ABSTRACT

GAINEY, KEVIN W. Determination of Possible Wetland Mitigation Sites Using NC-CREWS and an Integer Linear Programming Formulation. (Under the direction of Joseph P. Roise).

The objective of this project was to develop an optimization model for wetland mitigation site selection using a geographic information system for rating wetlands and traditional operations research methodologies. This project was conducted using a GIS based wetland assessment procedure entitled North Carolina Coastal Region Evaluation of Wetland Significance (NC-CREWS) developed by the North Carolina Department of Environmental Resources' Division of Coastal Management (DCM). NC-CREWS rates possible mitigation sites by the wetland functions they could perform if fully restored. Using this component of NC-CREWS, a conceptual model to optimize the selection of restoration sites based on their functions was developed and tested on a small, fabricated example to test workability. This model was adapted to include possible restoration site ratings from an actual watershed in Craven County, NC, provided by DCM. The 0-1 integer programming model that was developed was tested using trials to address issues of problem size, functional unit level required, and order of sites used in the model. Of the 180 tests, all but 37 reached an optimal solution by 200 million iterations of a branch-and-bound algorithm. The problem size and number of functional units required had little impact on the solution time. The ordering of sites as supplied to the model resulted in nonfeasible solutions if sites were chosen based on a physical characteristic such as size or perimeter length. Given the assumptions made in the

model it is possible to derive a list of possible mitigation sites to use for improving field recognizance.

DETERMINATION OF POSSIBLE WETLAND MITIGATION SITES USING NC-CREWS AND AN INTEGER LINEAR PROGRAMMING FORMULATION

by

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To Jerry and Pat Gainey

Without their constant encouragement, advice, and all-round support,
I would not be where I am today.

Thanks for always helping me find the answers,
even if the most common words I heard as a child were
"Look it up!"

BIOGRAPHY

Kevin Wayne Gainey was born October 24, 1973 in Concord, North Carolina. He received two years of high school education at A.L. Brown High School in Kannapolis, NC, and graduated from the North Carolina School of Science and Mathematics in Durham in 1992.

Kevin received the Bachelor's of Science degree in Forest Management from North Carolina State University in May of 1996. He started his research in July of 1996. Kevin received a Center for Transportation and the Environment Fellowship in May of 1997 and was also rewarded a Philip Morris Graduate Scholarship.

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Preface

Wetlands are a part of the natural landscape and have been the subject of countless scientific and legislative debate. Evolving from this debate, federal and state policies require that impacts to or degradation of a wetland be mitigated for, meaning wetland losses must be replaced (most notably, Section 404 of the Federal Clean Water Act). The process of mitigation can be *ad hoc*, in that there is no good tool for finding possible mitigation sites where the wetland replacement is based on functions instead of acreage (Bledsoe et al. 1997, Richardson 1994). Current practices within the 404 permit process does not distinguish between high and low quality wetlands when considering permit approval (Sutter & Wuenscher 1997) and it is up to the permit applicant to select sites for use as mitigation (Bledsoe et al. 1997). The applicant is often not ecologically qualified, and in the interest of time and money, settles for available land with little concern for the quality of wetlands that will be restored (Bledsoe et al. 1997).

Wetlands were once pervasive in the coastal plain of North Carolina but draining and development have converted many sites to agricultural fields, pine plantations, road corridors, and urban areas (Johnston 1994, Sutter & Wuenscher 1997). Because the societal and ecological values of wetlands have been emphasized in recent decades, there is a desire to better protect existing wetlands and improve the wetland restoration process. Wetland restoration is simply taking an area that was once a wetland but has been developed and converting it back into a wetland. This may require restoring vegetation, hydrology, and some soil characteristics to pre-disturbance levels, if possible.

Population growth, which requires larger transportation systems, extends humans' impact on the environment. Joy Zedler of the Pacific Estuarine Research Laboratory at San Diego State University claims highway agencies are one of the largest destroyers of wetlands due to corridor placement in low, flat areas where natural wetlands once flourished (ENR 1994). Highways located in floodplains can alter hydrologic relationships because of floodplain constriction and changes in flow rates due to roadbeds and culverts (Walbridge & Lockaby 1994). These changes can alter the energy signature of the wetland, precipitating a change in species composition and distribution. Walbridge and Lockaby also state that in time the biogeochemical input/output relationships re-establish. Depending on the amount of change, the overall capability of the wetland to perform the impacted functions may change. These changes in energy signatures can lead to slower moving water or stagnation. Conner and Day showed that net primary productivity is reduced as surface waters become more stagnant (1982) and Johnston recorded a similar decrease in southeastern bottomland forests (1994). These impacts affect the level at which a wetland performs various functions.

The North Carolina Department of Environmental and Natural Resources' Division of Coastal Management (DCM) has developed a wetland mapping and functional assessment initiative for the twenty coastal counties within their jurisdiction (Sutter &

Wuenscher 1997). This assessment method, titled North Carolina Coastal Region Evaluation of Wetland Significance (NC-CREWS), is a procedure based on spatial data layers contained in a geographic information system (GIS). NC-CREWS provides a method for rating existing wetlands as well as possible mitigation sites. NC-CREWS uses National Wetland Inventory maps and three classes from the hydrogeomorphic classification system developed by Mark Brinson (Brinson 1993) for defining and classifying wetlands. Using NC-CREWS ratings and a technique to optimize the selection of mitigation sites could provide a tool to improve the compensatory mitigation of wetland functions.

The need for a quantitative tool allowing transportation and mitigation planners to select possible restoration sites led to a research grant sponsored by the Center for Transportation and the Environment. The following chapters describe an approach to combine NC-CREWS with a linear programming model to enhance the restoration site selection process after a transportation project or other construction effort adversely impacts wetlands. Chapter 1 focuses on the development of a conceptual model and a simple test scenario. Chapter 2 refines the model and includes actual NC-CREWS ratings and tests the resulting model on a sample watershed using a series of trials.

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CHAPTER 1

Analysis of Road Locations in Wetlands
and Mitigation Site Selection

INTRODUCTION

The purpose of this work was to find a way to improve the transportation planning process by including wetland functions in a spatial analysis tool. Wetland functions are the ecological processes that occur in these systems. For example, the ability of a wetland to provide nesting habitat for waterfowl is a function. Groundwater recharge, pollutant removal, and floodwater storage are other wetland functions. These functions should not be used as synonyms for wetland values, the importance that society assigns to wetland functions. A wetland may play a large role in removing sediment and pollutants from a city's water supply, and therefore be valuable to the city. However, wetlands with the same functions but not directly affecting the water supply may not be as valuable to the city.

Whenever a transportation or other construction project detrimentally impacts wetlands, those impacts must be mitigated. Wetlands mitigation is the process of replacing the wetland functionality that was destroyed. This is most often done through wetland restoration, the process of reestablishing a wetland that has been converted. Policy defined ratios exist that control the number of acres that must be mitigated and are dependent on the type of mitigation being performed. However, the North Carolina Division of Coastal Management has cited this process as a contributor to failure of mitigation because wetland functions are not specifically considered in establishment of the ratios (Bledsoe et al. 1997).

DESCRIPTION OF THE MODEL

NC-CREWS Functions

NC-CREWS looks at a variety of wetland functions, but only three were considered in this first version of the model. The functions considered are terrestrial wildlife habitat, nonpoint source pollution reduction, and floodwater storage. Each function has a series of parameters which are combined to give each wetland unit in the GIS an overall rating for each function. The wetlands are rated High, Medium, or Low for each function being considered. The database developed by DCM contains these ratings for existing wetlands. Because this model also looks at sites that could be converted back to wetlands, these functional ratings must be calculated for each combination of land units chosen as satisfying the mitigation requirements. At the time of model development DCM was working on a method for rating possible restoration sites. Since this information was not available, a similar method was used for the purposes of this model that was based on the NC-CREWS method of rating existing wetlands. The rating strategy used for the three functions below comes directly from Sutter and Wuenscher (1997).

Terrestrial Wildlife Habitat

This function is rated on the quality of habitat provided for terrestrial wildlife. The parameters considered are interior size, percent surrounding habitat that is natural vegetation, and the length of a wildlife corridor that links to other natural vegetation.

To calculate interior habitat, a buffer zone of 100 meters around the perimeter is subtracted from the total area (Sutter & Wuenscher 1997). The rating strategy for wildlife habitat parameters is shown in Table 1.1.

Table 1.1: Ratings assigned to wildlife habitat parameters

Parameter	High Rating	Medium Rating	Low Rating
Interior Size	> 74 acres	0 - 74 acres	None
% Surrounding Habitat	> 50% wetlands	< 50% wetlands	Isolated from other wetlands
Wildlife Corridor	> 600 feet	< 600 feet	Isolated from natural habitat

Nonpoint Source Pollution Reduction

Three parameters of the nonpoint source rating system were considered. First, the proximity to agriculture, developed land, pine plantation, and natural vegetation are considered using the percent of surrounding habitat as the criteria. Second, the distance from a water source is used. Third, the position of the wetland relative to stream orders is used. Table 1.2 summarizes the rating scheme.

Table 1.2: Ratings assigned to nonpoint source pollution parameters

Parameter	High Rating	Medium Rating	Low Rating
Proximity to sources	> 50% perimeter agriculture + developed	> 50% perimeter agriculture + developed + pine plantation	> 50% perimeter natural vegetation
Distance to water source	Within 300 ft. Permanent source	Within 300 ft. intermittent stream	> 300 ft. from permanent or intermittent source
Wetland position	Intermittent or 1st order stream	2nd or 3rd order stream	Higher than 3rd order stream

Floodwater Storage

The position of the wetland in the landscape, the duration of flooding, and the width of the wetland perpendicular to the stream are the parameters considered for rating the floodwater storage capacity of a wetland. Table 1.3 summarizes floodwater storage rating criteria.

Table 1.3: Ratings assigned to floodwater storage parameters

Parameter	**High Rating**	**Medium Rating**	**Low Rating**
Position in landscape	> 25% stream bordered by developed land	5 - 25% stream bordered by developed land	<5% stream bordered by developed land
Duration of flooding	Long to very long	Brief	Very Brief
Width of wetland perpendicular to stream	> 100 feet	50-100 feet	< 50 feet

Methods and Assumptions

To make the NC-CREWS rating method work in a model, values had to be assigned to the rankings of High, Medium, and Low. The rankings were treated as indices and were assigned integer values of 1,2, and 3 (Low, Medium, and High). The acreage of the wetland is multiplied by the rating for each parameter in each functions and combined to produce a cumulative, numerical ranking that represents functional units supplied by the wetland. NC-CREWS does not use a straight summation of parameter ratings to obtain the function ratings. This method was used here to simplify the model for the purpose of providing a clear example of applying a linear programming formulation.

The generalized steps that the model employs are:

1. The total functional units existing in a watershed where a road is planned are calculated using the NC-CREWS GIS procedure.
2. The user indicates a transportation corridor by adding the link to an existing road network.
3. For links impacting wetlands, the functional units of the watershed are recalculated to measure the number of units lost to the road addition.
4. The mixed integer model is run to find the optimal combination of land units to be converted to mitigation sites.

In order to make a workable model based on NC-CREWS that would be usable in a GIS environment, several key assumptions have been made for this simple scenario:

1. All of the parameters and functions are equally weighted. Future models should allow the user to assign weights to different functions to better meet actual needs.
2. There is no requirement that units removed by a corridor at the parameter level must be replaced by the same parameters in the mitigation sites. Only the total number of units at the function level must be replaced. For example, the number of habitat units destroyed must be replaced by habitat units, but the units restored from interior size parameter do not have to match those destroyed for the same parameter by the road.
3. Within the GIS layers, only entire sites may be considered for mitigation. No portion of a possible site may be used. This assumption necessitates the

integer programming requirement. Without this assumption the model would be a great deal easier to solve, but it might not correctly represent the wetland ratings.

The Model

Following the above procedure and using the listed assumptions, the linear programming model has the form:

Maximize $\sum(A_iX_i(F_{Hab} \times R_{Habi} + F_{NPS} \times R_{NPSi} + F_{FS} \times R_{FSi} - c)) - C_{Road} - (F_{Hab})(H_{Loss}) - (F_{NPS})(NPS_{Loss}) - (F_{FS})(FS_{Loss})$ (1)

Subject to

$$R_{Hab}A^TX \geq H_{Loss} \quad (2)$$
$$R_{NPS}A^TX \geq NPS_{Loss} \quad (3)$$
$$R_{FS}A^TX \geq FS_{Loss} \quad (4)$$
$$C_{Road} + cA^TX \leq C_{Max} \quad (5)$$
$$X_i \in [0,1] \quad (6)$$

Where

A_i = acreage for land unit i for i = 1...n with n land units in study area
X_i = [0,1] decision variable to convert land unit i to wetland, i = 1 to n
F_{Hab} = scalar conversion factor of a habitat functional unit to dollars
F_{NPS} = scalar conversion factor of a nonpoint source functional unit to dollars
F_{FS} = scalar conversion factor of a floodwater storage functional unit to dollars
R_{Habi} = sum of ratings for habitat parameters, integer in [3 ..9], for site x_i
R_{NPSi} = sum of ratings for nonpoint source parameters, integer in [3 ..9] for site x_i
R_{FSi} = sum of ratings for floodwater storage parameters, integer in [3..9], for site x_i
c = cost per acre of converting land to wetland
C_{Road} = cost of constructing road corridor
H_{Loss} = habitat functional units lost to road corridor
NPS_{Loss} = nonpoint source functional units lost to road corridor
FS_{Loss} = floodwater storage functional units lost to road corridor
C_{Max} = maximum dollar value available for road and mitigation project

Equation (1) serves as the objective function and denotes that the goal is to maximize the financial return of restoring wetlands based on the associated dollar values for each function and the cost of restoring the sites. Equations (2), (3), and (4) denote the goal of restoring at least as many functional units as were destroyed (see assumption number 2 on page 6). Equation (5) states that the cost of the road and the cost of restoring sites may not exceed some specified project maximum. Equation (6) denotes the use of a 0-1 integer programming formulation where the decision variables take on values of 1 for choosing a site to restore and 0 for not selecting site X_i.

The constraints for nonpoint source (3) and floodwater storage (4) are based only on the total area of the land units when calculating functional units. However, when calculating functional units for interior habitat, if adjacent land units are chosen, the amount of interior habitat will increase because portions of the 100 meter buffer will become interior space. Therefore, for each iteration of the program, R_{Hab} must be recalculated. This would ideally be done by the GIS database accompanying the NC-CREWS system, but it is done by hand in the example in the next section.

The last four terms of the objective function (1) are costs incurred from road construction and do not depend on the combination of possible mitigation sites. For a single road corridor alternative, these terms may be dropped from the objective function and the maximum mitigation return can be calculated. The terms have been included in the equation for clarity and to support the need for transportation planners to analyze alternative corridors relative to wetland impacts.

An Example Using Habitat Functions

The following example uses the above model with only the habitat function to determine an optimal mitigation combination for a given road corridor. The resulting model formulation includes only equations (2), (5), and the terms from (1) pertaining to F_{Hab}, R_{Hab}, and H_{Loss}. Visual display of nonpoint sources and floodwater storage becomes difficult without a GIS since hydrology and land use data layers must be used together. The intent is to show how the model can be applied to a given scenario and the steps that an automated GIS approach would use.

Figure 1.1 shows the pre-road watershed and Table 1.4 contains the corresponding acreage information. After unavoidably placing part of a road through an existing wetland (Fig. 1.2) mitigation combinations must be calculated.

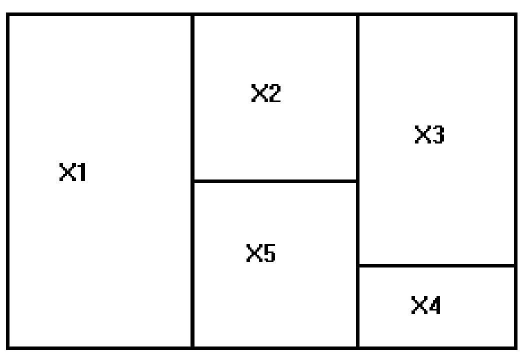

Figure 1.1: Simplified arrangement of land units in a watershed where road impacts will require mitigation.

Table 1.4. -- Characteristic of example watershed

Land Unit	Land Use/ Land Type	Total Acres	Interior Acres
X1	Wetland	150	80
X2	Pine Plantation	62.5	22.5
X3	Pine Plantation	70	25
X4	Pine Plantation	30	5
X5	Pine Plantation	62.5	22.5

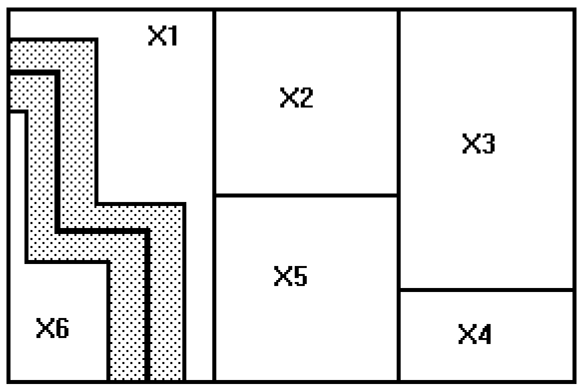

Figure 1.2: Example watershed with added road which requires mitigation.

The road added to the watershed splits X1 into two new land units, creating X6. X6 has an area of 22.5 acres, with interior space occupying 10 acres. The shaded area represents the 100-meter buffer around the road where the impacts occur. The undisturbed watershed contained 750 functional units. Adding the road destroyed 390 habitat functional units (calculated from the impact area of 82.5 acres and the values in Table 1.1) which requires mitigation. Table 1.5 shows the user-defined constants used in this example.

Table 1.5: User defined constants for test scenario.

Constant	Value ($)
F_{Hab}	2
F_{NPS}	2
F_{FS}	2
c	20

For each combination of the possible mitigation sites, the number of habitat functional units restored and the accompanying objective function value was calculated . When using the algorithm with only the habitat function, the optimum combination of land units to restore to wetlands is X2 and X5. Table 6 shows the functional units and mitigation returns possible from all combinations of X2, X3, X4, and X5. X1 and X6 remained wetland and therefore cannot be used for mitigation credit. The alternatives in Table 1.6 where the value for “Units Gained From Mitigation Sites” are less than 390 are not valid because they would violate equation (2) of the model.

This example shows the optimum combination of mitigation sites in terms of financial outlay. Using the figures given in Table 1.5, meeting the constraints results in a financial loss. Depending on the choices of F_{Hab}, F_{NPS}, and F_{FS}, it is possible that the optimum objective function value could have been positive for this scenario. These financial values were arbitrarily chosen and would be different for various interest groups, scientists, and policy makers.

Table 1.6. -- Functional Units Gained from Possible Mitigation Site Combinations.

Land Unit Combination	**Total Area of Wetlands in Watershed (acres)**	**Watershed Functional Units**	**Units Gained from Mitigation Sites**	**Objective Function Value (in $)***
X2	130	610	250	NF
X3	137.5	565	205	NF
X4	97.5	405	45	NF
X5	130	610	250	NF
X2 + X3	200	1090	730	-400
X2 + X4	160	740	380	NF
X2 + X5	**192.5**	**1052.5**	**692.5**	**-385**
X3 + X4	167.5	760	400	-670
X3 + X5	200	890	530	-800
X4 + X5	160	730	370	NF
X2 + X3 + X4	230	1240	880	-460
X2 + X3 + X5	262.5	1402.5	1042.5	-525
X2 + X4 + X5	222.5	1202.5	842.5	-445
X3 + X4 + X5	230	1172.5	812.5	-595
X2 + X3 + X4 + X5	292.5	1552.5	1192.5	-585

* Does not include last four terms of the objective function which are constants. NF denotes a nonfeasible solution.

DISCUSSION AND CONCLUSIONS

Given the simplicity of the scenario and the stated assumptions, the model formulation provides an easily adaptable and quick method for comparing different site selection alternatives. The choice of sites were quantitatively ranked based on their restoration of habitat functionality, allowing planners to better select ecologically viable sites.

Once automated with a computer the model's output will provide answers that were not possible under the test above. For example, by using linear programming techniques, the constraints can be analyzed to determine how additional functional units would impact the objective function. This type of sensitivity analysis would provide a means for adjusting the user-defined values given in Table 1.4.

Because of the varying opinions of wetland functions and assessment methods, this project used only the NC-CREWS system to drive the models. This system was developed for a specific geographic region to which this model is currently limited. Because some wetland rating systems try to attach numbers to wetland functions, this model, because of its simplicity, could be modified to meet needs in regions other than the coastal plain of North Carolina. As NC-CREWS capability to rate restoration sites is implemented, the model will need to be adapted to handle a more complex method of determining the rating coefficients. However, the general architecture of the model would remain the same, using the 0-1 integer programming formulation for choosing sites.

The next step in this process is to refine the formulation and attach the model to actual NC-CREWS ratings for an existing watershed. As with any complicated ecosystem, the model is only as good as the available input data. There is a wealth of quantitative data on wetland functions, but there is confusion as to which methods are correct, especially in light of current regulations and changing societal values. Because wetland mitigation restoration is performed on an acre basis using ratios defined by policy, this model is different in that it has no site size requirements. The focus is purely on replacing functional units. As Kulkarni and others noted (1993), any time you use values that denote tradeoffs, as with F_{Hab}, F_{NPS}, and F_{FS}, some subjectiveness is introduced. This subjectiveness cannot be avoided since quantitative measures of wetland values do not exist. As wetlands become better understood and the driving forces behind functions are viewed within the context of the entire watershed the model will need to be revised.

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CHAPTER 2

Determination of Possible Wetland Mitigation Sites Using NC-CREWS
and an Integer Linear Programming Formulation

INTRODUCTION

The purpose of this effort was to develop a tool to assist transportation planners in the process of determining road corridors relative to wetland impacts using a geographic information system (GIS) and traditional operation research methodologies. One phase of this work includes a tool that optimizes the choice of mitigation sites after the wetland impacts of the transportation project are known. This chapter looks at the development and testing of an integer programming model used to find possible wetland restoration sites that maximize wetland functions as rated by NC-CREWS (Sutter and Wuenscher 1997). This model expands that discussed in Chapter 1 to include actual NC-CREWS data, more functions, and computer automation of the model.

Like other natural resource disciplines, the use of GIS to map and analyze wetland trends has grown in the past decade. Some applications have included use of GIS to map wetland changes over time (Logan 1993, Michelson 1993, Young and Dahi 1995). Other uses include modeling, such as nonpoint source pollution determination relative to wetlands (Poiani and Bedford 1995). NC-CREWS uses GIS to incorporate different data layers and algorithms into a wetland rating system (Sutter and Wuenscher 1997).

Used to report the relative ecological significance of wetlands, NC-CREWS uses a hierarchical structure to assign values to wetland functions. There are four overall functions that receive ratings: Water Quality, Hydrology, Wildlife Habitat, and Risk of

Development. These functions receive their ratings based on a combination of sub-functions. For example, Wildlife Habitat is rated based on the ratings assigned to Terrestrial Habitat and Aquatic Habitat. In turn, sub-functions are rated according to parameter ratings. To extend the example, Terrestrial Habitat is a combination of Internal Habitat, Landscape Habitat, and Movement System Value functions. The fourth and final layer in the hierarchy consists of sub-parameters. Combining the sub-parameters and working up the hierarchy to reach a final function rating is a complex process. Because wetland functions interact in complex ways, a simple summation of ratings is not accurate (Bledsoe et al. 1997). This refined model addresses the summation issue unlike the model in Chapter 1 where the emphasis was placed more on the architecture of the optimization model formulation.

In addition to rating existing wetlands, potential restoration sites are also classified for the first three overall functions listed above. A site is assessed as if it were restored and fully functioning. This is the particular component of NC-CREWS that allows creation of a model for choosing mitigation sites that optimize the return of ecological functions. DCM notes that the site selection process is a major contributor to the failure of compensatory mitigation to replace wetland functions (Bledsoe et al. 1997). By combining the NC-CREWS framework with an optimization routine, the benefits of a tool that refines the selection process are increased.

MODEL DEVELOPMENT

The model was named Wetlands Mitigation Optimizer, or WetMOp for short. Most of the effort focused on converting NC-CREWS ratings into a mathematical model framework that could then be optimized with WetMOp.

NC-CREWS assigns ratings of High, Medium, or Low to the wetland functions. A system that attempts to assign numerical values along a scale would not be justified by the precision of our current knowledge base concerning wetland functions (Bledsoe et al. 1997). However, there does need to be some type of numerical transformation associated with the qualitative ratings for this study. The choice was to assign a value of 3 for High, 2 for Medium, and 1 for Low ratings. There was no indication in the NC-CREWS literature that a High was more or less than 3 times as ecologically important as a Low rating so these assignments were used as initial estimates.

Because a 100 acre wetland rated High would most likely be more "important" in the ecological landscape than a 10 acre wetland rated High, each site's functions' ratings were multiplied by the site's acreage to obtain a measure that was loosely termed "functional units." This leads to the question, "Is 30 acres of low rating wetland equal to 10 acres of high rating wetland?" This question was not addressed by the model but is an issue for further research. One goal of the model was to support a system that maintained mitigation levels for each function destroyed, not just the number of functional units (FU) overall. Meaning, if a transportation project destroyed 250 FU of hydrology, those units cannot be mitigated by 250 habitat FU. The restoration site(s) chosen must be rated with at least 250 hydrology FU. This was included in the model to maintain DCM's watershed approach to rating the possible restoration sites. Since the watershed is the extent of the system, functional units can be restored by more than one possible mitigation site. In short, as long as the functional units destroyed within the watershed are restored within the watershed, it does not matter which sites provide the functional units.

At the time of development the three available function ratings were Hydrology, Water Quality, and Wildlife. A Practicality of Restoration rating was in the works, but not available for use (personal communication with Mac Haupt of DCM). DCM provided a sample database. The watershed is located in the Swift Creek (also known as watershed 154) area of Craven County, NC. Watershed 154 contained 996 potential wetland restoration sites that were deemed to be a decent number for testing what would be an integer programming problem.

An initial concern about the model was the ability to handle the spatially dependent values of the rating system. While most of the functions in NC-CREWS depend on the spatial arrangement of wetland sites within the watershed, some additionally depend on the distance to other wetlands. Two important questions arose which effect the calculation efficiency of the model : If you mitigate two sites within a given distance, or even adjacent sites, will the ratings for either site change? If so, do the ratings have to be recalculated for those sites? Considering that NC-CREWS requires large amounts of computer processing time and the goal was to make an efficient model, a solution was desired to circumvent running NC-CREWS any more than absolutely necessary. From evaluating the NC-CREWS algorithms, it was found that the Habitat functions were mostly dependent on nearby wetlands. In reviewing the Habitat ratings for the watershed, which is mostly estuarine wetlands, it was discovered that only non-estuarine wetlands affected Habitat ratings in relation to surrounding wetlands. So the concerns and questions were not an issue for the sample watershed and allowed model development without making further assumptions.

A design objective of the optimization model is to provide a list of possible mitigation sites that meet the functional unit requirements lost by road construction while minimizing the number of acres to be mitigated. This type of qualitative formulation translates to a zero/one program where the decision to mitigate a site is denoted by a value of 1 and 0 denotes otherwise. Each of the three NC-CREWS functions can be represented by one equation. This general structure is expressed by the following mathematical formulation:

Minimize $\Sigma\, a_i x_i \quad \text{for } i = 1 \text{ to } n$ (1)

Subject to
$\Sigma\, HY_i a_i x_i \geq HY_{Loss}$ (2)
$\Sigma\, WQ_i a_i x_i \geq WQ_{Loss}$ (3)
$\Sigma\, HA_i a_i x_i \geq HA_{Loss}$ (4)

$x_i \in [0,1]$ (5)

Where a_i = acreage for land unit i for i = 1...n with n land units in study area

x_i = [0,1] decision variable to restore land unit i to wetland, i = 1 to n
n = the number of possible mitigation sites
HY_i = hydrology rating for possible site i
WQ_i = water quality rating for possible site i
HA_i = habitat rating for possible site i
HY_{Loss} = hydrology functional units lost to road corridor
WQ_{Loss} = water quality functional units lost to road corridor
HA_{Loss} = habitat functional units lost to road corridor

The objective function (1) of the model is to minimize the total number of acres mitigated. Cost minimization is a direct extension of this. One could replace the number of acres in site *i* with the cost of site *i* where cost could include both purchase and restoration costs. Cost coefficients from the model in Chapter 1 were removed here since they could be substituted in the objective function. Acre minimization must be done while satisfying the three constraints for hydrology, water quality, and habitat (equations 2, 3 and 4) that state the number of functional units mitigated must be greater than the number destroyed. The number of functional units destroyed is determined by multiplying the number of acres in an impact site by the site's functional ratings as determined by NC-CREWS and they provide the mitigation targets on the right side of the equation in (2), (3), and (4). Equation number 5 relates the concept of the decision variables being either 0 or 1 for not choosing or choosing the site, respectively.

One concern when testing this formulation was to determine at what problem size (number of possible mitigation sites) the integer program became intractable. That is, when the software package could no longer determine a solution because the problem may be too large. Knowing the maximum feasible size for the model provides a gauge for its usefulness in practical applications. Another concern was if the order the sites were imported into the model effected efficiency of the solution. A series of tests were designed to investigate these concerns.

ArcView was used to format the information for use in a linear optimizer. This process involved the use of scripts to create three trials that consisted of an equal number of tests. The tests consisted of running the model in incremental batches of 50 sites starting with 50 and working up to 996 (instead of 1000 since only 996 sites were available in the watershed). To obtain tests for the first trial, the sites were sorted by their internal polygon ID number, provided by ArcView. This basically related to working our way from the north end to the south end of watershed 154 when selecting sites to include. The second trial was based on sorting the sites by their perimeter in ascending length to see what impact a physical attribute of the sites might have on model efficiency and solutions. A third trial used a random selection of sites from all possible sites. All three trials used three different restoration requirement values: 100, 500, and 1000 functional units for each function as the mitigation target. This resulted in 9 trials, each with 20 models to test (See Table 2.1).

In addition to the above tests further investigation of possible integer programming solution software packages was required. With some modification, the ArcView output was used in three different linear optimizers. The first package used was the Solver add-in for Microsoft Excel. This program allowed excellent visual adaptation and testing of the model, but only for 32 variables. Larger, more powerful versions of the Solver are available at additional cost. The second package used was ORSYS by Eastern Software Products, Inc. The test trials ran predictably well on this package until the number of variables approached 600. At that point, the software package would lock up because it presumably could not handle the large number of integer variables.

Table 2.1: Tests for use in LINDO model

Site Selection Method	Functional Unit Requirements	Number of Possible Mitigation Sites
Polygon ID	100	50,100,…950,996*
Polygon ID	500	50,100,…950,996
Polygon ID	1000	50,100,…950,996
Perimeter	100	50,100,…950,996
Perimeter	500	50,100,…950,996
Perimeter	1000	50,100,…950,996
Random	100	50,100,…950,996
Random	500	50,100,…950,996
Random	1000	50,100,…950,996

* Results in 20 different tests.

The final package, LINDO, allowed us to run all the tests for each trial. The program was run on a Pentium 150MHz machine with 48Mb of RAM. At the time of testing, this was a "middle of the road" machine. It was selected because one goal was to determine solution times that the average user could expect. The machine used established an upper boundary for solution times since faster machines would solve the tests more quickly. Had the entire NC-CREWS algorithms been available from DCM, there would have been more incentive to incorporate the rating strategy (instead of using only the final outputs) and to use the model on a super computer or high-end workstation. Little or no problems were encountered using LINDO, which is rated to handle 16,000 integer variables for the version used. LINDO also allowed additional testing to examine methods of reducing computation time.

LINDO examines the possible combinations of sites to determine the optimal selection using a branch-and-bound algorithm. This method resembles a tree where branches represent a series of sub-problems. These sub-problems start with no constraints on the variables and become more constrained as the branch grows. At each branch the linear relaxation of the integer problem is solved and a check is made to see if a branch contains the optimal solution. For a more detailed explanation of the branch-and-bound algorithm see Winston (1994). It is sometimes possible to tell whether a branch will lead to a better solution or not without looking at all the sub-problems on the branch. LINDO allows only those branches whose sub-problems are within a certain tolerance or percentage of the current best solution to be explored. This saves computational time by not solving all the sub-problems, but sometimes at the price of accuracy (Schrage 1989). A trial was run for ID-sorted sites with 100 FU mitigation target levels without a tolerance level first. For comparison, the same tests were then ran using a tolerance of .0005. This tolerance required that the branch be .05% closer to optimal than the current solution. Also, in the interest of time, a 200 million iteration limit on all tests was imposed. The results from the trials are given in the next section.

RESULTS

For each test of the three trials we recorded objective function value (number of acres selected), number of algorithm iterations, number of variables, and the cumulative time to reach a solution. Though the number of variables were incremented by 50 for each test, there were some sites in the watershed that contained zero ratings for all three functions and therefore dropped out of the formulation as insignificant, so the actual number of variables used by the model was recorded.

Table 2.2 and Figure 2.1 display the results for the comparison of the standard branch-and-bound algorithm and the test of the .05% tolerance implementation. For these tests, the objective function values were equal for all 20 tests between the use of tolerance levels and without. The results of this test as the basis for deciding to use the .05% tolerance when conducting further tests, especially for the 500 and 1000 mitigation target tests, which in pre-testing showed solution times of over three days for a single test without the use of a tolerance. Identical acreage solutions were not expected for the larger functional unit target levels (which require more acres in most cases) however, since the tolerance is a percentage of the solution and not an absolute deviation.

Table 2.2: Number of Iterations Comparing Use of Tolerance for Wetlands Sorted by ID with a Target Mitigation of 100 FU

Number of Sites	Without a Tolerance	With Tolerance
41	1279	1983
71	1942	1083
92	2791	1101
114	11181	2785
148	566	189
195	3070	1192
244	8700	1706
294	6841	19320
344	6826	4228
394	8882	29367
444	11343	3115
493	27312	1055
541	30058	4956
590	35115	8164
640	34390	13216
690	66628	4631
740	237250	16901
789	529058	8805
839	660979	3545
885	228277	14275

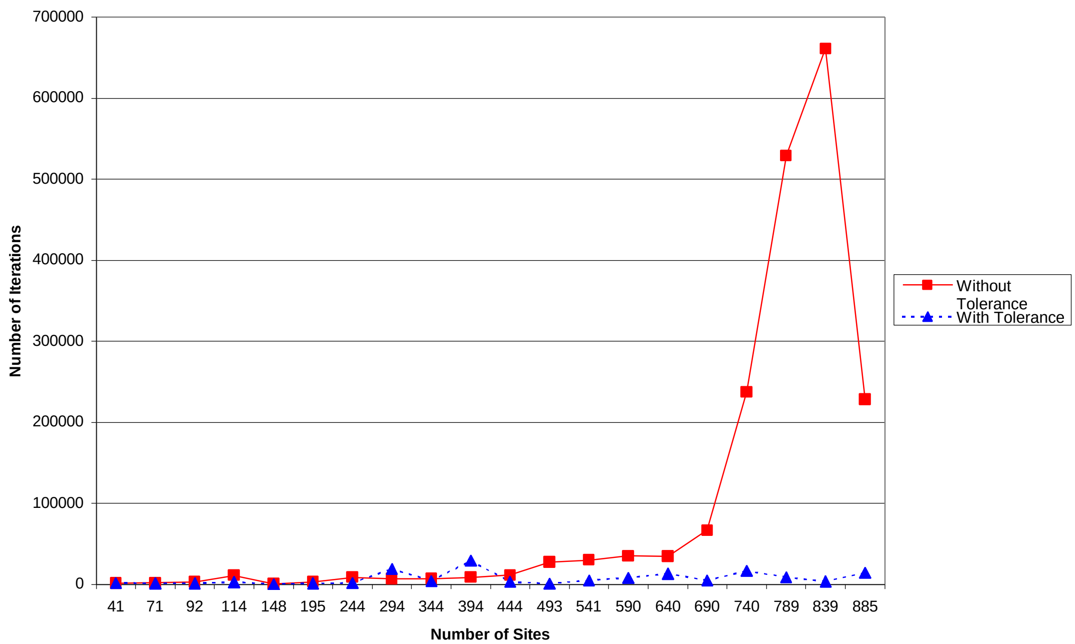

Figure 2.1: Comparison of Use of Tolerance with No Use of Tolerance

Tables 2.3 through 2.11 (following the DISCUSSION AND CONCLUSIONS) contain the results for all the trials tested at the three functional unit levels. Two important measures of performance are the time used to reach a solution and the number of iterations. Figures 2.2 through 2.4 show a comparison of the number of iterations required to reach a solution for the three trials. Those tests that did not reach an optimal solution within 200 million iterations or where no feasible solution was possible are not shown on the graphs to maintain readability. Figures 2.5 through 2.7 show the solution time for the trials. The solution times for the trials are somewhat misleading because LINDO reported the computational time to trace through the branches that met the tolerance requirements. Every branch is still visited on the tree and the test to see if a branch is better than the current optimal solution is a computation that takes time, but this time is not included in the output. For comparing the trials, this method is consistent because it was applied to all tests, so the comparisons are valid. However, it is not valid to assume that a model with 900 variables and a mitigation target of 1000 FU will take only 45 seconds. In actuality, the model ran for approximately 23 hours before eliminating all possible other solutions.

DISCUSSION AND CONCLUSIONS

The results from the trials confirm that with the given problem formulation and size, one can optimize the selection of possible mitigation sites. All but 37 of the 180 tests resulted in an optimal solution by LINDO. Fourteen of these were due to the imposed 200 million iteration limit. Overall the graphs show no clear pattern in solution times or number of iterations among the three trials or the target functional unit values when using a tolerance level. The erratic behavior of the graphs indicate there are numerous factors affecting solution time, but that solutions are possible with properly constructed models. The most important observation, however, was the nonfeasibility of scenarios when the mitigation target levels were high and a small number of sites were chosen based on their perimeter, which was sorted in ascending order. This means that even if all the sites had been restored, their areas and ratings were not high enough to meet the required mitigation target minimums. Therefore, for application purposes, cases can be constructed to arrive at solutions for different mitigation requirements and site selection criteria, as long as care is taken to avoid choosing sites to include in the model based solely on their size, especially at the low end of the spectrum. This can be extended to mean that if one is choosing possible sites to feed into the model based on total site cost, selecting all the lowest sites *could* translate into choosing the smallest sites. This depends, of course, on other factors that affect site cost, but should still be a consideration.

The times associated with solving the models with larger numbers of sites can be avoided by doing some logistical, political, and economical screening of sites to include in the model (for example, selecting only sites that are potentially purchasable). WetMOp used a sample watershed and assumed all sites were available for restoration. However, this is most often not the case.

There is some overhead work that must be completed before the information could be input into a model, but the majority of the tasks can be automated through scripts. The limiting factor at this point is the availability of the NC-CREWS final ratings data layers of the restoration functional assessment procedure. Because NC-CREWS focuses on the coastal plain of North Carolina, WetMOp would have to be adapted to manipulate the ratings from other assessment procedures. The model could also be expanded to include more than three functions if the ratings were determined by a consistent system. WetMOp also requires the input of functional units destroyed at the impact site, which should be arrived at using the same "rating times acres" process as used here to calculate restoration functional units.

Given the assumptions and limitations inherent in NC-CREWS and WetMOp, the combination of the two systems provides a technique for mitigation planners to narrow their field verification of possible sites. Future research and modification should focus on converting the wetland ratings into mathematical formulas as well as the issue of spatially dependent ratings when choosing sites. Larger processors and more efficient algorithms also could have an effect on the solution time and intractability of integer programming problems. It is important to choose a system and software package that matches the requirements and size of the specific case.

Lessons from this model have yielded several important questions for further research: What effect would non-estuarine wetlands have on the model since ratings may change with adjacent mitigation of sites? How would the use of a super computer to calculate NC-CREWS ratings and run the model increase model reliability? How sensitive is the optimization model to the input layers' resolution and accuracy? Would a network or some heuristic algorithm provide reliable answers in less time? Answering these questions would provide a better model and hopefully a better tool for selecting possible mitigation sites.

Table 2.3: Results of Tests for ID Sorted Trial with 100FU

Number of Sites	Solution (acres)	Iterations	Time (seconds)
41	48.74	1983	0.88
71	34.15	1083	0.66
92	34.15	1101	0.99
114	33.87	2785	1.65
148	33.38	189	0.49
195	33.34	1192	1.43
244	33.34	1706	2.14
294	33.35	19320	18.56
344	33.34	4228	5.27
394	33.34	29367	35.70
444	33.34	3115	5.71
493	33.34	1055	2.80
541	33.34	4956	9.34
590	33.35	8164	16.48
640	33.34	13216	25.81
690	33.34	4631	11.31
740	33.35	16901	37.90
789	33.34	8805	26.31
839	33.34	3545	10.33
885	33.34	14275	46.80

Table 2.4: Results of Tests for ID Sorted Trial with 500FU

Number of Sites	Solution (acres)	Iterations	Time
41	246.25	253	0.27
71	205.74	1079	0.77
92	202.94	10240	5.27
114	184.58	6933	3.57
148	169.21	65159	31.03
195	166.83	8002	6.21
244	166.68	5652	5.11
294	166.69	132	0.82
344	166.69	4767	5.27
394	166.69	9531	12.08
444	166.68	7637	12.14
493	166.75	6777	12.47
541	166.70	7486	16.09
590	166.74	2321	5.22
640	166.67	7109	16.09
690	166.67	37007	92.33
740	166.75	38274	61.13
789	166.71	6693	16.86
839	166.70	6318	21.26
885	166.74	4495	16.59

Table 2.5: Results of Tests for ID Sorted Trial with 1000FU

Number of Sites	Solution (acres)	Iterations	Time
41	NON-FEASIBLE	****	****
71	454.88	6475	2.03
92	452.82	5640	2.47
114	428.61	3935	1.98
148	386.73	4537	2.97
195	362.22	2000000	****
244	356.35	11098	7.25
294	353.51	2000000	****
344	352.74	29721	34.71
394	351.89	27879	34.22
444	350.68	569168	727.21
493	337.28	105.182	169.44
541	333.86	3638	8.24
590	333.48	8347	17.41
640	333.45	12010	26.25
690	333.36	14490	34.93
740	333.36	266	2.36
789	333.45	10435	36.85
839	333.35	16136	44.11
885	333.37	12448	44.38

Table 2.6: Results of Tests for Perimeter Sorted Trial with 100FU

Number of Sites	Solution (acres)	Iterations	Time
15	NON-FEASIBLE	****	****
33	NON-FEASIBLE	****	****
63	NON-FEASIBLE	****	****
112	75.37	621	0.66
161	55.98	292	0.88
209	40.72	37205	30.87
259	39.65	77366	50.97
306	39.64	1322426	1733.12
354	38.46	26744	41.52
402	38.08	18301	29.33
450	37.60	60856	118.58
500	35.90	200000000	****
550	35.42	7034641	11700.26
599	33.88	630798	1062.64
646	33.64	19497	52.51
694	33.35	21647	60.53
742	33.35	5994	15.76
792	33.35	8714	23.18
842	33.34	12734	34.93
885	33.34	31724	95.73

Table 2.7: Results of Tests for Perimeter Sorted Trial with 500FU

Number of Sites	Solution (acres)	Iterations	Time
15	NON-FEASIBLE	****	****
33	NON-FEASIBLE	****	****
63	NON-FEASIBLE	****	****
112	NON-FEASIBLE	****	****
161	NON-FEASIBLE	****	****
209	NON-FEASIBLE	****	****
259	NON-FEASIBLE	****	****
306	385.11	774	2.14
354	257.03	838	2.80
402	306.26	1467	2.75
450	240.40	1047	2.53
500	200.28	200000000	****
550	195.43	200000000	****
599	192.86	200000000	****
646	191.42	200000000	****
694	186.35	200000000	****
742	172.91	200000000	****
792	167.84	98580	260.95
842	166.71	15801	45.53
885	166.73	22359	70.80

Table 2.8: Results of Tests for Perimeter Sorted Trial with 1000FU

Number of Sites	Solution (acres)	Iterations	Time
15	NON-FEASIBLE	****	****
33	NON-FEASIBLE	****	****
63	NON-FEASIBLE	****	****
112	NON-FEASIBLE	****	****
161	NON-FEASIBLE	****	****
209	NON-FEASIBLE	****	****
259	NON-FEASIBLE	****	****
306	NON-FEASIBLE	****	****
354	NON-FEASIBLE	****	****
402	NON-FEASIBLE	****	****
450	740.39	690	3.46
500	654.93	2345	5.16
550	606.01	1090	5.11
599	529.97	4613	9.39
646	407.77	200000000	****
694	390.77	200000000	****
742	372.65	60544	139.07
792	365.74	34674	93.54
842	347.38	200000000	****
885	333.46	30209	91.45

Table 2.9: Results of Tests for Random Sorted Trial with 100FU

Number of Sites	Solution (acres)	Iterations	Time
44	37.01	1498	1.15
91	34.26	445	0.49
127	37.54	51597	48.39
178	33.55	47	0.55
217	33.49	1367	1.76
260	33.41	1591	1.98
314	33.36	9346	10.77
354	33.34	14315	15.05
406	33.35	4366	6.26
452	33.34	15743	26.91
492	33.34	11684	18.62
531	33.34	3112	5.88
582	33.34	11124	21.81
627	33.34	5632	13.02
655	33.34	16925	36.09
706	33.35	5949	17.08
754	33.34	11472	33.01
800	33.34	6284	17.58
849	33.34	13613	36.75
885	33.34	14275	46.80

Table 2.10: Results of Tests for Random Sorted Trial with 500FU

Number of Sites	Solution (acres)	Iterations	Time
44	3493.62	0	0.22
91	216.91	535	0.60
127	218.24	4134	1.81
178	191.08	52522	29.28
217	191.75	2000000	****
260	166.71	671	1.59
314	166.76	6651	7.25
354	166.71	7516	10.66
406	170.40	102244	139.68
452	166.69	5058	10.88
492	166.67	150	1.48
531	166.70	1778	4.89
582	166.70	26578	59.98
627	166.70	3865	9.61
655	166.74	8287	20.38
706	166.68	4826	14.67
754	166.67	8435	20.43
800	166.68	33243	97.11
849	166.69	15271	42.90
885	166.74	4495	16.59

Table 2.11: Results of Tests for Random Sorted Trial with 1000FU

Number of Sites	Solution (acres)	Iterations	Time
44	22467.75	3	0.33
91	1094.73	0	0.44
127	447.34	19298	6.26
178	432.40	1783	2.14
217	397.89	835560	559.31
260	358.42	2799	3.08
314	353.16	1061268	918.68
354	385.42	2000000	****
406	370.39	82446	95.90
452	333.44	6411	11.37
492	333.38	4867	9.89
531	333.38	8551	15.76
582	333.36	17363	34.00
627	333.37	2383	6.81
655	333.41	2138	7.00
706	333.37	155	2.14
754	333.41	15731	36.47
800	333.35	1846	6.54
849	333.38	17574	52.62
885	333.37	12448	44.38

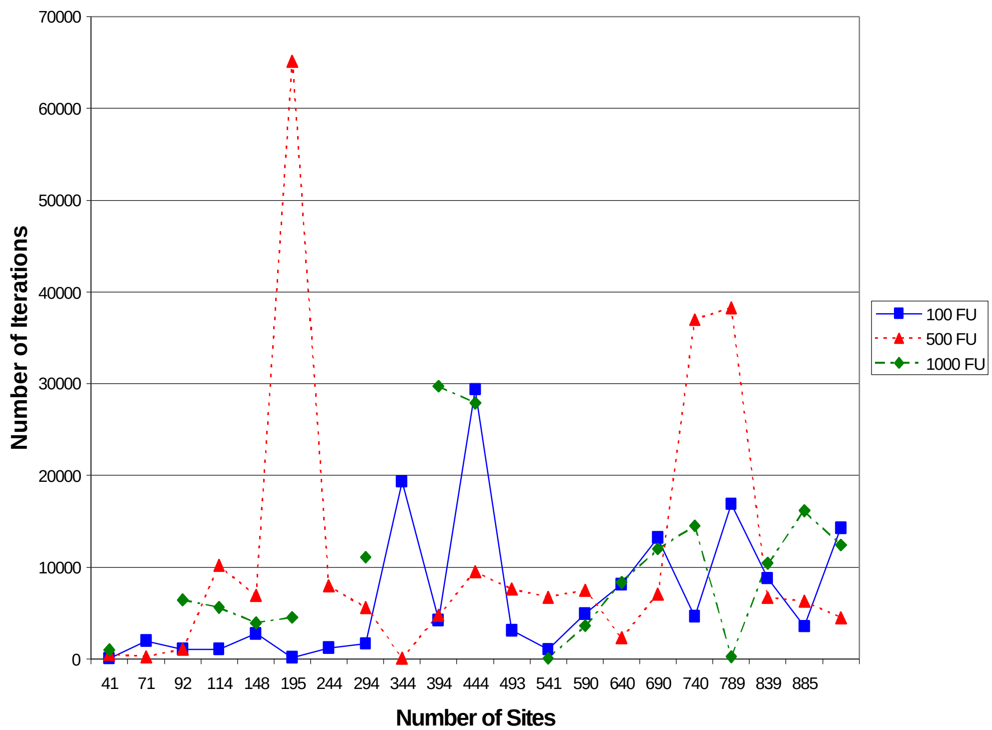

Figure 2.2: Number of Sites vs. Iterations for ID Ordering

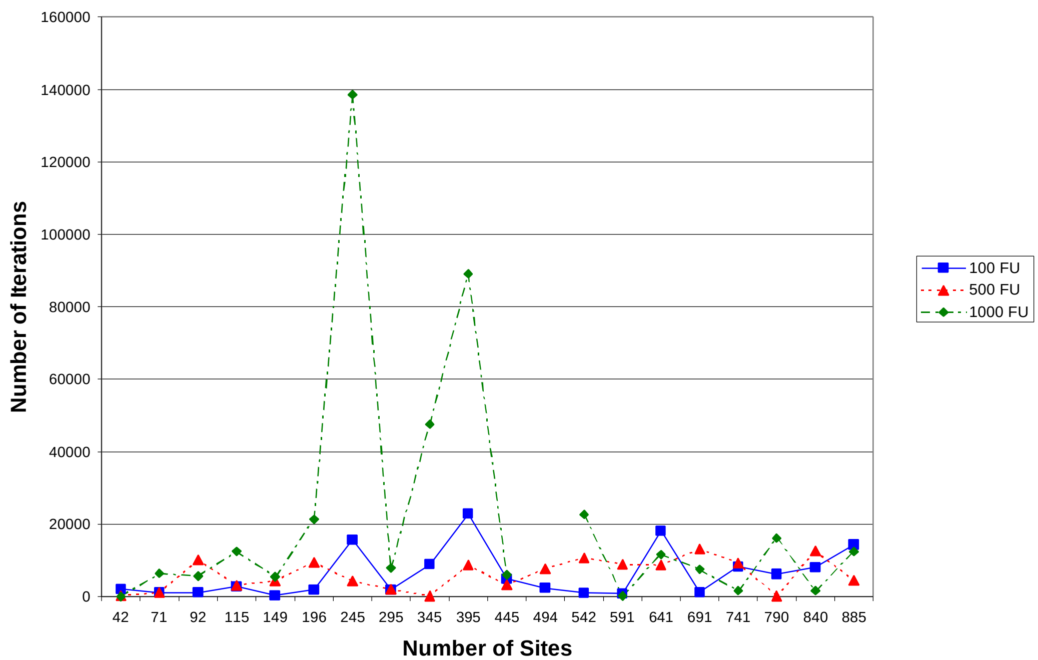

Figure 2.3: Number of Sites vs. Iterations for Perimeter Ordering

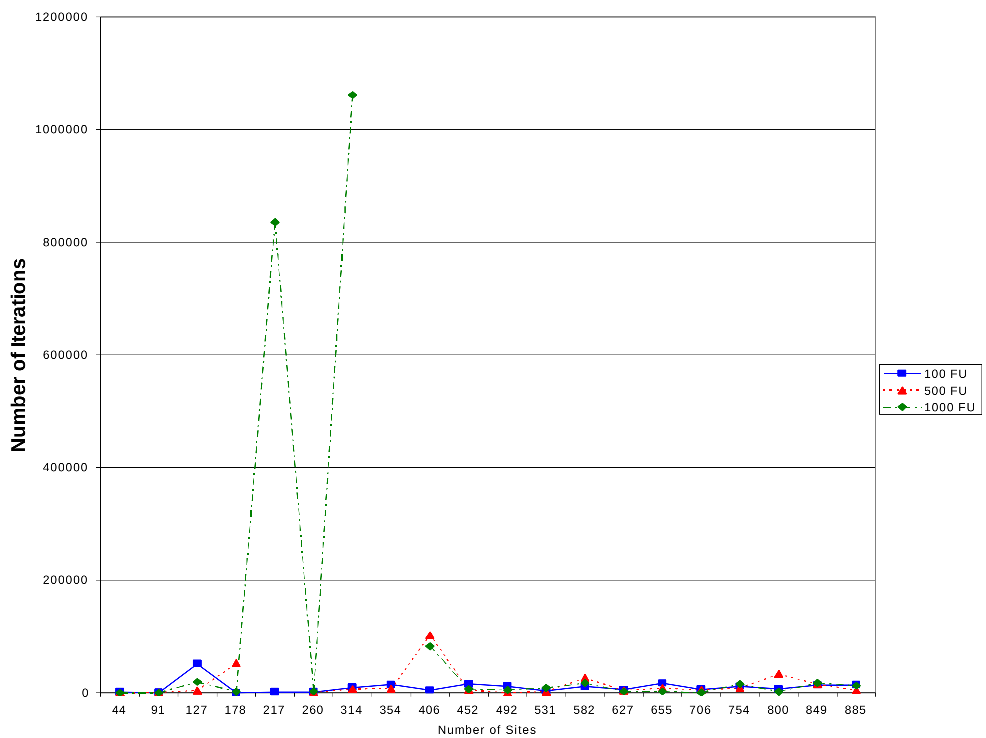

Figure 2.4: Number of Sites vs. Iterations for Random Ordering

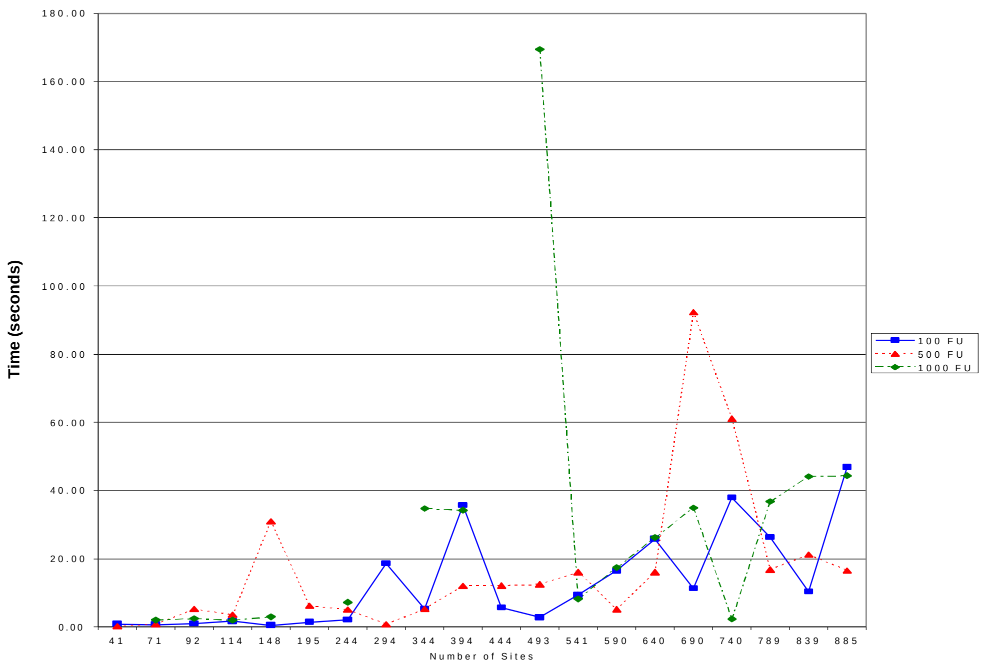

Figure 2.5.—Number of Sites vs. Time for ID Ordering

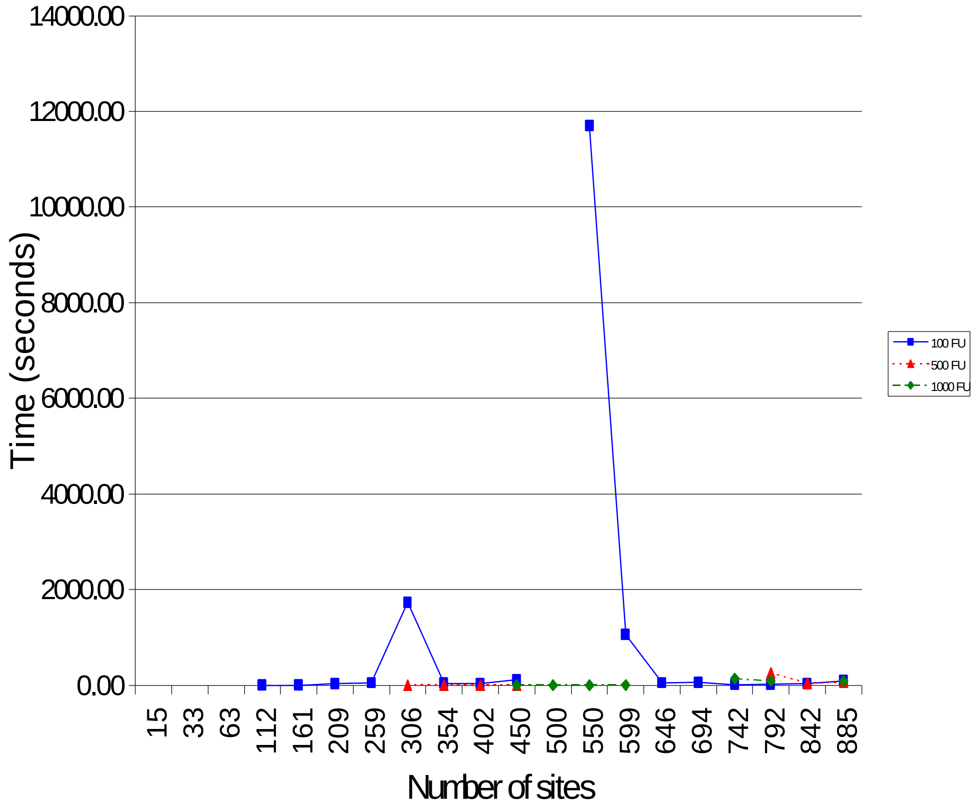

Figure 2.6: Number of Sites vs. Time for Perimeter Ordering

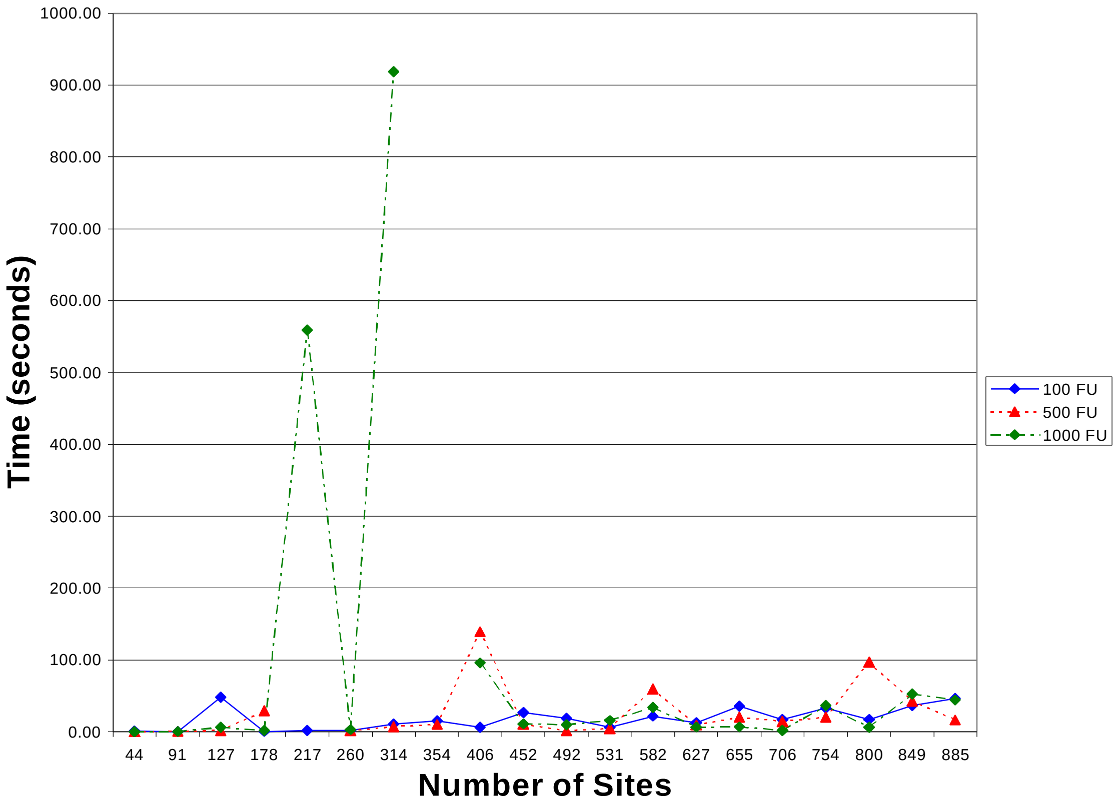

Figure 2.7: Number of Sites vs. Time for Random Ordering

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