APPENDIX 2: PREDICTIVE MODELS AND INTEGRATION

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I. Introduction

What is an integrated predictive model?

A model is a simplified representation of a phenomena or process. Predictive models usually take the form of a series of equations, which represent the relationship between the outcome of interest and expected drivers and mediating factors. The integration of existent regional models allows us to represent the coupled human-natural system by exploring the interaction between urban dynamics and ecological processes. By linking models that have already been developed and validated, we can increase the representation of relationships between subsystems. An example of an integrated model is a regional existent integrated model used by the UERL lab which integrates an urban development model (UrbanSim), a land cover change model (LCCM) and avian diversity model (Heppinstall et al 2008). The avian diversity model assesses the spatial distribution of bird communities as a consequence of urban development and resultant land cover change.

Why are we developing an integrated predictive model for this project?

The objective of the Snohomish 2060 Scenarios project is to explore how alternative future conditions will influence the efficacy of policies intended to maintain ecosystem services in the Snohomish Basin in 2060. Regional experts constructed the scenarios to explore the uncertainty and relationships between critical driving forces that cannot be described by past events alone. The model integration phase of this project is pursued to complement the scenarios by 1) exploring potential relationships between systems represented by separate existent regional models and 2) quantifying future baseline conditions associated with the alternative futures scenario hypotheses. By linking models we can estimate a plausible range of future baseline conditions of ecosystem services. Based on each scenarios' narrative, we can modify model assumptions and adjust model parameters. If the integrated model is sensitive to the differences between the scenarios, then the outcome (ecosystem service) will vary across the scenarios.

Predictive modeling and the development of scenario narratives are a nice compliment, as the strength of each of these addresses the limitation of the other. While the scenario narratives tell the story of what the future could look like depending on trajectories of important and uncertain driving forces, they are not suited to quantify the potential effects on the suite of ecosystem services of interest. On the other hand, predictive models can estimate baseline conditions and test hypothesized relationships between driving forces and baseline conditions, but are not suited to identify novel trajectories and interactions between uncertain drivers.

How are we developing an integrated predictive model for this project?

The blueprint for the integrated model will be created from discussions among regional modelers in personal interviews and a model workshop. We have identified an initial list of 10 regional models that simulate future ecosystem service conditions or driving force trends.

Models were selected based on the following criteria:

- Models that represent at least one of the 6 ecosystem service areas (species and habitat biodiversity, water quality and quantity and carbon storage and fluxes) or identified significant drivers of the outcome of interest (e.g. urban development).
- Models with a high level of development (ideally have undergone a scientific peer review).
- Models that have been developed specifically for the study area (Snohomish Basin or Puget Sound lowland region).

- Models with a flexible structure that can easily be (or that have already been) integrated with output from others models were a high priority.

We conducted a series of personal interviews with regional model developers during the summer of 2011. Our interview objectives were to 1) identify and summarize regional models in use (review their required input, spatial and temporal scale, assumptions and biases and results), 2) inventory the methods that have been utilized to estimate uncertainty and 3) explore suitability and methods for model integration. This report includes a summary of the information from these interviews and is intended as a reference for the modeling team to refer to as they explore model integration during the Integrated Model Workshop.

Overview of selected Models

This report contains information regarding eleven models (see Table 1). The first three models, UrbanSim, the Land Cover Change Model, and the Weather and Research Forecasting all represent systems which drive changes in ecosystem service levels. The models that follow provide estimates of ecosystem service indicators relating to biodiversity, water and carbon. These models include a salmon life cycle model, a potential vegetation zone model, four water movement and quality models, and two food web models.

- **UrbanSim** develops land use allocations (location of households, employment, etc) given a certain set of inputs.

- **The land cover change model (LCCM)** uses the simulated land use allocations from UrbanSim and projects land cover change as a result of the interactions between urbanization, transportation and biophysical factors.

- **Weather Research Forecast Model (WRF)** investigates what global climate changes mean at the local scale given our terrain.

- **Shiraz** a fish population model. It estimates the effects of changes in conditions (such as those resulting from land use and climate change) on fish abundance (in the selected models selected, Chinook salmon populations were assessed).

- **Potential vegetation model** stratifies the landscape into succession and growth potential vegetation zones.

- Four water movement models were investigated: **DHSVM, VIC, HSPF** and the water flow model module from the **Puget Sound Watershed Characterization Project**.

- **Ecopath with Ecosim (EwE)** is a mass balance equation model which simulates the dynamics of the marine food web under different management strategies or natural events.

The following section summarizes each model in terms of the purpose, approach, outcomes, assumptions and limitations and characterization of uncertainty. The purpose describes the systems and relationships modeled. The approach describes the model type (e.g. process based, probabilistic, etc.) and feedback between model components. The outcome summarizes model results and sensitivity to parameters and scale. Uncertainty explores how and if each model integrates and characterizes uncertainty. Uncertainty refers to situations where the current state of knowledge is such that: the order or nature of things is unknown, the consequences, extent or magnitude of circumstances is unpredictable and credible probabilities to possible outcomes cannot be assigned. Uncertainty can also refer to potential measurement or model error. Lastly, the assumptions and limitations section references how each model relies on limited knowledge to estimate future conditions, including simplifications and biases. Assumptions can come in the form of inputs (e.g. coarse resolution data), equations (e.g. square footage required per employee per industry sector) and the relationships between variables (e.g. how migrating species are handled outside the system studied, or two-way feedbacks between models). Table

2 compares and provides detailed information on the 11 models in terms of system modeled, model type, inputs and outputs and scales.

Table 1. Summary of Models

Model	**System Modeled**	**Related Driving Force or Ecosystem Service**
UrbanSim	Land use	Development, economy, infrastructure
Land Cover Change Model (LCCM)	Land cover change	Habitat diversity, development
Weather Research Forecast Model (WRF)	Climate change	Climate change
Shiraz	Fish population model (Chinook)	Species diversity
Potential Vegetation Model	Vegetation	Habitat diversity
Hydrological Simulation Program – Fortran (HSPF)	Hydrology	Water quality and quantity
Distributed Hydrology-Soil-Vegetation Model (DHSVM)	Hydrology	Water quantity
Variable Infiltration Capacity Model (VIC)	Hydrology	Water quantity
Puget Sound Watershed Characterization Project	Hydrology	Water quantity
Ecopath with Ecosim	marine food web biomass dynamics	Species diversity, carbon
Atlantis	marine food web biomass dynamics	Species diversity, carbon

Table 2. Model Synthesis

Model & System Modeled	**Model Type**	**Scales[1]**	**Inputs and Outputs**
LCCM: land cover change (land cover and landscape pattern)	Multinomial logit framework	**Time:** 3 year intervals	**Inputs:** Current & historic land cover, adjacent land cover, land use, transportation infrastructure, topography, critical areas (steep slopes, wetlands, etc), spatial contagion of development
		Space: 30 by 30 m pixel across the Central Puget Sound	**Outputs:** land cover change, probability of transition
UrbanSim: Urban development: household, employment + workplace locations, real estate prices, real estate development	Microsimulation, multinomial choice, multiple regression	**Time:** Annual, daily for activity-based travel	**Inputs:** households, people, parcels, buildings, natural amenities, accessibilities, employment, development restrictions, transportation, regional economic forecasts, activity-based travel (from EMME3)
		Space: buildings and parcels, travel network	**Outputs:** Location of households and employment, real estate prices, location, type and density of the built environment (dwelling units)
WRF-CCSM3: down-scaled climate predictions (atmosphere and land	Numerical simulation	**Time:** 6 hour intervals	**Inputs:** global climate simulations, topography, land cover
		Space: ~20 km grid across western US	**Outputs:** Meteorological fields (temperature, precipitation, wind, soil temperature, snow cover, soil radiation)
WRF-ECHAM5: down-scaled climate predictions (atmosphere and land	Numerical simulation	**Time:** 6 hour intervals	**Inputs:** global climate simulations, topography, land cover
		Space: ~36 km grid across continental US	**Outputs:** Meteorological fields
Shiraz: fish habitat and salmon lifecycle (Chinook)	Stochastic simulation	**Time:** annual timestep	**Inputs:** stream temperature, discharge, fine sediment, habitat types, forest cover, impervious cover, road density, precipitation, survival capacity, hatchery, harvest
		Space: user specified, often for sub-basins	**Outputs:** Salmon population attributes: abundance, productivity, spatial structure, and life-history diversity
Potential Vegetation Model: potential vegetation zone	Deterministic boundary equation model	**Time:** none	**Inputs:** total annual precipitation at sea level, mean annual temperature at sea level, fog effect, cold air drainage effect, topographic moisture, temperature lapse rate, aspect, potential shortwave radiation
		Space: 90 m pixel across WA state	**Outputs:** location of 15-20 potential vegetation zones
HSPF: local watershed hydrology and water quality	Empirically derived, deterministic discrete space/time	**Time:** subdaily	**Inputs:** rainfall and other meteorologic records (such as solar radiation) and land surface characteristics (vegetation cover, soil type)
		Space: spatially lumped into ~2 km^2 subcatchments	**Outputs:** hydrologic components (soil moisture, surface runoff, evapotranspiration), flood statistics (stream discharge, low flows), water quality

Model & System Modeled	Model Type	Scales[1]	Inputs and Outputs
DHSVM: regional hydrology	Deterministic discrete space/time mechanistic, physical (hydrologic) process[2]	**Time:** subdaily intervals (1-3 hrs depending on size of basin)	**Inputs:** meteorologic records and land surface characteristics
		Space: 30 – 200 m^2 resolution across Puget Sound basin	**Outputs:** hydrologic components and flood statistics
VIC: large scale hydrology	Deterministic discrete space/time mechanistic, physical (hydrologic) process	**Time:** daily (snow is at hourly intervals)	**Inputs:** meteorologic records and land surface characteristics
		Space: 1/16 degree (~32 km^2)	**Outputs:** meteorologic drivers (humidity, solar radiation), hydrologic components and flood statistics
Puget Sound Watershed Characterization Project: water movement	Deterministic qualitative model	**Time:** none	**Inputs:** land cover, soil types, discharge areas, habitat inventory, rain on snow areas
		Space: flexible, to a ~1 mi^2	**Outputs:** landscape indicators based of delivery and controls of water movement, surface storage, subsurface movement and recharge and discharge
Ecopath with Ecosim (EwE): a mass balance model for evaluating food web structure and community scale indicators	Trophodynamic mass balance simulation	**Time:** monthly	**Inputs:** functional groups, foodweb relationships, fishing, reproduction,
		Space: not explicitly modeled, represented with functional diet rules	**Outputs:** biomass allocation, functional group diversity, energy flow and mortality
Atlantis: biophysical ecosystem model	Spatially discrete deterministic biogeochemical whole of ecosystem	**Time:** 12 hour timesteps	**Inputs:** functional groups, foodweb relationships, abiotic features (temperature, circulation, nutrients, dissolved oxygen), spatial dynamics, species-habitat interactions, life history features, management policies
		Space: user specified	**Outputs:**

1. For some of these models, the minimum scale is finer than the recommended scale for interpreting results to inform decisions and management strategies.

2. Water and energy balance

II. Model Descriptions

URBANSIM

Purpose

The purpose of UrbanSim is to predict the locations of households and jobs across urban landscapes given current forecasts of population and economic dynamics. UrbanSim develops land use allocations (e.g. location of households, employment and population) based on the probability of transition. UrbanSim allows a user to investigate changes in future land use based on current conditions and parameterized changes in policies, transportation infrastructure or other variations. Users can run a series of UrbanSim simulations with a suite of potential future scenarios or varied boundary conditions to compare the divergence of future land use and development outcomes. Currently, the Puget Sound Regional Council (PSRC) operates UrbanSim to inform long range transportation and land use planning efforts.

Model Approach

UrbanSim is an agent based microsimulation model. It consists of a set of interacting multivariate regression and discrete choice models for estimating demographic transitions, economic transitions, household (re)location choices, employment (re)location choices, real estate development and land prices. The demographic transition model compares population and household characteristics (e.g. household size and income distribution) from a regional economic forecast model, to the UrbanSim household database to determine the number and types of households that will be added and lost in a given timestep. The economic transition model compares jobs based on economic forecasts and the UrbanSim employment database.

The household and employment relocation models predict the probability of a household or job relocating within the year. Additional and relocated households and jobs are then placed in the household and employment location choice models. The location choice models are influenced by a number of factors, including last year's land price, accessibility, household and job characteristics and neighborhood attributes. The land price model estimates real estate prices based on site characteristics (land use, critical areas, proximity to amenities, etc). Finally, the real estate development choice model predicts new or re-development occurrences, type and location.

Output

Output from UrbanSim includes the location and demographics of households, employment and population, real estate prices, and built environment characteristics across the landscape (e.g. location of dwelling units).

UrbanSim is sensitive to different variables over the short versus long term. Over the long range, exogenous demographic and economic growth is one of the most important determinants of UrbanSim model outcomes. However, dynamics over the short term range are more heavily influenced by market dynamics and location choices. Specification of policies or household and employment choice parameters (e.g. a preference for density or proximity to natural lands) influences short-range model output.

Uncertainty

PSRC has just adopted a Bayesian melding approach (Sevcikova et al 2007, Sevcikova et al 2011) to include an estimate of uncertainty in stochastic simulations. This statistically grounded method combines available observed data with simulation results for the same time period at a specific geographic level to estimate variance and bias. These measures are propagated into the last prediction time step and represented as confidence intervals. Under this approach, multiple runs could evaluate alternate model simulations using different scenarios, such as a different model structure. Bayesian melding allows you to take the uncertainty associated with model specification and merge it around all run scenarios and put it into 1 portfolio of results.

Assumptions and limitations

UrbanSim requires making several assumptions to simulate household and employee choices. Foremost are the assumptions of random utility theory, urban economic theory (rooted in bid rent theory), hedonic price theory, dynamic market equilibrium, price adjustment, and disequilibrium. In the real estate price models, households, businesses, and developers are all price-takers, and market adjustments are made by the market in response to aggregate demand and supply relationships. Each agent responds to information from a previous market period.

UrbanSim relies on external inputs and parameters that carry their own sets of assumptions and limitations. Population and household growth from OFM's model carries assumptions about future economic growth, natural increase and migration. Industry parameters including redevelopment considerations, developer costs, space (square feet) required per job by sector and development templates that identify what can be done on the land and where in the region are fixed. Environmental constraints (e.g. stream buffers) are represented as static, but could be mitigated. Transport decisions are modeled on behavior observed under relatively stable trends in the price of gas over time.

Land Cover Change Model (LCCM)

Purpose

Land cover change emerges as a result of the interactions between social (e.g. growth management policies, household preferences), economic (e. g. land development, business location), and biophysical (e.g. flooding, landslide) processes operating across multiple spatial scales. The LCCM predicts the location and quantity of land cover change in the Central Puget Sound urbanizing region (King, Kitsap, Piece, and Snohomish). In addition to characterizing the consequences of urbanization on land cover, the LCCM model output can be utilized in ecological modeling applications to investigate the implications of land cover change on ecosystem functions and services. There have been two applications where the land cover change model has been linked to an ecological model. The first includes an avian diversity model that used the land cover change predictions to assess the influence of urban development and the resultant loss of forestland and fragmentation of habitat on bird community composition across the Seattle metropolitan region (Heppinstall et al 2008). The other application was to estimate changes in aboveground plant carbon stocks due to land cover change across the Puget Sound region (Hutyra et al 2011).

Model approach

The LCCM is a high resolution spatially explicit land cover change model based on a multinomial logit framework. The LCCM estimates the land cover transition probability of a site from one land cover class to another over a four year time step using historical land cover images. The equations describing the probability of a site to transition from its current land cover to another are estimated empirically. These probabilities are determined as a function of a set of biophysical (elevation, critical areas), land use (type, development units and intensities) and change variables at three different operational scales, at the site, its location along various gradients and its spatial context (i.e. landscape patterns of neighboring pixels, such as contagion). Each land cover class has its own set of equations representing the transition probability based on the interaction of these components. Finally, the series of transition probability grids are used to simulate future transitions through a Monte Carlo process. Spatial masks were used to constrain urban land cover transitions based on empirical relationships which reflects the available space for growth based on policies (the growth management act, transfer of development rights associated with timber and agriculture), land ownership (Federal and state owned lands) and the physical limitations of the region (Cascade mountains to the east and Puget Sound to the west).

Output

Eight classes of land cover are simulated at 3 year intervals out to 2050 for the four county Central Puget Sound region. The eight classes include heavy urban (>80% impervious area), medium urban (50-80% impervious area), light urban (20-50% impervious area), grass, deciduous and mixed forest (>80% deciduous trees or 10-80% each deciduous and coniferous trees), coniferous forest (>80% coniferous trees), clearcut and regenerating conifer forest. This can then be summarized into a suite of landscape metrics which represent land cover composition (i.e. diversity, dominance), configuration (density, size, connectivity), and spatial neighborhood (contagion). A sensitivity analysis revealed landscape composition and configuration were important in predicting land cover change.

Uncertainty

The Urban Ecology Research Lab utilized the GeoPontius approach to assess uncertainty associated with both the amount of land cover change and the location agreement between observed and predicted land cover change at multiple resolutions. They are also considering the use of Bayesian melding uncertainty analysis approaches to address the temporal decay of uncertainty.

Assumptions and limitations

Land cover transitions emerge from interaction between human actions and biophysical resources and constraints of the landscape. However biophysical factors are not represented dynamically; they maintain a constant value in the model. The land cover change model does not explicitly model human behavior at the household or individual level. Urban development is simulated (UrbanSim) in tandem with land cover change; and the relationship is one directional. Being an empirically based model, land cover transition is affected by current urban patterns, so there is the implicit assumption that future trends will behave in a manner similar to the past (temporal stationarity). There are also assumptions of spatial stationarity; as such the model was also parameterized and run on sub-segments of the region that are believed to behave similarly.

Weather Research and Forecasting (WRF)

Purpose

The Weather Research Forecasting model has multiple uses and specifications; it is utilized for both operational forecasting and atmospheric research needs. In this report, we synthesize the ECHAM5–WRF and CCSM3–WRF regional models which investigate what global climate change means at the local scale. Global climate change models do not provide a fine enough resolution to account for the impact of the complex terrain, coastlines, varied ecological landscapes and land use patterns of Washington to assess the regional climate. The WRF[1] model runs create local climate scenario information which informs a cascade of models assessing the effects of projected local climate change on atmospheric (air quality), aquatic (water quality) and terrestrial systems.

Model approach

The WRF is a mesoscale atmospheric regional climate model. WRF simulates the physical processes in the climate system forced by global climate model output. It is based on fluid dynamics and principles of energy exchange. The physics package includes a microphysics scheme, a simple cloud model, a land surface model, a planetary boundary layer and an atmospheric shortwave and longwave radiation model. The microphysics scheme simulates water vapor, cloud water, rain, cloud ice, and snow. The cloud model integrates moist updrafts and downdrafts. The Land Surface Model predicts soil temperature and moisture, canopy moisture and snow cover. The planetary boundary layer represents heat and moisture fluxes from local and non-local gradients.

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[1] For brevity, in this report we refer to ECHAM5–WRF and CCSM3–WRF as 'WRF'. When necessarily to distinguish between the two we refer to the specific sub-model.

Global climate models provide the forcing conditions at the boundaries of the regional model (WRF). There are two applications of the WRF model in the Puget Sound region. The CCSM3-WRF was configured and run by the Pacific Northwest National Laboratory (PNNL); using forcing data from the NCAR Community Climate System Model version 3 (CCSM3). The second, ECHAM5-WRF, was run at the University of Washington in collaboration with the Climate Impacts Group at the Joint Institute for the Study of the Atmosphere and Ocean. It was forced with the ECHAM5 global model from the Max Plank Institute, Hamburg. Differences between the two simulation configurations are minor and primarily attributable to the choice of global forcing models, the grid spacing and spatial extent. CCSM3-WRF was operationalized on a 20 km grid using an extended buffer zone, while ECHAM5-WRF ran on a 36 km grid using nested grids and interior nudging with relaxation coefficients based on a linear-exponential function. The ECHAM5–WRF grid encompasses the continental US while the CCSM3–WRF grid covers just the western US. Finally, the CCSM3-WRF model is run using the Special Report on Emissions Scenarios A2, while ECHAM5 implemented the A1 B emissions scenario. Both global climate models provide data at six hour intervals.

Output

Weather data are simulated out 100 years, at 6 hour intervals by both models. The output includes temperature, precipitation, wind, soil temperature, snow cover, solar radiation and soil moisture. The largest differences in outcome between the ECHAM5–WRF and CCSM3–WRF simulations are due to the global models used to force the regional simulation. The ECHAM5 A1B simulation projects a minor temperature increase and an increase in precipitation of high magnitude, while the CCSM3 A2 projects a warmer and drier future in comparison to 19 other global climate change model projections using the same SRES emission scenarios.

Uncertainty

The output of both regional models was validated using gridded seasonal averages from a period of 30 years from weather station observations (1970-1999). An empirical model interpolated the station information, based on a simple terrain model for temperature and precipitation. Validation with the resultant gridded estimates, as opposed to raw station observations, may also introduce a small bias/uncertainty.

In general, the influence of major geographic features and the seasonal cycles are represented well with the simulated temperature profiles and overall magnitude of precipitation and its geographical distribution. However both models produce a substantial cold bias compared to the observations. The large precipitation peak over the Olympics is also poorly represented as the coarse resolution of the models effectively treat the lower elevation Cascades as more of an isolated hill than a ridge. There is also a combined bias from the global and regional model. As the regional model may introduce biases not present in the global model. Nor can it explicitly remove any systematic differences between the global forcing model and observations, except where such bias is due to unresolved processes.

Assumptions and limitations

The most important assumption of WRF is that the mathematical description of climate processes is realistic and that all significant processes are in the model. In addition, four assumptions may lead to estimation errors: lack of feedback from regional to global models, grid resolution, exogenous carbon emission estimates, and simplification of land cover classes. Mesoscale processes do not feedback onto the global climate simulation and large-scale features that depend on these feedbacks cannot be properly represented. In a comparison of the two model results, variability is likely a function of different grid resolutions. Generally, if the model resolution is too coarse, the affects from the mountains are not represented well; while a finer resolution is computationally demanding. The best global climate change models are defined by conservative criteria, so the impact of carbon emissions is likely underestimated. There are 25 dominant land cover classes in the Anderson USGS land cover data. WRF homogenizes the pixel to the dominant vegetation (type). The potential error from this simplification/aggregation of land cover is most relevant at the urban, natural interface.

SHIRAZ

Purpose

The Shiraz model is a spatially explicit fish life cycle model that estimates population abundance across space and time. Shiraz can be used to estimate the effects of changes in conditions such as habitat loss and/or restoration, harvest or fisheries management. It is a flexible model framework that enables the researcher to investigate changes in a set of future conditions (e.g. from climate change or land-use scenarios) into consequences for salmon population status and assess likelihood of recovery. The model has been applied in the Snohomish Basin to assess the influence of habitat restoration and protection (Scheuerell et al 2006) in addition to alternative future climate (Battin et al 2007) scenarios on two Chinook salmon populations in the Snohomish River Basin. The Shiraz model provided estimates of Chinook salmon abundance which can be translated into three indicators of viable salmon populations (VSP): productivity, spatial structure, and diversity.

Model approach

The Shiraz model consists of a set of user-defined relationships among habitat attributes, fish survival, and carrying capacity. At the core of Shiraz exists a multi-stage Beverton–Holt model (Moussalli and Hilborn 1986) describing the production of salmon from one life stage to the next (e.g. spawners, eggs, fry, smolts, etc). The user specifies initial conditions for how many individuals of each life stage and stock are alive and the proportion of each life stage occupying each geographical area. Then the number of fish surviving to the next life stage is a function of the number alive at the previous life stage, their survival between those stages, and the capacity of the environment to support them.

The underlying physical environment is the primary driver of fish survival and capacity at different life stages. The physical environment (climate, land use, and landscape processes) is specified through the habitat quality and quantity parameters. For example, Bartz et al (2006) related land use variables and geomorphic characteristics to habitat quality parameters. Scheuerell et al. (2006) then linked those parameters to salmon survival between various life stages using other previously published relationships. Battin et al (2007) characterized the effects of climate change on salmon performance by linking output from DHSVM, a hydrological model. In this study air temperature, precipitation, and land use affects on stream flow and temperature were estimated and translated into the Shiraz framework as habitat quality and quantity parameters which, in turn, drove salmon survival and capacity (Battin et al 2007). The influence of fish hatcheries and harvest rates can also be investigated within the model, although these have not been explored as of yet within the Basin using Shiraz.

Output

Model output is fish abundance, which can be used to estimate productivity, spatial structure, and life-history diversity. Shiraz has been run at a yearly time step out to 2050 at the sub-basin scale. In the Snohomish River Basin, the 62 sub-basins ranged from 12.2 to 246 km^2 in area, and from 0.34 to 98 km in stream length.

Uncertainty

Scheuerell et al (2006) suggested two ways to represent uncertainty of model inputs: use Monte Carlo simulation techniques or add a stochastic element to model parameterization by randomly drawing parameter values for each time step based on hypothesized statistical distributions of these parameters. Battin and colleagues (2007) used DHSVM-generated 72-year time series of flows and temperatures as the basis for a Monte Carlo analysis. For each climate and land-use scenario, the Shiraz model was run 500 times, each run was 100 years. At every (annual) time step, a year was randomly selected from the 72-year DHSVM flow and temperature time series and the appropriate functional relationships were applied to these values for that year. This approach maintained within-year correlations among variables while allowing the researchers to explore a wide range of future climate time series.

Assumptions and limitations

The Shiraz framework allows the model user to decide what level of spatial resolution to consider (from entire watersheds to as fine as individual stream reaches), although once defined the model treats all spatial units as identical in size with respect to fish movement. A number of assumptions were made in the parameterization of Shiraz in the Basin studies, however since the Shiraz framework is so flexible many of these parameters can be modified in future applications of the model. Below is a summary of some assumptions and choices modelers made in the previously discussed studies. Some of the peripheral driving forces were assigned temporal stationarity[2], such as hatchery operations, stray rates and harvest rates. Survival rates in the ocean were treated as a set of constants with the assumption that the ocean carrying capacity is infinite. The impacts of rising sea levels, ocean warming and ecological interactions with other species were not incorporated into local applications of the model. However with climate change, interactions with other species may affect Chinook populations differently due to changes in competitive edge under a new set of conditions. Additionally, plasticity of life-history traits may enable Chinook to adapt to climate change in ways not captured in the model.

Potential Vegetation Model

Purpose

Potential vegetation is the projected climax plant community that could occupy a site based on climate and environmental conditions. Potential vegetation is used in science and natural resource management for stratifying land relative to the environment and by informing questions regarding succession and growth potential. The potential vegetation model was created by the US Forest Service to predict and map the spatial distribution of broad categories of environmental (e.g. growth potential) and successional (climax) potential of the landscape. Predictive models which plot the location of potential vegetation zones contribute to the mapping of species and communities, a necessary tool in the management of natural resources, biodiversity, and the conservation of biotic communities.

Model approach

The potential vegetation model uses direct and indirect gradient analysis, factor analysis, and ordination methods to delineate the location of potential vegetation zones based on underlying environmental (biophysical) variables. Data on environmental and climate variables are linked to reference data of plant species presence (or sometimes absence), known plant community patterns, or field samples of plant community classes. For a full list of model input, see Table 1. Finally, boundary equations are utilized in lieu of more traditional regression-based algorithms. The boundary models are composed of a set of nonlinear quadratic equations which estimate the boundary between units of vegetation zones. The best fit line was determined by the sum of errors. Refer to the USFS General Technical Report (Henderson et al 2011) for full details.

Output

The model output is a 90 m pixel based map of the boundaries delineating potential plant association groups for the state of Washington. There are 15-20 plant association groups represented in

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[2] Relationships and rates of change associated with model components remain constant over time.

the model; but only 5 are found in our study area (Snohomish Basin). These include the Western hemlock zone, silver fir and western hemlock zone, mountain hemlock and silver fir zone, subalpine zone and the alpine zone.

Precipitation at sea level is the most important determinant of the boundaries between potential vegetation zones in the model. It alone can explain 50% of the variation. The fog affect is also significant; its influence is felt along the coast and at a small band along the east side of the Cascades. Fog affect includes tree drip, fog condensation, and the direct and indirect effects of evapotranspiration. Along the coast and foothills of the Cascades the effect is equivalent to approximately 40" of precipitation at sea level. Temperature at sea level, aspect and solar radiation have little effect.

Uncertainty

The boundary equations were validated by producing a map of the potential vegetation zones of the study area and by comparing it to an independent set of observations. The validation to a set of 155 independent plots showed an accuracy of 77.4 percent and the model accurately predicted the vegetation zone for 76.4 percent of the 1,497 eco-plots used to build the model. Spatial uncertainty along the edges/boundaries is hard to separate from sampling error.

Assumptions and limitations

Model assumptions stem from the simulation of simplifying complex vegetation changes and the resolution of vegetation mapping. The nature of vegetation is that it is dynamic over time, but randomness is bounded by environmental conditions on site. While every site on a landscape is different, or unique, it can be classified into an aggregate vegetation association group. In addition, while the full suite of drivers of vegetation can be discovered, the variables in the model are surrogates for much more complex relationships. Further, the model assumes that as the climate changes different species assemblages will stay the same. However, it is believed that the region will exhibit new assemblage groups from climatic changes.

Quantifying map accuracy between data from field plots collected at one scale with a map of pixels at a different scale is difficult, both conceptually and practically. The resultant pixel-based map of potential vegetation zone locations was based on fine scale field plots. The model assumes that one can translate across different scale resolutions from fine scale field plots to moderately coarse landscape classifications. Often the resolution of the types of vegetation on the ground is finer than the resolution of pixels (or polygons) used to portray them. Thus a single 90-m (0.81-ha) pixel can contain two or more fine-scale field plots of different community types or plant associations. The size of a pixel is often a function of the technology being used and the constraints of computer hardware and software used to represent them.

HYDROLOGY MODELS

Purpose

There are a suite of spatially explicit hydrology models which simulate water movement across a region's land surface. In this report we focus on three of these models in use in the Puget Sound Lowlands: the hydrological simulation program – Fortran (HSPF), a distributed hydrology-soil-vegetation model (DHSVM), and a variable infiltration capacity model (VIC). These models use continuous rainfall and other meteorologic records (e.g. solar radiation) and land surface characteristics (e.g. vegetation cover, soil type) to compute water movement. These models have been applied operationally to explore streamflow prediction, and in research endeavors to examine the effects of land use and land cover change, and climate change on hydrologic processes. While DHSVM was originally developed to predict effects of forest harvest on flooding, the model was recently modified to include parameterization to assess impacts on the hydrology of Puget Sound by urbanization (Cuo et al 2009). In addition to water quantity investigations, HSPF can be used to assess the water quality consequences of reservoir operations, point or nonpoint source treatment alternatives and flow diversions. VIC and DHSVM were developed by Land Surface Hydrology Research Group at the

University of Washington, while the modern HSPF was developed jointly by the Environmental Protection Agency and US Geological Survey.

Model approach

HSPF is an empirically derived water transport model; whereas DHSVM and VIC are mechanistic, physical (hydrologic) process models. HSPF contains hundreds of process algorithms developed from theory, laboratory experiments, and empirical relations from monitored watersheds. The VIC model is a large-scale, semi-distributed grid-based hydrology model which solves for full water and energy balances. DHSVM uses an approach similar to VIC, while DHSVM operates at a finer scale and is a fully distributed hydrology-soil-vegetation model.

One of the biggest differences between VIC and DHSVM is how water movement is transferred across a boundary between grid cells. VIC is semi-distributed, meaning all cells of the same elevation are treated as one, or as bands of land with the same elevation ranges. While DHSVM explicitly routes water over the surface and through the subsurface within and between neighboring grid cells, resulting in a more realistic representation of water movement patterns due to variation in the landscape. Effects of topography on incident and reflected solar radiation are explicitly represented. Therefore the topography and mountain ranges in the Pacific Northwest are better represented in DHSVM (at the moderate spatial resolution of 30-200 m^2). VIC is more appropriate for applications focusing on large river basins, DHSVM for smaller watersheds and HSPF for finer scale applications.

Output

Many variables are simulated by these models, including meteorological drivers (e.g. humidity, solar radiation), hydrologic components (e.g. soil moisture, surface runoff production, evapotranspiration, snowpack, etc), and flood statistics (e.g. stream discharge, low flow). In addition, HSPF can simulate water quality for both conventional and toxic organic pollutants. Soil moisture, precipitation and snow are the dominant drivers of model results.

Uncertainty

The uncertainty regarding the potential variability in hydrologic conditions due to climate change has been explored by linking and assessing different global climate models.

Assumptions and limitations

There are a number of required assumptions when translating information from observations into the mathematical hydrology model. To name a few, there are assumptions regarding the fundamental relationships between soil moisture and runoff and how information from rain gauges is interpolated across the study region. Gridded meteorological forcing data can be estimated in VIC from weather station points and translated into DHSVM. Additionally, as HSPF is predominantly an empirically derived model calibrated from data for historical conditions the model's investigative power to estimate the effects of future climate change or alternative policies on water quantity and quality are limited. Flow is dominated by elevation within DHSVM, not the gradient of the water table. There are no deep groundwater models integrated with any of the three focus hydrology models. One implication of this assumption is that the hydrology in areas with a low slope is not estimated well.

PUGET SOUND WATERSHED CHARACTERIZATION

Purpose

The Watershed Characterization Project is a coarse scale assessment tool that helps prioritize watershed actions by evaluating both the potential of and impairments to watershed processes. The project is an interagency effort funded by the EPA, and includes the Department of Ecology, Puget Sound Partnership and Washington Department of Fish and Wildlife. The goal of the project is to assist in the identification of areas on the landscape that are important for maintaining watershed processes and to characterize and map the degree to which human activity has degraded these processes. This information is intended to assist planners in identifying both priority areas to protect or restore and areas which are less sensitive to impacts from new development and changes in land use. The characterization consists of the assessment of water flow and water quality processes (Volume 1), freshwater fish and upland terrestrial habitat (Volume 2) and nearshore habitat (Volume 3).

Model approach

The water flow models are based on a conceptual understanding of the surface and subsurface movement of water and published empirically derived indicators of importance and impairment to water flow processes. Indicators of importance involve physical controls of water movement. Two examples of these control indicators include depressions in the landscape (which retain and slow the release of surface water) and permeability of surficial deposits (which facilitate recharge and subsurface storage of water). Indicators of degradation involve known relationships between a land cover change, such as impervious surfaces, and a water flow component such as delivery (e.g. timing of delivery is altered).

There are five components to the waterflow model: delivery of water (precipitation, amount of forest cover), surface storage (wetlands and floodplains), recharge and subsurface movement (type of surficial deposits), discharge of subsurface water (streams and wetlands), and evapotranspiration. The water quality assessment module estimates export potential and degradation for the following pollutants: sediment, phosphorous, nitrogen, metals and pathogens. The export potential model evaluates both sources and sinks for a constituent. The degradation model is the NSPECT model (developed by NOAA) which uses known coefficients of pollutants associated with different types of land cover. The terrestrial wildlife and freshwater fish models are being developed in partnership with the Washington Department of Fish and Wildlife (WDFW) while the marine nearshore model is being developed in partnership with the Puget Sound Nearshore Ecosystem Restoration Project and WDFW.

Output

The output of the water flow characterization models is a series of spatially explicit maps that categorize the importance index and the degradation index into areas suited for protection, restoration and development. The outputs for the water quality assessments are very similar and include a set of spatially explicit maps that display the export potential index and degradation index from the NSPECT model. The spatial resolution of the model is flexible; however given the coarse scale of the data sets the finest recommended scale of application is one square mile. This scale is appropriate to inform planning actions (Shoreline Master Programs and Comprehensive Plan Updates) and conventional mitigation strategies. A resolution of 2-5 mi^2 is the recommended assessment unit for most of the Puget Sound lowland areas and 7-10 mi^2 is recommended in mountainous regions. Temporal scales are not represented within the model.

Uncertainty

The water flow model is in the validation stage. Model output is being compared to an HSPF flow model and other watershed characterization model(s) to assess level of agreement. They are also looking to compare model outcomes with measures of biotic integrity such as the biological index of biotic integrity (BIBI) commonly used to assess stream impairment.

Assumptions and limitations

An assumption of the water movement and water quality models is that the selected indicators reasonably depict the delivery, movement and loss of water and water quality constituents (e.g. sediment, phosphorous, metals, pathogens, nitrogen) as these indicators are supported by known geologic, physical, and chemical properties and processes.

ECOPATH WITH ECOSIM (EWE)

Purpose

The Ecopath with Ecosim (EwE) modeling software simulates the effects of user specified management strategies or events on the marine food web. The results provide insight into marine system functions, highlights potential unintended consequences of policies, and enables the assessment of tradeoffs between alternative ecosystem management strategies. Researchers at the University of British Columbia initially developed EwE for the purpose of assessing fishery management strategies, but more recently National Oceanic and Atmospheric Administration (NOAA) has applied the model in the Central Basin of Puget Sound to characterize the food web structure and function in the Puget Sound.

Model approach

EwE simulates community dynamics using principles of mass balance and energy conservation. There are two modules, Ecopath and Ecosim. The first, Ecopath, is a static mass-balance model of the perceived "initial" conditions or reference state of the food web. The second module, EcoSim, dynamically simulates biomass pools and vital rates of change through time in response to perturbations. In each different species or guilds[3] are represented as biomass pools which are regulated by gains and losses. Gains are the result of consumption, production, and immigration. Losses are due to mortality, emigration, and fisheries extraction. Habitat types are represented within the model and mediate productivity (e.g. a species is linked to eel grass). The impact of fisheries is modeled on both the targeted groups and bycatch.

Ecopath consists of a series of linear equations describing the flow of biomass into and out of discrete pools, or functional groups. The Ecopath master equations contain four core parameters that describe the basic biology of each functional group: biomass, production to biomass ratio, consumption to biomass ratio, and ecotrophic efficiency. The user needs to specify this collection of input data and parameters specific for each functional group in order to describe the reference state. NOAA staff assimilated key parameters from direct data sources and literature, and indirectly through correlations, mechanistic models, and mass balancing procedures. Typically, all but one of the four core parameters are input and the remaining parameter is estimated by the Ecopath mass balancing algorithm. In the Central Basin Puget Sound model application, the unknown parameter for a particular group was typically either ecotrophic efficiency or biomass; then Ecopath achieves mass balance by simultaneously solving for these unknowns for all functional groups.

The second module is the simulation component, Ecosim. It is governed by coupled differential equations that stem from the Ecopath linear equations. In the simulation module, parameters can be changed and perturbations simulated from the reference state in order to investigate the food web structure. For example, the strength of trophic interactions (e.g., the extent of top-down or bottom-up control), stock-recruitment relationships, or temporal patterns of fishing or climate variability can be examined in EcoSim.

Output

The Central Basin of Puget Sound EwE model application includes sixty-five functional groups (composed of either individual species or guilds of ecologically similar species). Marine mammals, communities residing in the intertidal zone, fish, sea birds and fisheries fleets are a few of the groups included. Several indices and rates are calculated as part of the mass-balancing step, for example productivity rates, changes in diet, mortality and the ratio of productivity to respiration.

A comparison of a suite of simulation runs, each with a slight modification of the model specification, reveals parameters that are highly influential in determining results. Altering the biomass

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[3] guilds are a classification scheme where species that occupy a common niche, or habitat, within a given community are grouped into categories, or functional groups.

of a top predator, especially raptors (e.g. bald eagles), results in a very different marine system. NOAA's EwE application is also very sensitive to migratory species with a large biomass (e.g. salmon and eagles), when these migrators re-enter the marine system, they introduce a lot of new biomass. However, since they spend a lot of time outside the system, NOAA discounts their perturbation. Finally, the introduction of stochastic variation on phytoplankton initial conditions reveals that a little variability in these primary producers can result in large fluctuations of the system.

Uncertainty

Modelers at NOAA have utilized hypothesis driven scenarios to assess model structure, behavior, performance, and overall sensitivity to perturbation parameters. They run hundreds of simulations for a single question to see how responsive the model is and to identify single parameters that operate as important drivers of community structure. Users treat simulation results as hypotheses to be verified with data or other methods. These simulations were an initial means of gauging the feasibility and stability of model estimates and predictions.

Assumptions and limitations

Model assumptions stem from two overarching challenges, the representation of dynamic relationships both within and into the model, as well as limitations of incorporated data and spatial heterogeneity. The EwE model can be characterized as unrealistically resilient. Thresholds are not represented well as the model tends to move toward the starting equilibrium state. With a perturbation, the model will move to an alternative stable state, but once a stressor is removed, the system returns to the original equilibrium domain. As such, it is hard to maintain chronic effects such as an oil spill, as the model treats it more as a one-time perturbation. Further, migratory species are poorly represented as EwE cannot dynamically model things outside of the model domain (e.g. cannot model high mortality of salmon in open Pacific). EwE is not clearly linked to physical forcings or chemical cycling.

EwE was developed for fisheries, so the primary focus was tailored to fisheries objectives. As such, the lower trophic levels are aggregated heavily; the taxonomic resolution is coarse at these lower levels. Input parameters were assimilated from data and reports from no later than 1990, limiting incorporation of recent change. Finally, the spatial heterogeneity is not explicitly represented, however the user can be clever specifying diets within the equations to represent spatial constraints.

NOAA is switching to the Atlantis model, which is spatially discrete. Atlantis is governed by space, physical forcings and chemical cycling (e.g. nutrient cycles, etc); however it is time intensive to calibrate and get the system to behave in a stable manner.

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