting flow (R^2 range: 0.62 to 0.78; Nash Sutcliffe coefficient range: 0.6 to 0.77), and in predicting total nitrogen loads (R^2 and Nash Sutcliffe coefficient range: 0.34 to 0.65). For total phosphorus loads, the model predictions were more variable and generally poorer (R^2 range: 0.16 to 0.62; Nash Sutcliffe coefficient range: -0.05 to 0.38). When we used the calibrated parameters to predict flow and nutrient discharge in the Queenstown study area, differences in predicted water quality among alternative land use scenarios were small, within 10 percent of nutrient loads predicted under current conditions. These differences were especially small compared to differences among all of the model predictions for any single scenario, which varied by 100 to 300 percent. Predictions from the 100 year climate scenarios produced more distinct differences due to underlying differences in the model structures. Compared to SWAT, the GWLF model predicted more significant increases in flow and total nitrogen discharge under wetter climate conditions; whereas the SWAT model predicted larger decreases in flow and TN loads than did GWLF under the drier climate scenario. These differences likely occurred because the GLWF predictions responded largely to changes in precipitation infiltration and transfer to stream baseflow, whereas the SWAT predictions responded to changes in temperature and predicted effects on evapotranspiration. Variation in the models' response to land use and climate change was especially helpful for understanding differences in the model structure and identifying scientific knowledge gaps. The large differences in the model predictions together with the relatively small differences in discharge estimates from different land use scenarios, however, provided limited information for land managers. The models are better suited for regional identification of nutrient sources and identifying knowledge gaps limiting model performance. The multiple model frameworks can provide guidance for refining the models and improving their performance. Maintaining the ensemble through time could provide an efficient strategy for expanding our scientific understanding and ultimately providing more accurate and precise information to land managers.

Introduction

Despite reduced point source contributions, sediment and nutrient pollution remains high and habitat quality remains impaired across the Chesapeake Bay (Stankelis et al. 2003; Kemp et al. 2005). These trends emphasize the importance of non-point pollution sources (Boesch et al. 2001) which generally are associated with land uses and land cover. In addition, climate change effects, including shifts in the frequency and intensity of rain events, could exacerbate impacts from land management. Mandates by the federal government to improve impaired waterbodies will require municipalities across the Chesapeake Bay watershed to consider surface water quality impacts in the face of climate change when evaluating master development plans and water resource protection policies. Watershed modeling provides an essential tool for explicitly stating the dominant hydrologic mechanisms hypothesized to control the interactions between human stressors and the landscape, and for making predictions about land management impacts to flow and water quality. However, it has been difficult for land managers to take advantage of models, in part because model applications often focus on land units that are relatively large compared to the scale of management decisions, and also because it is difficult to communicate the reliability of the model predictions to land managers and the general public.

Ensemble model averaging provides an attractive alternative to relying on a single model, especially when there is not enough information to identify the best model or the data do not favor a particular model (Kadane and Lazar 2004). Briefly, point predictions are obtained from competing models, and overall predictions are based on an average over the set of model outcomes. If observational data are available, a weighted average can be calculated by considering how well each model has performed historically (Carpenter 1990; Tobias and Li 2004). From a scientific perspective, the multiple-model approach provides a framework for evaluating different hypothesis regarding the causal factors associated with the system dynamics. From a management perspective, the range of predictions from the model set provide a basis for communicating the uncertainty in the underlying science, and the model average provides a more reliable predictions than any single model prediction (Boomer et al., in review). Because our study area lacked long-term, continuous water quality data, we proposed using a multiple-model approach to support decision-makers while advancing scientific understanding of watershed processes. Convergence of the models' predictions would provide greater confidence in results, whereas differences in model predictions highlight uncertainties in the model structures.

A source prioritization analysis identified the sub-watershed areas predicted to have the strongest influence on surface water flow and water quality. Changes to stream discharge estimates due to incremental changes in land use are compared across sub-basins based on yield (discharge per unit area per year). The resulting rank index was used to optimally locating development areas or other high impact land uses.

On Maryland's Eastern Shore, where development pressures continue to increase, the Town of Queenstown provided an excellent opportunity to evaluate the utility of multiple watershed modeling in land planning. We proposed to predict impacts to surface water quality from different planning scenarios, as well as cumulative impacts of development through time. Due to the limitations of relying on a single model, we proposed to identify critical areas of the township based on averaged results from a suite of watershed models.

Objectives:

- Implement a suite of watershed models to predict flow, nutrient, and sediment discharge in response to development for the coastal community of Queenstown, MD.

- Estimate flow and nutrient discharge associated with changes in land cover, increased residential and commercial densities, population growth, and climate change by combining results from modeling efforts.

- Identify critical watershed sub-areas with the greatest potentials of impacting water quality; provide the Town of Queenstown with a set of maps and summary tables that describe impacts from projected land use and climate change scenarios.

- Provide the Chesapeake Research Consortium and the Chesapeake Community Modeling Program (CCMP) with summaries of our findings, model code, and input data. Information was made publicly available through their website and through CCMP-sponsored workshops and meetings.

Methods:

Study Area: The Queenstown study area includes 10.1 km^2 which occurs within the outer Coastal Plain physiographic province of Chesapeake Bay watershed (Figure 1). The planning area ranges from 0 to 10 meters above mean sea level and straddles two sub watersheds. The current densely developed municipality drains to the tidal portion of the Chester River. Development occupies 44 percent of the subbasin, and croplands and forest each occupy 24 percent of the subbasin. The remaining planning area drains to the Upper Wye River sub-basin. In this sub-basin, 10 percent of the watershed is developed; and croplands and forest occupy 60 and 30 percent of the subbasin, respectively (Table 1).

Technical Methods:

LULC Scenarios: To assess potential impacts from future development, a baseline scenario representing current conditions and three alternative LULC scenarios were developed with the Queenstown Planning Commission (Figure 2). The "distributed growth" scenario assumes full build-out across the entire planning area to the levels permitted by the current county zoning. Housing density would range between 1 and 20 acres per residential unit. In two "consolidated growth" scenarios, development would occur in designated areas adjacent to the current municipality while outlying areas would remain as croplands or forest. The consolidated build-out capacity was defined by assuming a 50 percent increase over the county zoning build-out capacity with additional commercial development to support that residential growth. The designated growth area was defined by assuming a housing density similar to the existing municipality targeted to locations adjacent to the current municipality but not in sensitive or flood-prone areas, including wetlands and areas within 300 m of streams. Approximately 70 percent of the Queenstown planning area would remain as open space in the consolidated growth scenarios. The two consolidated growth scenarios differed in the land management of the non-developed open space. In the consolidated, high impact scenario (Cons Hi), the open space is

used for row crops. In the second consolidated growth scenario, the open space is used as pasture (Cons Lo).

Future Climate Scenarios: We evaluated impacts from two climate change scenarios downscaled to a half-degree spatial resolution (Figure 3). The Hadley Climate Model 2 (HADCM2; Johns et al., 1996) forecasts a 5.5 cm increase in average annual precipitation with a 2.0 °C in temperature. In contrast, the Canadian Global Model (CGM; Flato et al., 2001) predicts precipitation will decrease by 14 cm with temperatures increasing by 5°C.

Modeling Approach: To compare impacts from alternative development and climate scenarios, we used four watershed models, including the Soil & Water Assessment Tool (SWAT; Neitch et al. 2001 a, b), the Generalized Watershed Loading Function (GWLF; (Haith et al. 1992), and the Chesapeake Bay Program's application of the Hydrologic Simulation Program FORTRAN (Cheung and Fisher 1995). We also implemented the Maryland Nutrient Assessment spreadsheet, a tool endorsed by Maryland to develop a state-mandated water resource impact analysis. The following provides a brief overview of each watershed model.

- GWLF is a lumped parameter watershed model (Haith and Shoemaker 1987; Haith et al. 1992). Precipitation is partitioned into surface runoff and infiltration using the curve number method, and estimates of groundwater recharge are based on differences between rainfall and runoff amounts. Seepage to groundwater is adjusted or calibrated to match the observed declines in streamflow following storms. Predicted nutrient loads represent a response to long-term average conditions. Solid-phase rural nutrient loads are given by the product of monthly sediment yield and average sediment nutrient concentrations. The yield in any month is proportional to the total transport capacity of daily runoff during the month. Urban nutrient loads, assumed to be entirely solid-phase, are modeled by exponential accumulation and washoff functions. Nutrient loads from septic systems are calculated by estimating the per capita daily load from each type of system and the number of people in the watershed served by each type. Key calibration parameters included the groundwater recession constant, and the nitrogen concentration in surface runoff.

- SWAT (Neitsch et al. 2002a, b) is a distributed, process-based hydrologic and water quality model developed to quantify impacts from LULC change and agricultural best management practices. The model's major components include hydrology, weather, sedimentation, soil temperature, crop growth, pesticides, and agricultural management. The model divides each sub-basin into hydrologic response units (HRUs), which are delineated based on similarities in land use, soils, and topographic slope. For each HRU, summarized landscape characteristics are used to estimate runoff and sediment yield based on the Curve Method method (US SCS 1986) and the Universal Soil Loss Equation (USLE; Wischmeier and Smith 1978). Groundwater recharge relates to differences between the amounts of rainfall and estimated surface runoff. It is one of the few watershed models that explicitly model biogeochemical processes affecting nutrient dynamics. Key calibration parameters included recharge rate, groundwater flow response to recharge, runoff curve number, soil infiltration capacity, and fertilizer application rate.

- HSPF: The Chesapeake Bay Program's HSPF application (CBP-HSPF) is a lumped-parameter simulation model that uses hourly meteorological data to drive water transport and storage through watershed segments. Modeled components include surface-water runoff, surface depression storage, ground-water flow, evapotranspiration, and interception by vegetation. Landscape attributes, including topography, land cover, hydrography, are used to define hydrologic response parameters that control the partitioning of water among different flow routes. Nutrient and sediment loads in response to management practices for major land uses are simulated with integrated sub-models. Organic and inorganic nitrogen constituent are estimated with a mechanistic model that simulates biological processes which regulate the transfer of land surface N-additions to different soil, water, and atmospheric pools. Phosphorus constituents are estimated using export coefficients which vary with land use and soil properties and are applied to calculate the percentage of the phosphorus pool that is delivered to streams. Total phosphorus delivery is closely associated with sediment delivery, which is estimated based on USLE-calculated erosion rates. In contrast to GWLF and SWAT, which were calibrated and applied only locally, the CBP HSPF was applied to the entire Chesapeake Bay watershed, though sub-basins are calibrated located. Key calibration parameters included the evapotranspiration coefficient, soil infiltration rate, the soil moisture storage index, and the ratio of shallow soil interflow to surface runoff.

- The MDE model is an export-coefficient model that assumes a constant TN or TP yield for each land use class (MOP (Maryland Office of Planning) 1993; MOP (Maryland Office of Planning) 1995; Tassone et al. 1998; MDP (Maryland Department of Planning) et al. 2007). The model has been used throughout Maryland to help local planners develop growth strategies that minimize aquatic impacts. The export coefficients are adjusted by the average amounts of impervious surface area associated with different developed land densities. The loading factors were derived from the Chesapeake Bay Program's CWM Phase 4 modeling effort. The model does not predict water discharge.

Input Data: We drove the models with inputs from meteorological, topography, land cover, and soils datasets. Hourly and daily weather data for 1985 - 2006 (precipitation, temperature, wind speed, relative humidity, dew point temperature, solar radiation, and cloud cover) were acquired from the CCMP website (www.ches.communitymodeling.org/models.php). A 10-meter DEM of the region was extracted from the USGS National Elevation Database (http://seamless.usgs.gov/) and used to derive topographic inputs. Soil properties were obtained from the Soil Survey Geographic database (http://soildatamart.nrcs.usda.gov/). Land use data were obtained from the 2002 MD LULC inventory (http://planning.maryland.gov/ourproducts/mapping.shtml) provided by the Queen Anne's County Planning Commission (2009). Plant nutrient and water uptake rates needed for SWAT were provided by the application's built-in database.

Model Calibration and Validation: Flow and water quality data were not available for the Queenstown study watersheds. Therefore, we calibrated and validated the SWAT and GWLF models using measured flow, TN, and TP discharges from six gauged watersheds located approximately 20 km east of the study area (Figure 4). Three watersheds (SERC 304, SERC310, and USGS at Greensboro) were used to calibrate the SWAT and GWLF models, and the other three watersheds (SERC 305, SERC 306, and USGS at Ruthsburg) were used to verify the

models. The calibrated parameters derived for each of three sub-basins (304, 310, and Greensboro) were averaged and then transferred to the models applied in the Queenstown area.

Model comparison and synthesis: We calculated a variation index to compare the variability among among predictions for the four LULC conditions by a single model and the variability among the predictions from all models for a single scenario:

$$(1) \qquad Variation\ index\ (\vartheta) = \frac{1}{n\bar{Q}} \times \sum_{1}^{n} |Q_i - \bar{Q}|$$

where n is the number of predictions in the target set; $\bar{Q}$ is the average of those n predictions for that target set, and Q_i is the ith prediction. A value of zero indicates all predictions are equal whereas increasing values indicate higher variability. We averaged the output from all of the models for each land use scenario and compared that the model average outputs for current conditions. Each model was assigned a weight for each constituent based on its performance at the validation sites using the equation:

$$(2) \qquad \lambda_{i,j} = \frac{e^{\left(Ens_{i,j}-1\right)}}{\sum_{i=1}^{n} e^{\left(Ens_{i,j}-1\right)}}$$

in which *Ens* is the Nash–Sutcliffe efficiency obtained from validation results, *i* is the model number with *n* being the total number of models used (3). The *j* index indicates the constituent (flow, TN, or TP). *Ens* can theoretically range from $-\infty$ to 1, where higher *Ens* values correspond to a better match of model simulation results to the observed data. The term $e^{(Ens_i-1)}$ has 0 as its lower limit and 1 as the upper limit, so superior models are assigned higher weights.

The Source prioritization factors (the sensitivity indices) were calculated for flow, TN, and TP to indicate the relative response of each HUC to the prescribed land use. The sensitivity indexes calculated for TN and TP were summed for each HUC unit to unify the environmental impact of that HUC unit in one factor called γ. Each HUC unit has three γ factors, one for each model. For each land use scenario, these factors were averaged and sorted from largest to smallest to obtain an aggregate ranking. Positive values represent negative environmental impacts (higher TN and TP loadings), whereas negative values indicate for improvement in the environmental conditions (less TN and TP loading).

Evaluation methods: From a technical perspective, we evaluated our success based on how well the watershed models reproduced observed flow and nutrient discharge in the calibration and verification watersheds. From a policy perspective, we evaluated our success based on a qualitative assessment of the utility of our work to the targeted stakeholders/intended users, the Queenstown Planning Commission.

Collaboration methods: To develop the project plan and disseminate the results of our efforts, we regularly attended monthly Planning Commission meetings. During these meetings, we developed the alternative build-out scenarios and presented the results of our modeling effort. For more technical issues, which required a finer level of detail than could be discussed at public meetings, we met in private meetings with the Planning Commission.

Conversations initially focused on defining land management objectives and developing management alternatives that were tractable and consistent with the anticipated population growth. Translating these qualitative zoning descriptions to spatial land use data sets which could be used as input to the watershed models also required extensive collaboration. During the later stages of the project, we worked closely with the Planning Commission to interpret the results and present them in a format that could be incorporated into a state-mandated water protection plan ("Water Resource Element") and other supporting documents.

Knowledge dissemination methods: We provided maps and written documents describing the current water resources and potential human impacts to those resources. These materials were incorporated into the Town's and Water Resource assessment and Comprehensive Plan. A subset of these materials also was incorporated into the Queen Anne's County Comprehensive Plan. In addition to the stakeholder outreach, we presented the results of our projects to the broader scientific and management community through a number of presentations.

- *Presentations:*

  Boomer, K.B., D.E. Weller, X. Li, L. Kalin, and A. Sharifi. Linking watershed modeling to local land management in a coastal community. 66th International Annual Conference of the Soil and Water Conservation Society. Washington, D.C. July 17 – 20, 2011.

  Boomer, K.B.. Using multiple watershed models to link science and land management. University of Maine. Orono, ME. October 13, 2010.

  Boomer, K.B. Using multiple watershed models to link science and land management. SERC Science Seminar Series. Edgewater, MD. October 7, 2010.

  Boomer, K.B., D.E. Weller, X. Li, and L. Kalin. The role of watershed models in municipal land planning and protecting aquatic ecosystems. 2010 Joint Meeting sponsored by the American Society of Limnology and Oceanography and the North American Benthological Society. Santa Fe, NM. June 6 – 11, 2010.

  Boomer, K.B., X. Li, L. Kalin, and D. Weller. The role of watershed modeling in local land management decisions. Integration & Application Network Seminar Series 2010. Annapolis, MD. May 20, 2010. http://ian.umces.edu/pdfs/ian_seminar_series_65.pdf

  Sharifi, A. and L. Kalin. Effect of land use uncertainty on watershed modeling. World Environmental & Water Resources Congress: Challenges of Change. Providence, RI. May 16-20, 2010.

  Boomer, K.B., X. Li, L. Kalin, and D. Weller. The role of watershed modeling in local land management decisions in MDcommunities. The Chesapeake Community Modeling Program's Chesapeake Modeling Symposium. Annapolis, MD. May 10-11, 2010.

  Xuyong Li, K. Boomer, (joint first authors) D. Weller, and L. Kalin. Flow and nutrient discharges from Eastern Shore Tributaries in response to climatic change. The

Chesapeake Community Modeling Program's Chesapeake Modeling Symposium. Annapolis, MD. May 10-11, 2010.

Boomer, K.B., P. Faux, B. Galloway, L. Kalin, X. Li, and D. Weller. Promoting Ecosystem-Based Management in a Chesapeake Bay Coastal Community. 2009 Chesapeake Research Consortium Conference. Baltimore, MD. March 22-25, 2009.

- *Journal articles, papers, and reports:*

  In prep: Sharifi, A., L. Kalin, K.M.B. Boomer, X. Li, and D. Weller. Multi model ensemble to assess impacts on water quality from changes in land use and climate in a Chesapeake Bay Coastal Community. *Target:* Journal of American Water Resources

  In prep: Li, X., K.M.B. Boomer, L. Kalin, A. Sharifi,, and D. Weller. Utility of a watershed model ensemble to assess climate change impacts to the DelMarVa waterways. *Target:* Journal of American Water Resources.

  K.M.B. Boomer 2010. Report: Water Resources Element for the Town of Queenstown.

Results and Discussion

Multiple Model Calibration and Validation: With one exception, all models performed comparatively well in predicting flow (R^2 range: 0.62 to 0.78; Nash Sutcliffe coefficient range: 0.6 to 0.77), and total nitrogen loads (R^2 and Nash Sutcliffe coefficient range: 0.34 to 0.65) (Table 2 and 3). The CBP HSPF model did not predict flow at the SERC 306 watershed as successfully as the other models. For total phosphorus loads, the model predictions were more variable and generally poorer among all models (R^2 range: 0.16 to 0.62; Nash Sutcliffe coefficient range: -0.05 to 0.38). The performance metrics did not change considerably between the calibrated and validation watersheds. Overall, no single model outperformed others in the model set.

Model Application – Evaluation of impacts from changes in land use and climate:
Impacts to flow and nutrient discharge from current conditions and three future alternative land use scenarios (distributed growth, consolidated growth, and consolidated growth with agricultural best management practices) were evaluated using the multiple watershed model framework (Figures 5 and 6). Overall, the models indicated that significant improvement to water quality could be expected only if best management practices were applied across 100% of the agricultural area in the planning area (Tables 4 and 5). The density and distribution of development considered in this study generally did not significantly influence predicted flow and nutrient discharge.

The impacts of the different land use scenarios varied by constituent and model. All models indicated that TN loads would decrease under all the growth scenarios because of the conversion of croplands to developed land. For any given model, predicted TN loads varied by less than 7% across the entire set of alternative growth scenarios (υ: 0.0 to 0.06). In contrast, predictions among all models for any specific land use configuration varied by 40 to 70 percent (υ: 0.1 to

0.2). The CBP5 HSPF model consistently predicted the highest TN loads while SWAT consistently predicted the lowest TN loads. Predicted impacts of future growth scenarios on TP loads were less consistent than the predictions for TN loads, but similar trends emerged when the variability of the predictions among alternative growth scenarios for a single model were compared with the variability of the predictions among all watershed models for a single growth scenario. Impacts from the different growth scenarios generally differed by less than 15% (υ range: 0.0 to 0.2), but model predictions for a specific scenario differed by 100 to 200% (υ range: 0.2 to 1.0). The SWAT model predicted major increases in TP loads to occur under any of the future growth scenarios, with the distributed growth scenario have the smallest impact. The CBP5 HSPF and GWLF model predicted the greatest decrease in TP loads to occur under the distributed growth scenario. The relatively small changes in nutrient loads associated with different land use scenarios and the large differences among the models for any given scenario, however, highlighted the uncertainty in the model predictions and the difficulty of using the complex models to inform land management decisions at the local scale.

Flow and nutrient discharges estimated using the 20 years of historical weather conditions were similar between SWAT and GWLF, but predictions using the 100 climate scenarios produced distinctly different trends (Figure 7). Using the wetter HADCM2 climate scenario, GWLF predicted approximately a 30 percent increase in flow and TN yield and a 20 percent increase in TP yield over current discharge rates. The SWAT predicted little or no change in flow and nutrient discharge. Using the warmer and drier CCC scenario, GWLF predicted a 30 percent decrease in flow and nutrient discharge. The SWAT predicted stream flow and nitrogen yield to decrease by more than 65 percent. The large differences between the two sets of model predictions were related to changes in the estimates of average annual evapotranspiration (ET). Estimated annual evapotranspiration rates increased from 69 cm, using historic period (1984-2005), to 80 cm using the warm, dry CCC scenario (2006-2099). While the increased temperatures explained a large proportion of the change, the lack of supplementary data in the future climate scenario also influenced the outcome. More specifically, for the historic period, observed daily solar radiation and wind speed data were available to generate evapotranspiration losses. For the future climate scenarios, only precipitation and temperature data were available. Therefore, SWAT generates the weather related data using an internal database of historical weather data. The generated data have monthly averages equal to observed monthly records available from a nearby climate station in the model's database. The higher solar radiation predicted for future by SWAT weather generator in addition to the temperature increase foreseen by HADCM2 resulted in the higher of evapotranspiration and lower runoff generation for future compared to the historic period. In contrast to the LULC analysis, TP predictions under both climate change scenarios were most similar between the two models.

Model Application – Identifying critical source areas: Results of the source prioritization analysis indicated that QT HUC QT13, located mostly outside of the Queenstown Planning Area on the Upper Wye River, is expected to be most sensitive to human impacts, followed by QT HUC QT01, where the municipality is established (Table 6). The sensitivities of the sub-watersheds varied with the land use scenarios. For example, HUC QT8 is ranked second in the distributed growth scenario, but has a relatively low impact rank in either of the consolidated growth scenarios. QT HUC07, located closer to the headwater areas of the Upper Wye River and on the edge of the Queenstown Planning Area, had the greatest variation in the sensitivity

index. Overall, impacts increased under the consolidated growth scenario without agricultural BMP implementation. Positive impacts or a reduction in nutrient loads were predicted for either the distributed growth option or the consolidated growth option with agricultural BMP implementation.

Decision support and outreach: Watershed models currently are most useful at a regional scale, or in a research context. Implementing a multiple model framework, or model ensemble, to evaluate impacts from long-term climate scenarios was an effective way to explicitly recognize how differences in the underlying model frameworks influence model predictions. Given the time and financial resources needed to implement even a single model and the lack of precision in the model predictions, we concluded that the simulation models provide limited value to local county and municipal land planners. The lack of more sophisticated tools to evaluate management impacts on other planning objectives resulted in a disproportionate evaluation of the alternative land management strategies. Even though more effort was invested in the watershed analysis, the analysis had relatively little influence on the decision-makers (Table 7).

3. STATE OF THE TECHNOLOGY

Rather than relying on a single model to guide land management decisions, we explored the utility of a multiple model framework. We believed that this approach would provide a strategy to deal with model errors in a management context (Viney et al. 2009). Using a single model limits our ability to communicate uncertainty in the model predictions, potentially leads the public to distrust science when the model inevitably fails. Using multiple, competing models provides a strategy for explicitly highlighting different hypotheses (and uncertainty) in the model structure. Tracking model performance and subsequent model refinement will improve model performance over time. Because of the resources needed to implement even a single model, and also interpreting the model results, we suggest this level of effort is best conducted by regional regulatory agencies. These organizations have the capacity to coordinate modeling efforts across multiple research teams and integrate the results to support land management. Presenting model averaged loading coefficients along with the range of predicted loading rates represents one strategy for using the model ensemble.

4. NEXT STEPS

Results from this effort and our previous work in Maryland's Patuxent River watershed demonstrate the challenges to predicting nutrient loads and guiding land management, but also the advantages to using an ensemble model approach to improving our understanding of the uncertainty in the models as well as the source(s) of that uncertainty. In addition to completing the manuscripts, we will continue to use our work to advocate for using an ensemble model approach for developing county-based Total Maximum Daily Loads across the Chesapeake Bay watershed and assessing alternative land management strategies.

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Table 1: Land use currently and under three future build-out scenarios for the Queenstown Study Area

Scenario	Watershed	Area (km^2)	Land Use %				
			Urban	Forest	Cropland	Pasture	Other
current	Chester river	4.7	43.9	23.3	23.9	0.0	8.9
	QT Creek	8.3	14.4	22.7	57.2	0.8	4.9
	Upper Wye	24	10.2	25.2	59.6	0.0	5.0
	Queenstown	37	15.5	24.4	54.6	0.2	5.4
Build Out	Chester river	4.7	31.4	35.8	23.9	0.0	8.9
	QT Creek	8.3	27.3	22.8	44.3	0.8	4.9
	Upper Wye	24	23.6	26.6	45.1	0.0	4.8
	Queenstown	37	25.4	26.9	42.2	0.2	5.3
Cons. Hi	Chester river	4.7	31.4	35.8	23.9	0.0	8.9
	QT Creek	8.3	22.1	22.8	49.5	0.8	4.9
	Upper Wye	24	14.8	25.8	54.6	0.0	4.8
	Queenstown	37	18.5	26.4	49.5	0.2	5.3
Cons. Lo	Chester river	4.7	31.4	35.8	23.9	0.0	8.9
	QT Creek	8.3	22.1	22.8	44.3	6.0	4.9
	Upper Wye	24	14.8	25.8	45.1	9.5	4.8
	Queenstown	37	18.5	26.4	42.2	7.5	5.3

Table 2: Calibration results

Watershed & Time period		*SWAT*		*GWLF*		*HSPF-CBP5*	
	Variable	R^2	Ens	R^2	Ens	R^2	Ens
SERC 304 Apr-1989~Dec-1992	Flow	0.7	0.67	0.74	0.77	0.67	0.66
	TN	0.58	0.36	0.65	0.56	0.52	0.49
	TP	0.46	0.26	0.28	-0.3	0.31	0.10
SERC 310 Jul-1990~Oct-1995	Flow	0.73	0.69	0.76	0.73	0.77	0.75
	TN	0.74	0.54	0.74	0.61	0.80	0.77
	TP	0.14	-1.66	0.19	-0.92	0.31	-0.07
USGS Greensboro Jan-1984~Dec-1999	Flow	0.7	0.67	0.74	0.7	0.73	0.73
	TN	0.63	0.49	0.55	0.59	0.75	0.73
	TP	0.29	0.11	0.52	0.3	0.49	0.45

Table 3: Validation results

Watershed & Time period		*SWAT*		*GWLF*		*HSPF-CBP5*	
	Variable	R^2	Ens	R^2	Ens	R^2	Ens
SERC 305 Apr-1989~Dec-1992	Flow	0.78	0.73	0.62	0.6	0.65	0.64
	TN	0.5	0.44	0.65	0.5	0.58	0.57
	TP	0.42	0.38	0.41	-0.05	0.28	0.18
SERC 306 Apr-1989~Feb-1992	Flow	0.64	0.54	0.63	0.6	0.38	0.34
	TN	0.65	0.59	0.57	0.55	0.34	0.34
	TP	0.62	0.21	0.37	0.36	0.16	0.1
USGS Ruthsburg Nov-2000~Mar-2005	Flow	0.66	0.61	0.69	0.62	0.64	0.63

Table 4: Total nitrogen (TN) loads (kg/year) and variation indices for predictions among land use scenarios and among models for a single scenario.. The model set included the Maryland Department of Planning's Non-Point Source Assessment Model (MDP), the Chesapeake Bay Program's Hydrologic Simulation Model (CBP5), the Generalized Watershed Loading Function (GWLF), and the Soil Water Assessment Tool (SWAT). The Queenstown Planning Area straddles the Lower Chester River and the Upper Wye River watersheds.

TN Loads to the Lower Chester River

Growth Scenario	MDP	CBP5	GWLF	SWAT	Variation Index
Current	**14,197**	**14,586**	**12,807**	**10,105**	**0.11**
Distributed Growth	**13,432**	**13,927**	**12,017**	**8,440**	**0.15**
Consolidated, No BMP's	**13,681**	**13,977**	**12,338**	**8,983**	**0.13**
Consolidated, Ag BMPs	**13,007**	**13,582**	**12,018**	**9,164**	**0.12**
Scenario Mean Variation Index	0.03	0.02	0.02	0.05	

TN Loads to the Upper Wye River

Growth Scenario	MDP	CBP5	GWLF	SWAT	Variation Index
Current	**37,166**	**47,374**	**35,287**	**31,166**	**0.13**
Distributed Growth	**36,419**	**42,205**	**37,426**	**25,121**	**0.14**
Consolidated, No BMP's	**36,154**	**44,302**	**34,541**	**29,112**	**0.12**
Consolidated, Ag BMPs	**35,291**	**42,420**	**37,810**	**29,858**	**0.10**
Variation Index	0.01	0.04	0.04	0.06	

Table 5: Total phosphorus (TP) loads (kg/year) and variation indices for predictions among land use scenarios and among models for a single scenario.. The model set included the Maryland Department of Planning's Non-Point Source Assessment Model (MDP), the Chesapeake Bay Program's Hydrologic Simulation Model (CBP5), the Generalized Watershed Loading Function (GWLF), and the Soil Water Assessment Tool (SWAT). The Queenstown Planning Area straddles the Lower Chester River and the Upper Wye River watersheds.

TP Loads to the Lower Chester River

Growth Scenario	MDP	CBP5	GWLF	SWAT	Variation Indices
Current	**685**	**1071**	**905**	**1385**	**0.21**
Distributed Growth	**693**	**944**	**784**	**2961**	**0.60**
Consolidated, No BMP's	**679**	**980**	**833**	**3122**	**0.61**
Consolidated, Ag BMPs	**615**	**963**	**818**	**2972**	**0.61**
Variation	0.04	0.04	0.04	0.19	

TP Loads to the Upper Wye River

Growth Scenario	MDP	CBP5	GWLF	SWAT	Variation Indices
Current	**2,182**	**3,718**	**2,678**	**4,624**	**0.92**
Distributed Growth	**2,088**	**2,963**	**2,541**	**9,001**	**1.00**
Consolidated, No BMP's	**2,092**	**3,278**	**2,668**	**10,966**	**1.03**
Consolidated, Ag BMPs	**2,024**	**3,196**	**2,995**	**9,041**	**1.02**
scenario mean Variation	0.02	0.07	0.05	0.23	

Table 6. Results of source prioritization analysis of the sensitivity of Queenstown HUC units to human impacts from development or agriculture. The red color shows negative impact (more nutrients released whereas blue ones had positive (less nutrients released) environmental impacts. The values were based on predictions for flow, TN, and TP by the three simulation models including the Chesapeake Bay Program's Hydrologic Simulation Model, the Generalized Watershed Loading Function, and the Soil Water Assessment Tool.

Rank	Build Out	Cons. Hi	Cons. Lo
1	QT13	QT1	QT13
2	QT8	QT13	QT1
3	QT1	QT7	QT16
4	QT12	QT16	QT12
5	QT6	QT8	QT4
6	QT4	QT4	QT6
7	QT16	QT6	QT17
8	QT17	QT12	QT14
9	QT14	QT10	QT5
10	QT5	QT17	QT8
11	QT2	QT7b	QT10
12	QT19	QT14	QT7
13	QT9	QT5	QT9
14	QT18	QT9	QT19
15	QT10	QT2	QT18
16	QT3	QT19	QT2
17	QT7b	QT18	QT3
18	QT7	QT3	QT7b

Table 7: Decision framework developed by the Queenstown Planning Commission to evaluate impacts on different planning objectives from the alternative future land use scenarios. Because no significantly different impacts to surface water resources were predicted for the alternative growth scenarios, the related objectives effectively cancelled out of the decision-making framework.

Concern	No Growth	County-Zoned Growth	Consolidated Growth
ENVIRONMENT			
Minimize TN loads	ChR: -5%; Wye: 1%	ChR: -4%; Wye: -3%	ChR: -8%; Wye: -5%
Minimize TP loads	ChR: 1%; Wye: -4%	ChR: -1%; Wye: -4%	ChR: -10%; Wye: -7%
Maximize open space (forest & ag)	1,782 acres	1,639 acres	1,750 acres
Limit development in headwater reaches	1	3	2
Limit development in critical areas	1	2	3
COMMUNITY DEVELOPMENT			
Facilitate professional job development	3	2	1
Minimize infrastructure sprawl	1	3	2
Minimize suburban sprawl	1	3	2
TRANSPORTATION			
Maximize access to regional highways	3	2	1
Provide access to areas S of Rte 50	3	3	1
Promote pedestrian friendly community	2	3	1

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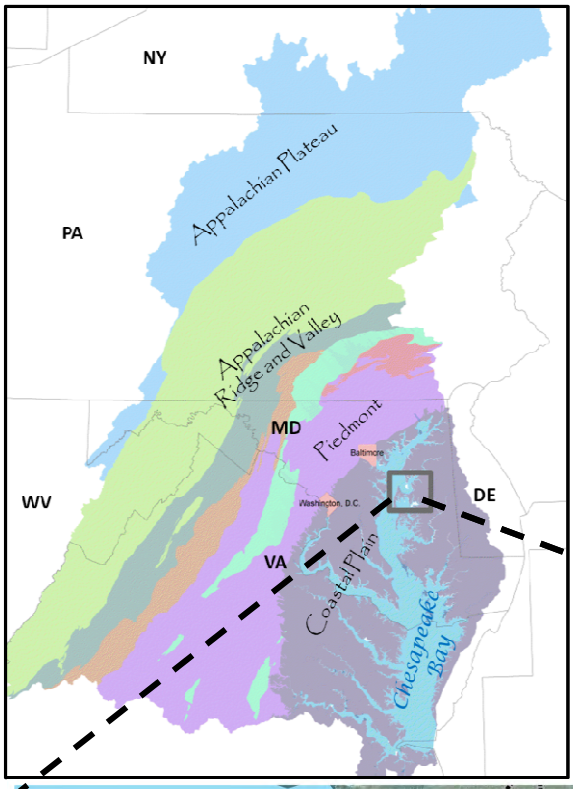
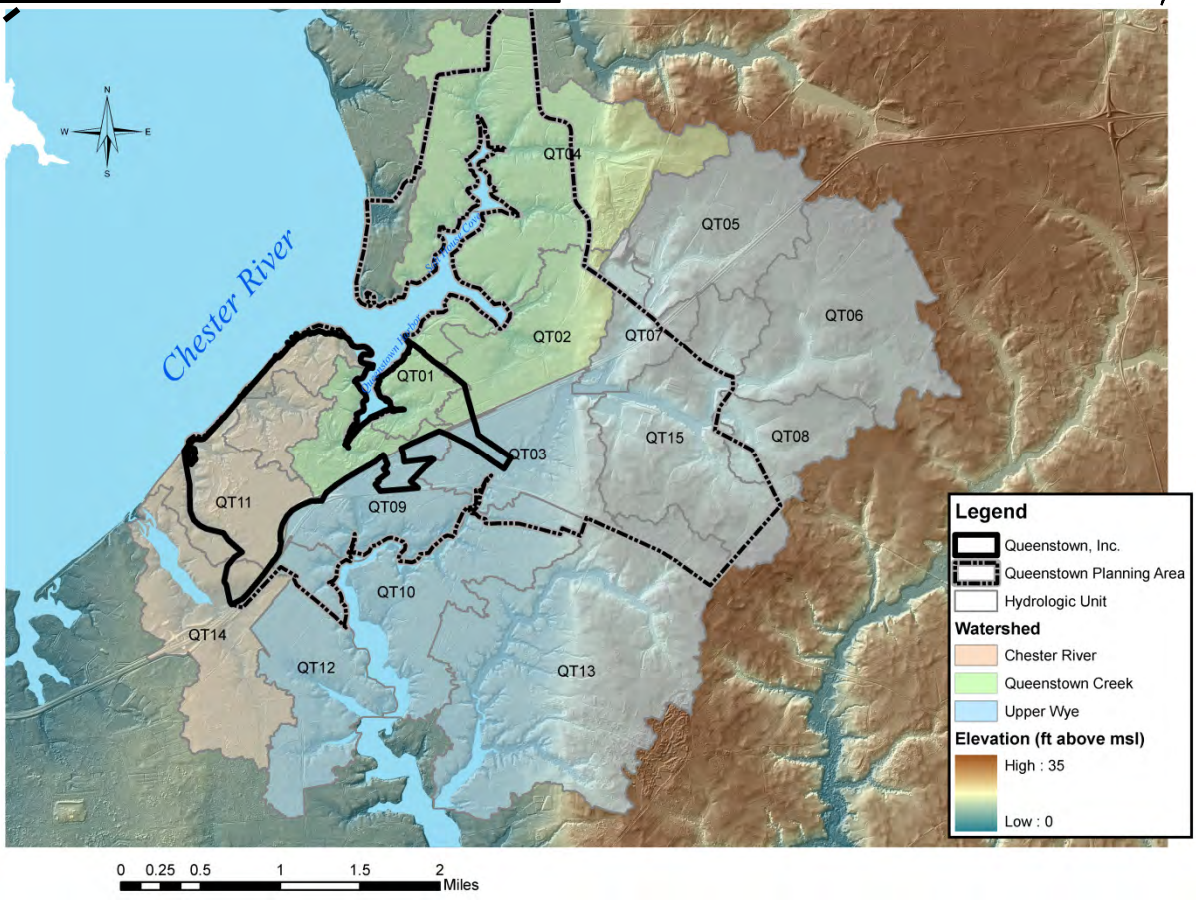




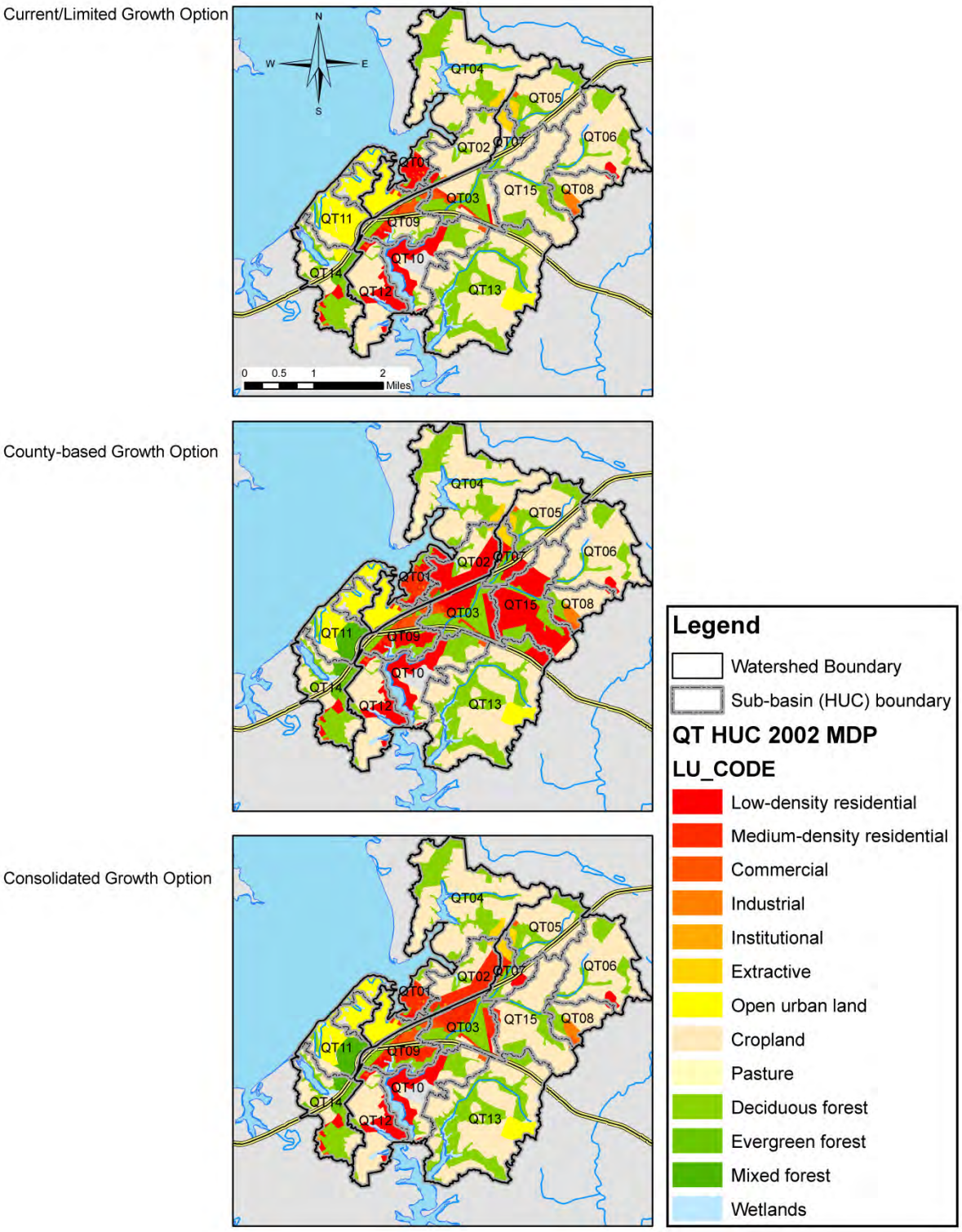
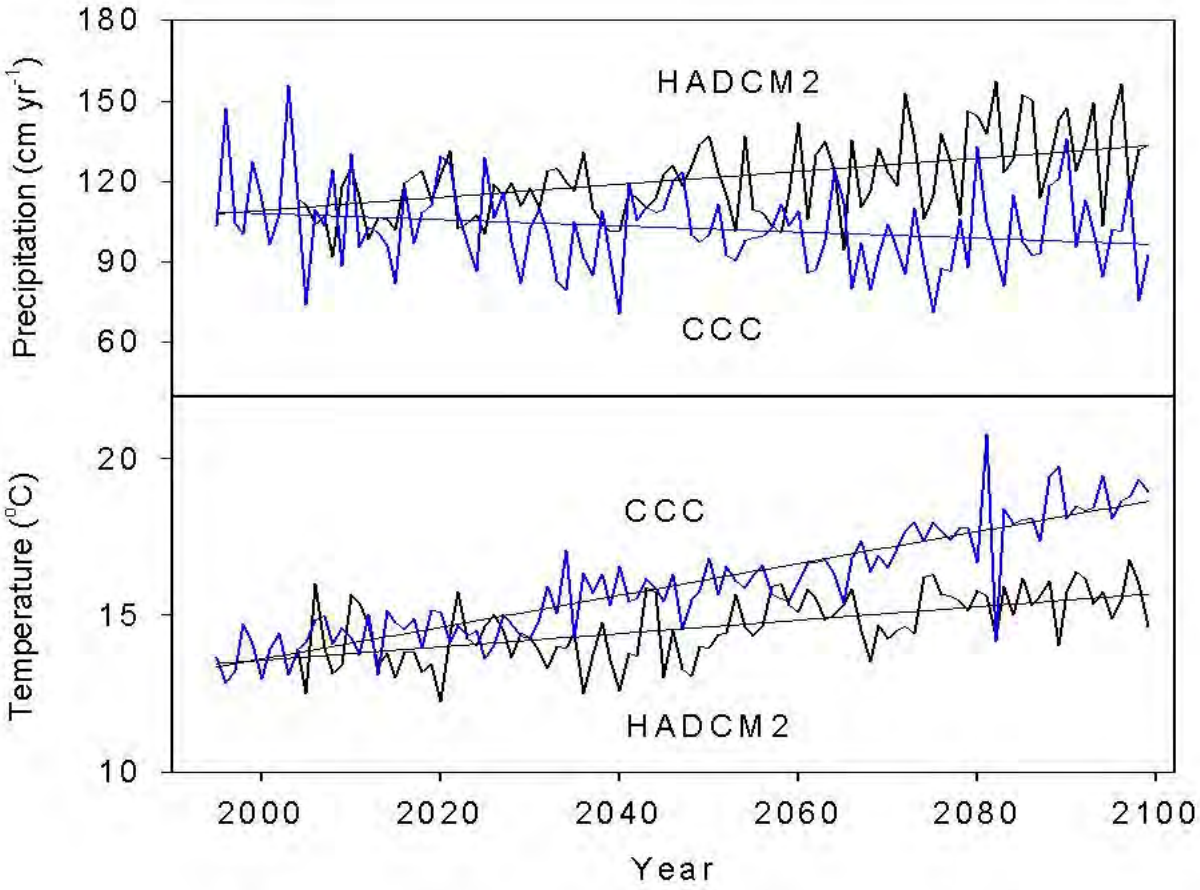


Figure 2. Land cover/land use configurations for evaluating effects of land use change in the Queenstown Planning Area.; a) Current conditions according to the MDP 2002 LULC data set; b) Future distributed growth scenario assuming full build-out allowed by current county zoning; c) future consolidated growth scenario in which all growth occurs adjacent to the existing municipality with comparable low-to-medium residential density,



Parameter	GCM	Change by 2095
Temperature (^{0}C)	HAD	+2.0
	CCC	+5.0
Precipitation (cm)	HAD	+16.8
	CCC	-14.8
Precipitation (%)	HAD	+14.4
	CCC	-12.7

Figure 3. Future climate conditions predicted by the Hadley Center (HADCM2) and Canadian Climate Center (CCC): a) Precipitation; and b) Temperature

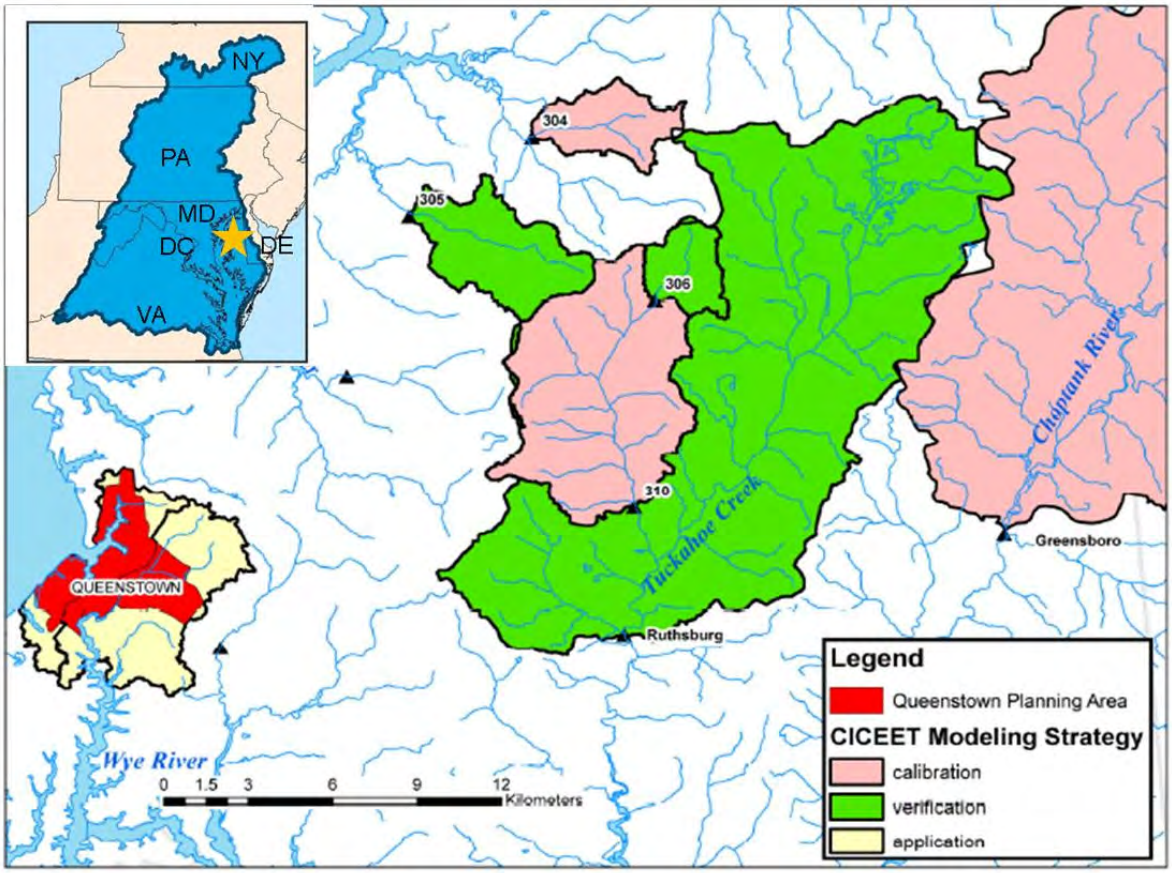


Figure 4. Calibration and verification watersheds located near the Queenstown study area / model application areas.

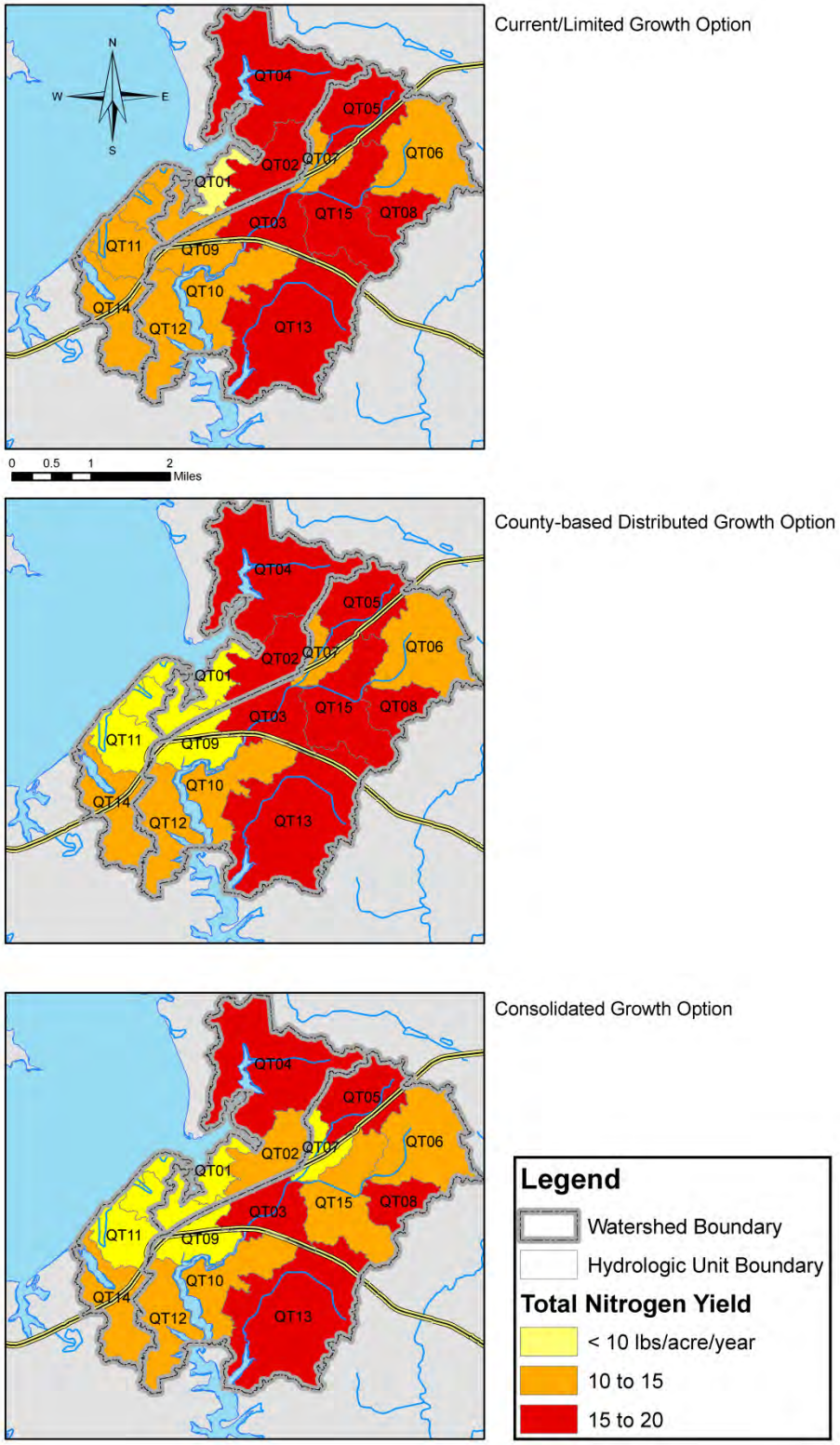


Figure 5. Annual average total nitrogen (TN) yields associated with alternative land use/land cover configurations in the Queenstown Planning Area. A) Current conditions according the to 2002 MDP LULC data; B) Future distributed growth scenario assuming full build-out under county zoning; and c) Future consolidated growth scenario in which all growth occurs adjacent to the current municipality with comparable low-to-medium residential density.

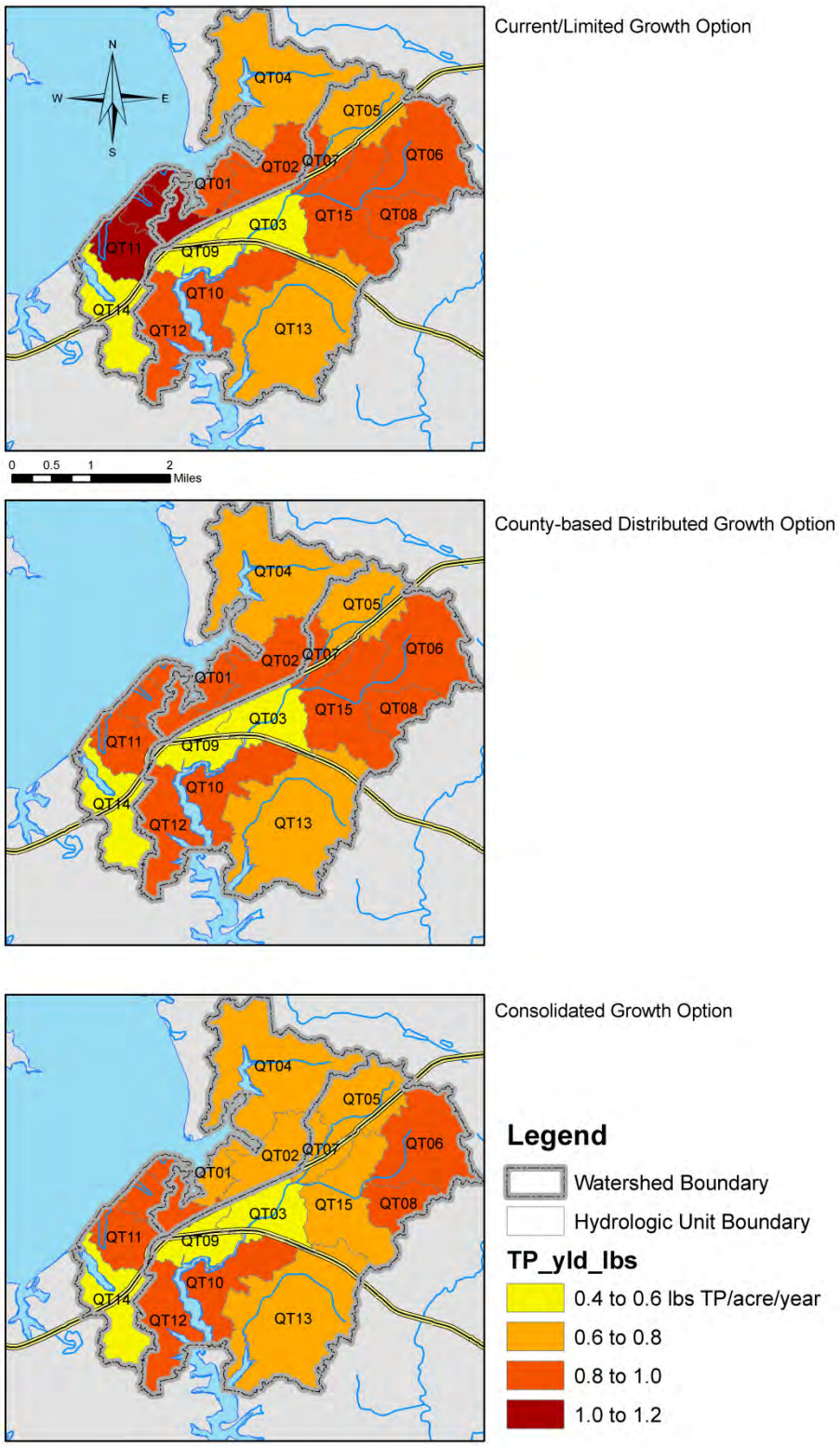
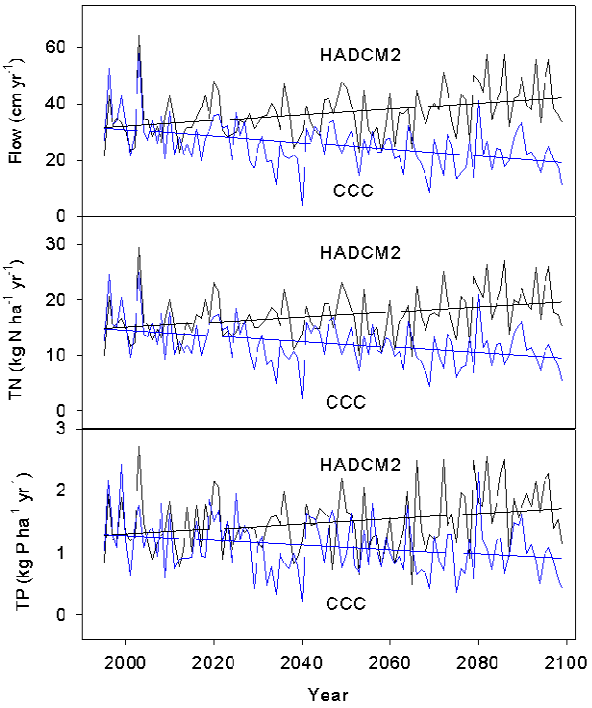
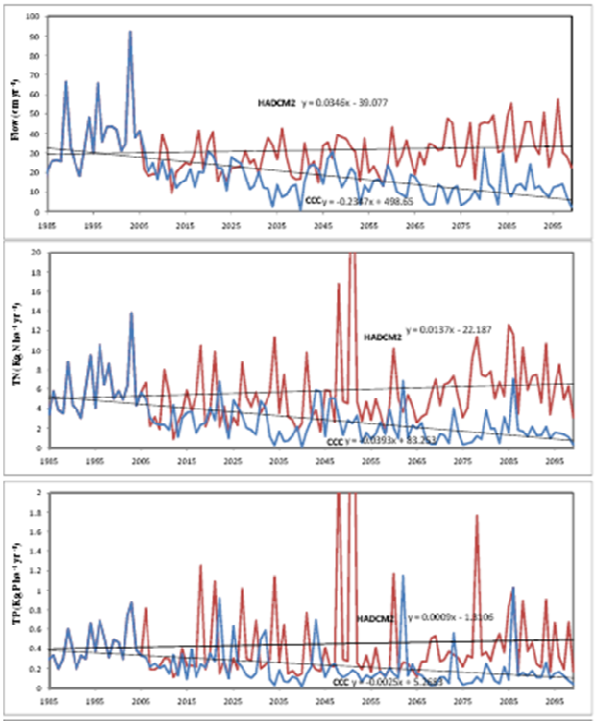


Figure 6. Annual average total phosphorus (TP) yields associated with alternative land use/land cover configurations in the Queenstown Planning Area. A) Current conditions according the to 2002 MDP LULC data; B) Future distributed growth scenario assuming full build-out under county zoning; and c) Future consolidated growth scenario in which all growth occurs adjacent to the current municipality with comparable low-to-medium residential density.





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