Uncertainty and Sensitivity of Ecosystem Restoration Decisions: A Case Study from Coastal Louisiana

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OVERVIEW: Effective ecosystem restoration decision making requires analysis of the costs and benefits of alternative actions. The outcomes of restoration actions are often uncertain – and the models used to assess the outcomes are equally uncertain – due to incomplete ecological knowledge and other factors, such as limited data. These uncertainties can impose some risk. This technical note provides an overview of two quantitative methods for assessing risk associated with restoration decisions, sensitivity, and uncertainty analysis. An example of these methods is provided for a Louisiana coastal wetland restoration study.

RISK ASSESSMENT: A risk is a potential adverse consequence that may (or may not) be realized in the future and is typically defined by the product of the likelihood of an outcome (i.e., probability) and the consequence of that outcome (Suedel et al. 2012). Forecasting the outcome of a restoration project often includes considerable uncertainty due to incomplete knowledge, imperfect models, stochastic environmental conditions, and many other factors. Risk-informed decision making requires explicit acknowledgement of key sources of uncertainty and seeks to minimize adverse outcomes related to those uncertainties.

Risk assessment is a field of study that applies an array of qualitative and quantitative tools to define likelihoods and outcomes of a given decision (Suedel et al. 2012). Assessment of project risk and uncertainty has been required of US Army Corps of Engineers (USACE) planners since the establishment of Principles and Standards in 1973. Qualitative risk assessment methods include listing sources of risk and uncertainty, relative rankings of risks, and multi-objective comparison of risks. Although qualitative methods have been used in restoration decision making, few quantitative risk assessments have been undertaken (Suedel et al. 2012). This disparity is partly due to the complexities in scoping and conducting quantitative risk assessments. Here, the authors focus on two quantitative risk assessment methods (sensitivity and parametric uncertainty analysis) and demonstrate their application in the planning of a large-scale coastal wetland restoration project.

Sensitivity Analysis. The risk of a given decision may be defined by plausible future scenarios, the outcome for each scenario, and the probability of each scenario occurring (Schultz et al. 2010). When elements of the future are uncertain or incomplete (e.g., climate change, land use, invasive species), different scenarios can be analyzed in an effort to capture this uncertainty and inform

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decision making. Analyzing model outcomes for multiple, plausible, future scenarios provides one technique for assessing risks and increases the overall chances of project success (Suedel et al. 2012). For instance, a team may identify three plausible future scenarios such as low, moderate, and high development at an urban project site. If alternatives at this site are consistently ranked across all scenarios, then the team may be more confident in the robustness of their decision.

Sensitivity analysis is the systematic testing of model outcomes to changes in parameter values (Schmolke et al. 2010). These analyses are often undertaken to better understand the impact of model assumptions or parameterization (e.g., Convertino et al. 2012, McKay and Fischenich 2013). Scenario analysis is a specific form of sensitivity analysis. In this case, a project team is assessing the sensitivity of the decision (rather than the sensitivity of the model) to changes in model parameterization.

Uncertainty Analysis. At the basal level, uncertainty is a lack of knowledge (Schultz et al. 2010). Numerous alternative typologies exist to characterize sources of uncertainty. Ascough et al. (2008) present the following types of uncertainty:

- Knowledge or epistemic uncertainty: current limitation of knowledge, which may be reduced by additional data and research

- Variability uncertainty: inherent variability or stochasticity with a system

- Decision-making uncertainty: ambiguity regarding the quantification of objectives

- Linguistic uncertainty: vague, ambiguous, and/or context-dependent language

The authors focus herein on the most reducible form of uncertainty, epistemic. Knowledge of ongoing processes may be limited by incomplete scientific understanding. Process understanding is often poorly understood and understated until additional data are brought to bear (i.e., "there are things we do not know we don't know"[1]). Epistemic uncertainty also arises in modeling from the following sources.

- Parametric uncertainty: data uncertainty arising from measurement error, small sample size, analytical techniques applied, and presentation methods (e.g., incomplete spatial and temporal data collection and subsequent reduction to a mean and standard deviation)

- Structural uncertainty: inadequate representation of the system or multiple alternative representations (e.g., linear v. exponential regressions with similar support)

- Technical uncertainty: hardware and software errors (e.g., bugs, rounding)

EXAMPLE APPLICATION – WETLAND RESTORATION IN COASTAL LOUISIANA:
Since 1978, Coastal Louisiana has lost marsh at an average rate of over 30 km^2/yr due to river/floodplain disconnection, sea level rise, subsidence, coastal erosion, and other factors (Barras et al. 2008). In the fall of 2005, Hurricanes Katrina and Rita awakened the United States' public to the natural protection and ecological value coastal wetlands provide in reducing effects of hurricanes on coastal communities. In response to these catastrophic events, the US Congress directed the USACE to "conduct a comprehensive hurricane protection analysis and design…to

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[1] Rumsfeld, D. 2002. US Department of Defense News Briefing.

develop and present a full range of flood control, coastal restoration, and hurricane protection measures." The Louisiana Coastal Protection and Restoration (LACPR) project was created to develop coastwide, comprehensive plans to conduct these activities. The following case study highlights the explicit consideration of two alternative scenarios and parametric uncertainty in the coastal restoration components of this project. Though this paper highlights compelling issues associated with restoration components of LACPR, it should not be considered a summary of techniques or results.

Coastal restoration alternatives were developed at a coastwide scale and analyzed by an interagency Habitat Evaluation Team (HET) consisting of federal, state, and local partners. The HET not only collaboratively developed alternatives, but also worked side-by-side in analyzing these alternatives. Freshwater flow diversion to coastal marshes has been suggested by many scientists to be the most promising method to create new marsh communities and sustain existing communities by offsetting losses due to sea level rise, subsidence, and coastal erosion. Benefits of flow diversions are derived through two major mechanisms: 1) addition of mineral sediments from the diversion water source and 2) addition of nutrients, which can stimulate marsh vegetative growth and increase organic accretion.

The HET required a model to assess flow diversion benefits that would account for the quantity and quality of wetlands throughout the study area over a 50-year planning horizon, but time constraints prevented the development and application of a completely mechanistic, spatially explicit tool. A spreadsheet model accounting for both organic and inorganic diversion benefits on an annual time scale had been previously applied under the Coastal Wetland Planning, Protection, and Restoration Act (CWPPRA; Boustany 2010). However, the limited temporal resolution (annual averages) of the CWPPRA model was of concern due to variability in inputs and operational criteria on finer time scales. Several other model limitations were identified, so the CWPPRA model was adapted to the study needs by improving several model features, including sediment retention and consolidation calculations and adding intra-annual temporal variability in hydrologic and sediment inputs. The revised model was named the Diversion Benefits Assessment Tool (DBAT)[1]. Model alterations were critical to calculating flow diversion benefits with respect to diversion location, magnitude, structure type, and operation (USACE 2009b).

Sensitivity analysis to sea level rise scenarios. Scenario analysis was applied to quantitatively assess the sensitivity of decisions to plausible alternative future conditions. Because Coastal Louisiana is virtually without vertical relief, small changes in sea level exert a disproportionately large influence on ecosystem processes. Thus, two sea level rise scenarios were incorporated into the project planning: 1) a low sea level rise projection made by the International Panel on Climate Change based on historic rates and 2) a high projection made by the National Research Council[2]. Figure 1 presents an example of multiple outcomes from restoration alternatives under two sea level rise scenarios. By conducting scenario analysis, decision makers were able to examine potential outcomes of restoration based on two alternative futures. If the same alternatives are

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[1] Subsequent to the case study application described in this technical note, the DBAT was further revised and renamed the Sediment and Nutrient Diversion (SAND) model. At publication, the SAND model was undergoing final testing prior to submittal for certification as a USACE Planning Model.

[2] Note that current policy for addressing uncertainties in SLR should be used and may differ from the approach used in this case study. At publication, current policy is addressed in Engineer Circular (EC) 1165-2-212 (USACE 2011).

identified regardless of scenario, then decision makers can have greater confidence in the decision. Figure 1 shows that five alternatives are consistently ranked for both sea level rise scenarios.
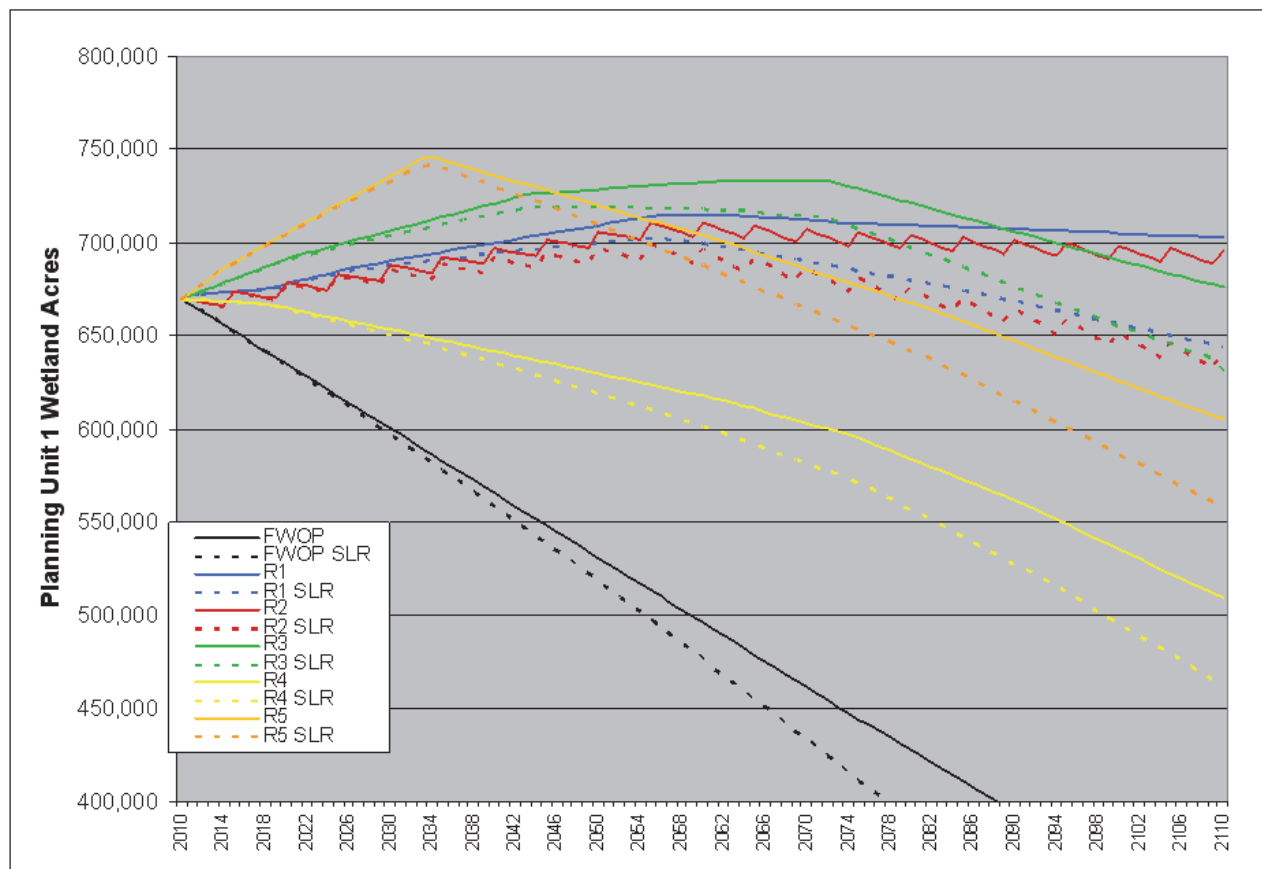

Figure 1. Sample plan comparison for two sea level rise scenarios (SLR indicates higher sea level rise).

Parametric uncertainty analysis. The model utilized numerous physical and ecological variables (Table 1). Existing data and literature sources were used to parameterize the model, requiring professional judgment in cases with conflicting or limited data. Given the inherent uncertainty in many of the model variables, a parametric uncertainty analysis was conducted using parameters in Table 1.

Uncertainty about the true value of model inputs was described using probability distributions for each parameter developed from a combination of literature review and HET professional judgment. Each parameter was assigned a range of values that were then randomly sampled, combined, and analyzed using the model and the probability distribution function (PDF) for each variable. A Monte Carlo analysis was performed in Microsoft Excel using ten thousand combinations of input values for model variables based upon a random sampling of the PDFs. Input sets were computed for a select study site (Figure 2). Understanding parametric uncertainty is crucial to the development of any ecological model (Schmolke et al. 2010), and this analysis informed the HET of the potential impacts of this form of uncertainty on model results.

Table 1. Parameters for the adapted freshwater diversion model.

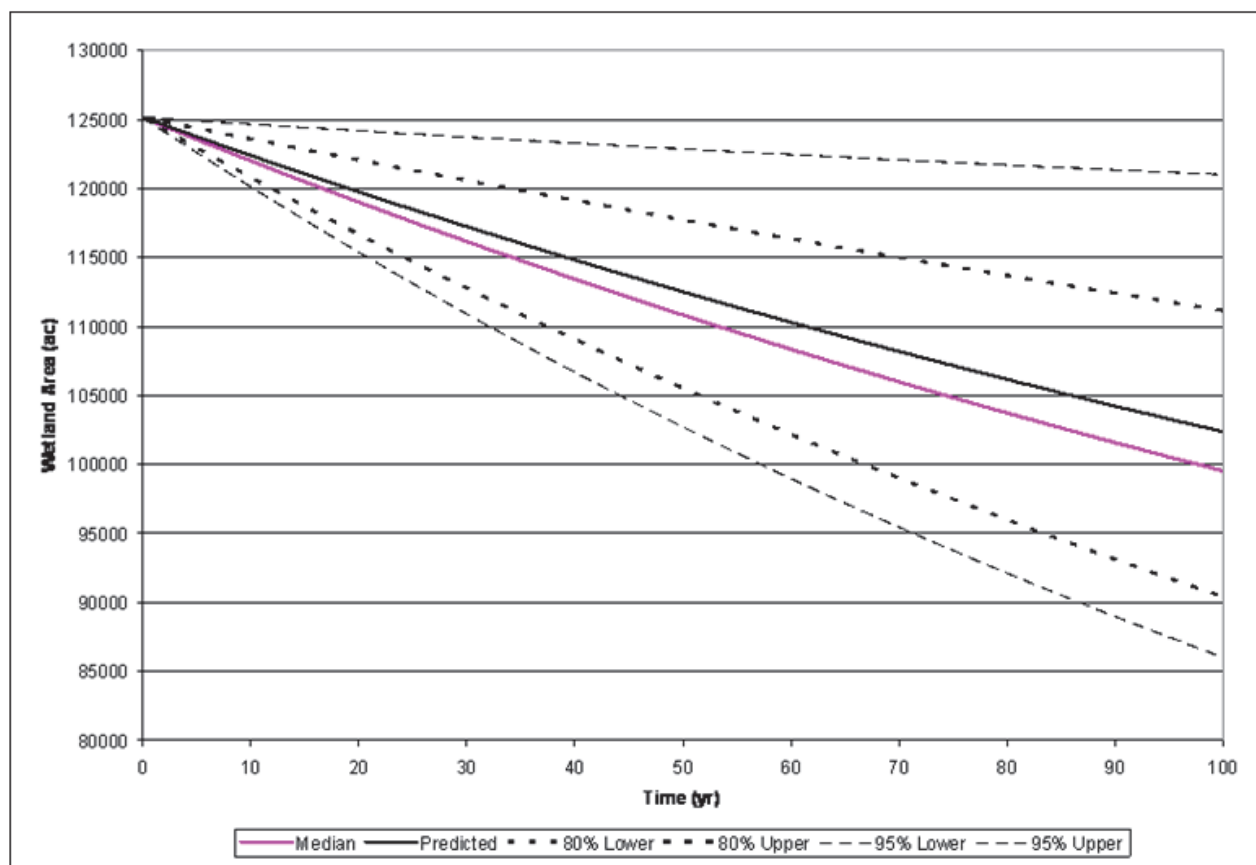| Parameter (units)	Source
Initial land and project area (ac)	Available data
Average water depth and width (ft)	Data when available and professional judgment
Maximum tidal velocity (ft/s)	Data when available and professional judgment
Roughness height (ft)	Data when available and professional judgment
Land loss rate (%/year)	Available data (USGS1978-1990)
Bulk density (g/cm^3)	Data coupled with professional judgment
Sediment rating – intercept and exponent	Snedden et al. (2007)
Size fraction – sand, silt, clay, flocculants (%)	Snedden et al. (2007)
Fall velocity – sand, silt, clay, flocculants (ft/s)	Calculated based on Soulsby (1997)
Plant productivity rate (g/m^2*yr)	Professional judgment informed by Gosselink (1984), Nyman et al. (1995), Visser et al. (2004), and other sources.
Percent of plant biomass that is N and P (%)	Foote and Reynolds (1997)
Background concentration of N and P (mg/L)	Hyfield (2004)
Sourcewater concentration of N and P (mg/L)	Available data
Nutrient retention (%)	Professional judgment

Figure 2. Example of the parametric uncertainty analysis results showing the predicted marsh acreage for the Future Without Project condition bounded by confidence bands.

DISCUSSION: Historically, quantitative risk assessment methods (such as sensitivity and uncertainty analysis) have created a challenging computational hurdle for practical implementation, but with increased computer power and readily available software, the obstacle is fading away (Ascough et al. 2008). The example presented in this technical note describes an interagency effort to assess the implications of uncertainty on environmental benefits for a coastal restoration project in Louisiana. All of the analyses were conducted using Microsoft Excel, and required just a few days of effort. Discussions among the HET regarding the source and magnitude of uncertainties and associated risks helped inform later decisions regarding alternative formulation, alternative comparison, and project benefit analyses.

Quantitative risk assessment can include a variety of methods not employed for this case study, and a more detailed discussion of the subject is provided by Suedel et al. (2012). The selection of an appropriate strategy for addressing uncertainty is case-specific. However, nearly every study can benefit from efforts to identify, characterize, and quantify the primary sources of model uncertainty. As demonstrated by this case study, such efforts are easily implemented and the ability of these analyses to inform decision making justifies their use.

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