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A DETERMINATION OF MARSH DETRITAL EXPORT FROM LANDSAT MSS DATA - A FUNCTION OF TRANSPORT DISTANCE AND WATER BODY CHARACTERIZATION

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ABSTRACT

A model has been developed to characterize the phenomenon of detrital/nutrient export from the marsh using Landsat data for both information and data base format. Model development emphasized the use of Landsat data to measure the independent variables significant to export. Marsh vegetative biomass, the detrital source, was inferentially quantified from a species classification. Two computer programs are introduced that use Landsat MSS data to define detrital export from hydrographic variables. Program WBOD identified water body type from the combination of a land/water classification and other digitized data. Program DIST determined the distance between each cell identified as marsh, from which detritus originates, and the nearest cell identified as water, from whence it is assimilated in the estuarine food chain. By using the model to relate biomass produced, the distance it must travel for assimilation in estuarine waters, and the type of water body it first enters, a map was generated indicating the relative productive capacity of a marsh test site in southeast Louisiana.

I. INTRODUCTION

The wetlands of the U.S. Gulf and southeast Atlantic coasts exhibit certain common characteristics. Vegetation type is a common factor. Spartina sp., Distichlis spicata, and Juncus roemerianus are grasses that dominate the nonforested areas, or marshes.[1] Hydrography is another common factor. Slow-moving, meandering rivers and bayous typify these coastal areas. The marshes are interlaced with ponds and lakes and flushed by tides and rains. The elevation approximates mean sea level in the low-lying areas of these coastal plains.

In the coastal wetlands environment, vegetation and hydrography make a combined contribution to the support of the estuarine food chain. Detritus, decomposed plant material from the marsh, is reported to be a major food source for estuarine/marine organisms.[2] Previous investigations have shown there is a relatively high net export of detritus to the water, where it is consumed by filter feeders.[3,4,5] In particular, Browder substantiated the importance of marsh-originated detritus to the support of estuarine-dependent fish.[6] She also designed an energy flow model of the marsh/estuary that recognizes the influence of hydrography on detrital export.

This paper reports on a technique that uniquely incorporates remote sensing technology in a model to determine the value of the coastal marsh to the estuarine food chain. In particular, two computer programs are introduced that have been developed to describe the export function in the model. The model is a refined version of a concept reported by the author earlier.[7]

In a broader sense, this paper demonstrates the utility of the Landsat MSS system beyond its basic use for generating a land cover classification. The MSS data are a source of input for the model, but of equal significance, the georeferenced digital data format provides the foundation for a facilitated data base system.

II. DEVELOPMENT OF THE MODEL

In the development of the model, we seek to obtain for any point in the marsh its relative trophic value to the estuarine food chain. The fact that plant biomass produced in the wetlands is a significant food source for estuarine-dependent fish and shellfish is a fundamental assumption. Thus, the model has been created to arrive at the relative estuarine trophic value for any point. Henceforth, this value is termed "productive capacity," or PC. Since it is a relative indicator, this value carries no units. The model has been designed to capitalize on information that can be derived from Landsat MSS data and on the georeferenced, digital data format advantageous for data base construction.

We assume that the productive capacity of a location in the marsh depends on its annual production of vegetation, the distance plant biomass travels to enter the nearest water body (which is the point at which the terrestrial plant matter can begin to mix with estuarine waters, leading to assimilation in the estuarine food chain), and the type of first water body into which this transfer of detritus occurs. Plant production, the first variable, identifies the commodity. The latter two variables describe the effective export of this commodity. That is, the calculation of the distance to nearest water represents a way to measure retention of detritus vs. its export over land in a probabilistic manner. The identification of the type of water body first entered by the detritus represents a way to qualify its deposition vs. dilution and trophic assimilation in estuarine waters.

The following assumptions are made in the model, where PC is productive capacity, B is annual production of plant biomass, D is the export distance to water, and W is the importance value of the water body type.

Assumption:

$$PC = fD \qquad (1)$$
$$PC = fB \qquad (2)$$
$$PC = fW \qquad (3)$$

D, B, and W are considered independent variables in the model, while PC is the dependent variable. Previous results of correlation analyses by the author on B and D support this hypothesis.[7] The independence of W is an intuitive assumption considered valid because W represents the discrete component of export that occurs when detritus enters the water system. B and D are determined quantitatively. W has a qualitative assignment.

The statements below describe the interrelationships among the variables.

Statement:

PC decreases when D increases. (1)
PC increases when B increases. (2)
PC increases when W increases. (3)

In other words, productive capacity will be enhanced by high annual plant production or when the type of water body to which the export distance is measured has a high importance value for any point with a given distance to the nearest water. Allowing B and W to be constant, productive capacity will decrease as one considers points on the ground increasingly distant from the nearest water body, the point where assimilation of detritus can be initiated.

The relationship in statement 1 is intuitively assumed to be nonlinear; i.e., as the export distance increases, productive capacity will decrease in an exponential manner, as shown schematically in figure 1a. Statements 2 and 3 describe relationships assumed to be linear, as shown respectively in figures 1b and 1c.

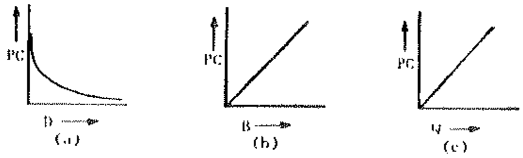

Figure 1 Schematic Graphs of the Relationship Between PC and D, B, W

Refining the above assumptions, we can now make the following statements, where b and d are coefficients, n and n' are scalars, and m is an exponential coefficient. Since W is a qualitative term, any coefficient for W is implicit in W. It should be recognized that W is a term which itself is a function of currents, tidal influence, and circulation patterns, and merits further investigation. The expression for D describes the nonlinear relationship between PC and D and is derived from the expression $y = be^{xm}$ for a typical exponential curve depicted in figure 1a.

Statement:

$$PC = fD = de^{Dm}, \text{ where } m < 0 \qquad (4)$$
$$PC = fB = n \cdot bB \qquad (5)$$
$$PC = fW = n' \cdot W \qquad (6)$$

Combining statements 4-6, we can express the following master equation for the model.

Equation:

$$PC = (n \cdot bB + n' \cdot W)de^{Dm} \qquad (1)$$

III. STUDY AREA AND LANDSAT DATA SELECTION

A portion of the Louisiana/Mississippi coastal area was selected for study. The biological and physical characteristics of its wetlands were acknowledged in the model development. The extent of the area was defined by the authors' desire to demonstrate the full capability of the computer programs developed to support the model.

Landsat MSS data for the study area were reviewed for cloud-free coverage. The following images acquired on a June 3, 1977, satellite pass were used: Landsat frames 1776-14463 and 1776-14460.

IV. PROCEDURE

The procedure used to process and analyze the Landsat MSS data and to implement the model will be described in four basic steps: A.) preprocessing, classification, and georeference, B.) calculation of distance to nearest water, C.) identification of water body type, and D.) data base construction. All computer programs utilized in this investigation and cited in this paper are a subset of ELAS, a comprehensive software system developed by the Earth Resources Laboratory (ERL), an element of the NASA National Space Technology Laboratories.[8,9] All computer processing was performed at ERL on a 32-bit minicomputer configured with adequate memory, associated peripherals, and image display devices.

A. PREPROCESSING, CLASSIFICATION AND GEOREFERENCE

MSS data from the two adjacent Landsat frames of the same pass were merged edge-to-edge. The data were reformatted and corrected for the sixth scan line anomaly using programs DSTB and DSTR.

Training samples were selected automatically using SEARCH, a program that uses homogeneity of spectral reflectance within a defined neighborhood of Landsat pixels as the selection criterion. The Landsat data were classified by program MAXL31 using the spectral signatures developed from SEARCH.

The Landsat data were georeferenced to USGS 1:250,000 topographic maps using programs OGCN and OGEO. Each georeferenced cell represented a 50m x 50m locus.

B. CALCULATION OF DISTANCE TO NEAREST WATER - DIST

The distance between any point on the ground and the nearest water body can be calculated from Landsat data with program DIST. This section will elaborate on the performance of DIST since it has been developed as a tool in implementing the productive capacity model and has not been reported in the literature previously. Its utility extends beyond application to the model, as will become obvious in the text below.

Explanation of DIST. DIST is an ELAS module which computes for each pixel the Euclidean distance to the nearest pixel of a particular type. Although any category can be the object category, for the purposes of this investigation DIST was used to compute the nearest distance to water pixels.

The ELAS data file used as input by DIST may have several different classes which are all types of water. DIST may be run on all these as a group by indexing the input data through a function created in the ELAS module TBED. This function should contain only the values 0 and 1. The 1's represent each water category and the 0's represent all other land cover categories. Thus, after indexing through this function, DIST will view all data as either water or not. However, the capability does exist to identify the specific type or class of water to which distance is measured.

The distance computations in DIST are performed in two passes through the data. The first pass consists of reading line by line from top to bottom and computing distances from each pixel to the nearest water pixel above or to the left or right. The second pass consists of reading the data line by line from bottom to top, computing distances from each pixel to the nearest water pixel below or to the left or right, and selecting the minimum distance for each pixel from the two passes. The benefits are that only one line of data needs to be in memory at once and all distances are accurately computed from the center of the reference pixel to the center of the subject pixel.

The first pass through the data begins with an initialization section. In this section each location of an array named LINES is loaded with the value -10000. This is done to assure that if no water pixels exist in the first line all pixels will be assigned the maximum possible distance value. This maximum value, being stored as one byte, is 255. After the LINES array is full of -10000's DIST proceeds to analyze the data by reading in the first line. For each pixel in the line, DIST retrieves the function value (0 or 1) and if that value is 1 (indicating a water pixel) then the line number of the line being analyzed is placed into the LINES array at the location corresponding to the column number of the pixel. After this is done for each pixel, the LINES array contains sufficient information to compute for each pixel in the line being analyzed the distance to the nearest water pixel above or to the left or right. This is indeed done for each pixel by comparing the distances within a known maximum possible radius from the pixel to those water pixels represented by their column locations and line locations (the value stored in the appropriate locations of LINES).

Once a minimum distance value is computed for an input pixel, an output value must be assigned to represent the distance. At this point the distance value is exactly known and the value could be any distance from 0 to the limits of the geographical area represented by the data file. Since these values might be greater than 255, DIST assigns output values by using an index table also built in TBED. The index table is a table of distance values beginning with a value of 0.0 and increasing until a maximum is reached for location 255 of the table. DIST will assign to each output pixel the largest value j such that the table value at j is less than or equal to the actual distance for that pixel. Thus all output values are values between 0 and 255 representing distances as defined by the index table. The table values can represent variably or equally increasing distances depending on the requirements of the user with respect to maximum measured distance and measurement precision.

The second pass is quite similar to the first. The differences are that the LINES array is loaded with 30000, the data are read from bottom to top, and comparisons are made to the results of the first pass. After the second pass, the output file contains distance values determined as accurately as is possible given the classification accuracy of the data and the index table supplied by the user. If the user chooses the option to identify the type of water to which each distance is measured, that information is recorded in a second channel of the output file.

<u>DIST Applied to the Productive Capacity Model</u>. Following the steps involved in DIST, the land cover classes derived from the Landsat data were identified as either land or water and indexed as 0 or 1, respectively.

For the index table required in DIST, precise distance coefficients were calculated between the center of a marsh pixel to the center of a water pixel for all possible theoretical distances in a 13-pixel square up to a value of 15. These are shown in table 1. These coefficients in increasing order were assigned an integer index value from 1 to 59. Multiplying the coefficient by the cell size gave the true distance; e.g., 15 x 50 meters equaled 750 m.

Table 1. Distance Coefficients Derived From a Thirteen-Pixel Square. All possible coefficients between 1 and 15 were used in the DIST index to generate actual distance values up to 750 meters.

Water -0-	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00	11.00	12.00
1.00	1.41	2.24	3.16	4.12	5.10	6.08	7.07	8.06	9.06	10.05	11.05	12.04
2.00	2.24	2.83	3.61	4.47	5.39	6.33	7.28	8.25	9.22	10.20	11.18	12.17
3.00	3.16	3.61	4.24	5.00	5.83	6.71	7.62	8.54	9.49	10.44	11.40	12.37
4.00	4.12	4.47	5.00	5.66	6.40	7.21	8.06	8.94	9.85	10.77	11.71	12.65
5.00	5.10	5.39	5.83	6.40	7.07	7.81	8.60	9.43	10.30	11.18	12.08	13.00
6.00	6.08	6.33	6.71	7.21	7.81	8.49	9.22	10.00	10.82	11.66	12.53	13.42
7.00	7.07	7.28	7.62	8.06	8.60	9.22	9.90	10.63	11.40	12.21	13.04	13.89
8.00	8.06	8.25	8.54	8.94	9.43	10.00	10.63	11.31	12.04	12.81	13.60	14.42
9.00	9.06	9.22	9.49	9.85	10.30	10.82	11.40	12.04	12.73	13.45	14.21	15.00
10.00	10.06	10.20	10.44	10.77	11.18	11.66	12.21	12.81	13.45	14.14	14.87	-
11.00	11.05	11.18	11.40	11.71	12.08	12.53	13.04	13.60	14.21	14.87	-	-
12.00	12.04	12.17	12.37	12.65	13.00	13.42	13.89	14.42	15.00	-	-	-

Beyond 750 m and up to 1800 m, distance coefficients were indexed incrementally by 0.5, or by 25 meters in the 50-meter cell reference. They were assigned integer values 60-101. Distances greater than 1800 m and less than or equal to 10 km were assigned values 102-200, where each integer increase represented a 50-meter increment. Beyond 10 km and less than or equal to 12.25 km, distances were effectively measured in 100-meter increments and assigned integer values 201-255.

Using such an index scheme for the application of DIST to the model, any center-to-center distance in the digital format between 50 meters and 750 meters could be precisely quantified. There is no error in this measurement due to program DIST. However, the accuracy of distance measurements greater than 750 m depends on the difference between the true value and the value to which it was rounded off in the incremental system. The maximum possible distance obtained by use of this index was 12.25 km. The index table was specifically defined for use with the PC model.

C. IDENTIFICATION OF WATER BODY TYPE

Water body type is a prime variable in the PC model. The computer-based technique developed to identify water body type can be described as interactive and semi-automated. It depends on the discrimination of land from water using the Landsat land cover classification and the imbedding of salinity data in the Landsat format. Program WBOD was developed in support of the technique and will be described in detail.

Explanation of WBOD. WBOD is a computer program written to differentiate open versus closed water bodies. The program operates on a rectangle of data in an ELAS data file. The ELAS data file consists of a land/water classification which is the product of a pattern recognition analysis to discriminate water pixels from all other land cover types. Any water pixel touching an open water pixel from above, below, right, left, or diagonally will also be considered part of the same open water body. All other water pixels will be considered parts of closed water bodies. These closed water bodies are divided in two categories, ponds and lakes, depending upon their size in comparison to the minimum lake size defined by the user. The output file then has three water categories--open water, ponds, and lakes.

The differentiation of water bodies in WBOD is accomplished in two phases. The first phase consists of reading the input file from top to bottom and, for each pair of lines, writing interval information into an intermediate file. This interval information consists of the location of each contiguous interval of water pixels in each line of data, the occurrences of junctions of different strings of intervals between adjacent lines, and the terminations of strings of intervals. The second phase consists of reading the intermediate file from bottom to top and writing data to the output file about the types of water bodies as dictated by the interval information.

To explain more specifically, the first phase of WBOD begins with an initialization section which sets the number of water intervals to 0 for the line preceding the initial line to process. Following the initialization, WBOD reads the first line of data, determines the locations of all intervals of water pixels in the line, and compares the locations of these intervals to the interval locations of the previous line to check for adjacent strings. All pertinent information is written to the intermediate file and the process repeated for each line to be processed.

After reading in a line of data WBOD calls a subroutine which checks the class of each pixel in the line and returns interval information for each interval of water pixels in that line. This interval information consists of:

i - the interval number,
B_i - the starting column,
E_i - the ending column,
T_i - the number of pixels, and
X_i - the edge adjacency factor.

The edge adjacency factor is set to 0 if the interval starts or ends at any edge of the rectangle being analyzed. Otherwise, it is set to 1. This factor is used to distinguish open water from closed water. The interval number is an integer from 1 to 1000 associated with each unique interval. When two intervals are joined to form a string, the interval number of one interval is changed to be the same as the interval number of the other interval.

After all the intervals are determined in the line, WBOD compares these intervals with those of the previous line. Intervals which touch intervals in the previous line are joined to those intervals by assigning to them the same interval number. The joining of interval i to string j consists of adding T_i to T_j, multiplying X_j by X_i and writing the junction occurrence to the intermediate file.

Once all intervals of the current line are compared to those of the previous line, WBOD writes the locations and numbers of all intervals to the intermediate file. Also, for each terminating water body, a termination record is written to the intermediate file. For the termination of string j WBOD compares T_j with the user-defined minimum lake size to decide whether string j represents a pond or lake. Thus the termination record defines what type of water body has terminated.

This process of reading in a new line, determining intervals, and comparing to the previous line is continued until the last line has been processed. At that point WBOD starts its second phase of operation.

In the second phase WBOD reads the records of the intermediate file in reverse order. This allows each string of intervals to be retraced and all water pixels identified as parts of open water, ponds, or lakes. The updated intervals are then written to the output file.

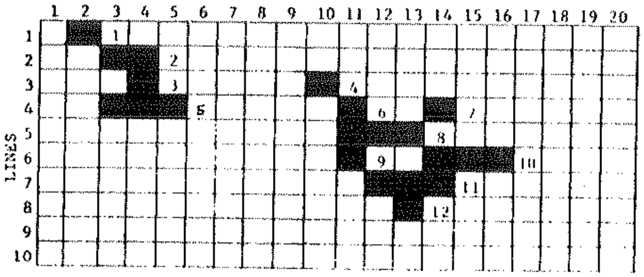

Figure 2 Identification of Two Water Bodies by WBOD

Figure 2 provides an example of a data file with two water bodies--one classified as open and one as closed. The sample data file has 10 lines and 20 columns. There are 21 water pixels depicted in gray. These form an "open" water body in the upper left and a closed water body to the right. In analyzing these data WBOD distinguishes 12 different intervals. The numbers for the intervals are to the right of each interval. Interval 1 is adjacent to the top and X_2 would be 0. B_1 would be 2, E_1 would be 2, and T_1 would be 1. When line 2 is read, WBOD detects that intervals 1 and 2 are diagonally connected. Thus interval 2 is reassigned as part of string 1. T_2 is added to T_1 and X_1 is multiplied by X_2. After the junction, T_1 is then 3 and X is 0. After reading line 5, WBOD detects that no intervals of line 5 are adjacent to any interval of string 1 on line 4. Thus, a termination record for string 1 is written defining it as an open water body. Similarly, intervals 4, 6, 7, 8, 9, 10, 11 and 12 are all joined to define a closed water body 14 pixels in size. If the user defines a lake as any closed water body greater than 10 pixels in size, then WBOD classifies this water body as a lake.

For the purposes of the PC model closed water bodies greater than or equal to 4 Ha. were called lakes. Those less than 4 Ha. were called ponds. This was consistent with a conventional definition.[10]

Other Aspects of the Water Body Identification Technique. The output of WBOD identifies three types of water bodies: lakes, ponds, and open water. The program recognizes as lakes and ponds only those water bodies that are truly closed. It will identify as open water those water bodies conventionally called lakes and ponds if they are connected by inlet or outlet channels to water occurring at any edge of the data file. Consequently, the WBOD output was refined by interactively updating the file via the image display device to also recognize lakes and ponds adjoined to open water. Program PGUD was used for this purpose. Any water occurring at the edge of the data file which was not truly "open" by virtue of being Gulf water was also appropriately updated. Another interactive update was performed to identify linear water bodies in a separate class called rivers/canals. The USGS topographic maps were the reference for all updating.

Many narrow rivers and canals located in the study area were unresolvable in the Landsat data. These features were digitized from the USGS maps as line segments and imbedded in the refined WBOD output using PGUD. The width of each river/canal equaled a cell width (50m).

The water body type classification at this point contained ponds, lakes, open water, rivers/canals and land. It was modified further to include salinity information and to distinguish whether the rivers/canals and lakes and ponds were closed or adjoined to open water.

D. DATA BASE CONSTRUCTION

The construction of the digital data base effectuated the application of the PC model. The data base via program DBAS facilitated the storage and manipulation of data and performed the mechanics of quantitatively relating all the data variables in the PC model. Each unique data set required in the model was stored as a separate channel of the data base.

Development of Data Base Channels. The water body classification after interactive updating was stored in a data base channel. Salinity data reported by Chabreck for the study area were stored in a second channel.[11] The salinity data were entered as polygons to distinguish fresh vs. estuarine areas according to an accepted definition for the salinity regimes.[10] The study area did not include any marine water.

These two channels of data were combined with a third channel that was a subset of information generated from

Table 2. Data Base Channels

Channel	Description
1	Classification of Water Body Types: lakes, ponds, rivers/canals, open water
2	Salinity Data: fresh $\leq$0.5ppt, estuarine >0.5ppt and <30ppt.
3	Open Water
4	Final Water Body Types: Product of Merging channels 1, 2, and 3
5	Water Bodies Ranked by Importance (from channel 4)
6	Plant Production Levels Inferred from Land Cover Classification
7	Distance to Nearest Water Classification
8	Identification of Water Bodies to Which Distance was Measured
9	PC Model Results: Combination of channels 6, 7, and 8 according to equation 1.

WBOD and represented all Landsat cells identified as contiguous open water. This output was stored in channel 4. Table 2 summarizes the above steps and the subsequent handling of all data in the data base.

The final water body type classification contained an array of water classes more specific than the basic lake, pond, river/canal, and open water categories. Table 3 indicates the theoretical combinations possible as a result of combining basic water body type, salinity data, and contiguous open water. It also indicates how each type ranks in its importance to detrital export using an arbitrary relative scale of one to 13, or low to high importance. The author determined the importance ranking based on the degree to which each water body type hypothetically influences detrital export. Importance values were stored in channel 5.

Table 3. Water Body Importance Values with Respect to Detrital Export. Values are assigned on a relative scale. Thirteen is most important and one is least important.

BASIC WATER BODY TYPE		SALINITY		
		FRESH	ESTUARINE	MARINE
OPEN WATER (LARGE BODY)		9	12	13
PONDS	OPEN	2	5	7
	CLOSED	1	4	3
LAKES	OPEN	2	5	7
	CLOSED	1	4	3
RIVERS/CANALS	OPEN	8	10	11
	CLOSED	4	6	11

To complete the information needed for solution of the PC Model (equation 1), the basic land cover classification of the study area was recorded in channel 6. The distance to nearest water measurement and the importance value of the water body to which the distance was measured for each cell, derived from program DIST, were recorded in channels 7 and 8, respectively.

Solution of the Equations for the PC Model. Recalling the variables in the PC Model, data stored in channels 6, 7, and 8 had to be converted for consistency with the function definitions of the variables. Accordingly, three levels of annual plant production values were assigned to the land cover classes identified as marsh vegetation. Actual assignment was relative and based on previous work reported by the author.[7] Vegetation communities where Spartina patens dominated by 90% were the most productive. Communities dominated by S. patens in an ammount less than 90% had intermediate production. Communities dominated by S. alterniflora were the least productive. Production for the respective communities varied by the linear ratio 3:2:1.

The ratio of the influence of plant production to that of water body importance value in the PC model was established as 2:1, based on the authors' familiarity with the environment. Thus, for a relative solution of PC for each cell the following conditions were set forth.

Condition 1. The term $n' \cdot W$ was considered equal to W, and $1 \leq W \leq 13$.

Condition 2. The term $n \cdot bB$ for the three production levels equaled 24, 16, and 8, maintaining the production ratio among the vegetation communities of 3:2:1 and weighting production to water body importance by an approximate factor of 2X. The production term was associated with channel 6 via an index table.

Condition 3. $D = de^{Dm}$, where $d = 1000$ and $m = -.005$. The distance function was solved for each distance derived from DIST. Each value of the function was associated with the appropriate distance in channel 7 via an index table. d and m were obtained deductively from the relationship shown in figure 1a based on empirical data for D.

Channel 8 contained the identification of the water to which nearest distance was measured for each Landsat cell which originated from the second output channel of DIST.

The final computation for PC then became a matter of adding the production index value of channel 6 to the water body importance value of channel 8 and multiplying that sum by the distance index value of channel 7 for each Landsat cell. The resulting values were transformed to a scale of zero to 255 and stored in channel 9.

Frequency Distribution Data. The percentage and/or frequency of occurrence of data values was determined for each channel in the data base. The use of this information is evident in the analysis of the results.

V. RESULTS AND DISCUSSION

The presentation of results includes the products developed for input to the productive capacity model and a representation of the model solution.

A. LAND COVER CLASSIFICATION RESULTS

The land cover classification is the most basic tool needed in the PC Model. Its use in the discrimination of land vs. water is fundamental to programs WBOD and DIST. Further, an identification of the marsh vegetation classes provides the basis for the inference of plant production. The Landsat classification produced for the entire study area had 29 distinct spectral classes. Of these, five classes represented water. Though an accuracy evaluation was not performed specifically on this classification, previous analyses by the author indicated a routine Landsat classification accuracy for water of about 95%. The total area for which data were classified was about 3,000,000 Ha.

B. WATER BODY TYPE CLASSIFICATION RESULTS

The objective to develop a water body technique that could work for multiple ecosystems and a full range of water salinity dictated the size of the study area for which Landsat data were acquired and processed. The study area also satisfied a practical consideration in that ground truth data were already available for the investigation.

Figure 3 shows the outcome of exercising WBOD on the data and updating those results as outlined in the PROCEDURE to achieve the four basic types of water bodies: pond, lake, river/canal, and open water. Figure 4 shows only the open contiguous water identified by WBOD. The latter was merged with the four basic types and by adding salinity data a channel was created with 12 classes. Table 4 provides the area and percent of each water body type class for the four-class and 12-class products. Because the coastal waters of the study area are greatly influenced by the volume of freshwater discharge from the Mississippi River, there was no water in the scene with salinity high enough to satisfy the definition for marine water. Thus, no marine water bodies were identified.

A determination of the accuracy of the water body type identification results was difficult to obtain because of a lack of a standard for comparison. The USGS topographic maps were outdated by

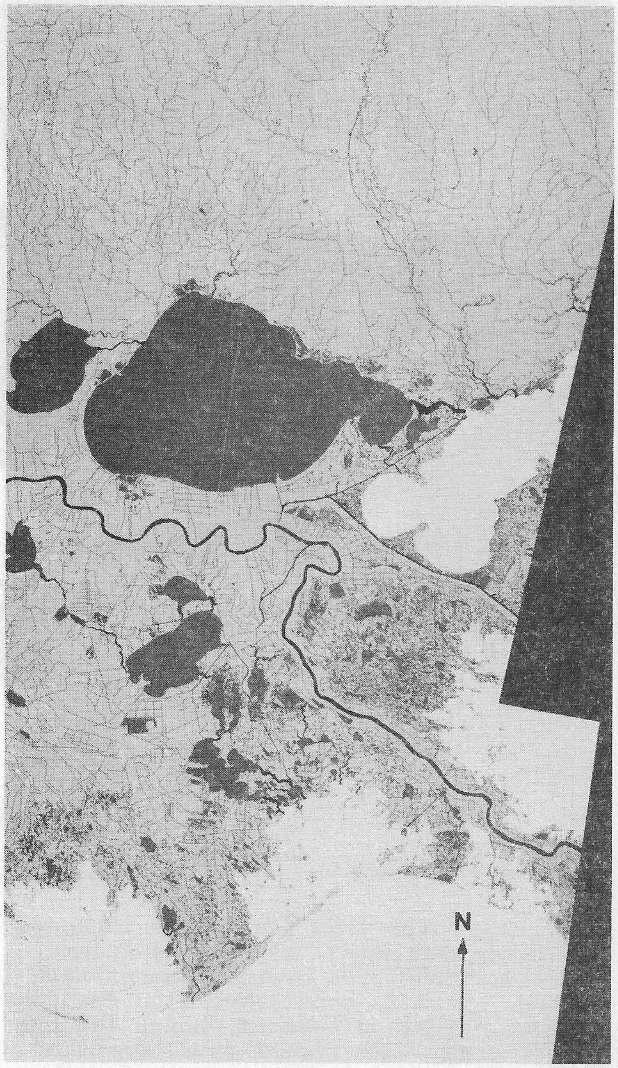

Figure 3. Classification of Four Types of Water Bodies. The categories are open water - white, lake - dark gray, river/canal and pond - black. Land is light gray. The study area represents about 3,000,000 Ha in southeast Louisiana and Mississippi. New Orleans is located just south of Lake Ponchartrain, the largest lake in the scene The Gulf of Mexico is the open body of water at the bottom of the scene.

10 to 20 years. The study area is considered dynamic, exhibiting relatively rapid changes in structure due to ponding and shoreline variations, both phenomena due to subsidence and erosion. Numerous canals have been dug, changing the hydrography of the area. However, data acquired from field observation and published by Chabreck in 1968 provided a source for comparison.[11] Table 5 compares the results of the present technique with those of Chabreck for hydrologic unit II of Chabreck's study.

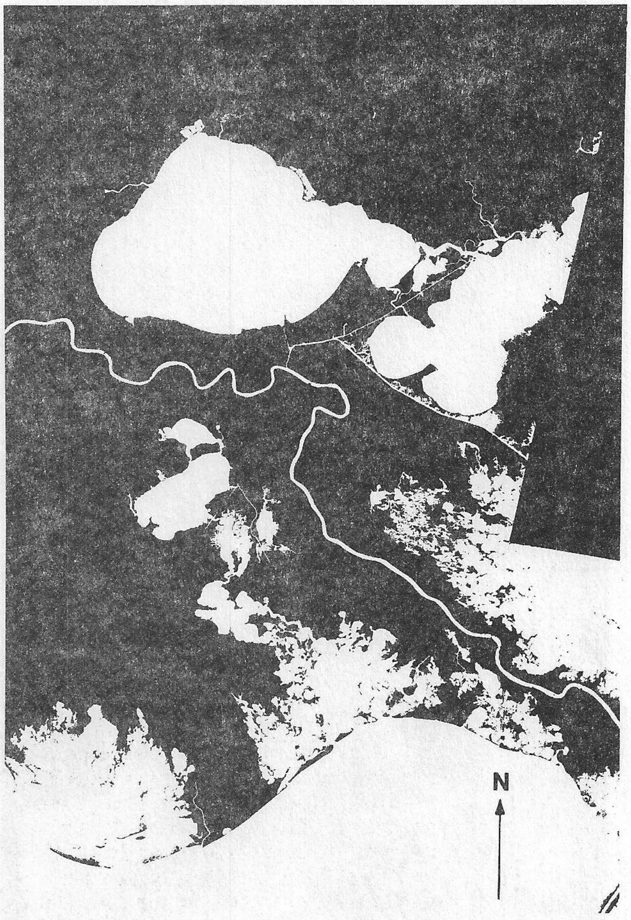

Figure 4. Open Contiguous Water Identified by WBOD. The scene represents the southeast La./Ms study area. Water is white; land is black.

One notes from table 5 an increase in lakes and ponds, as well as rivers/canals, identified by the Landsat technique. This is consistent with the geomorphological pattern of change for the study area. The recent development of oil and gas canals may account for the almost twofold increase of rivers/canals. However, Chabreck's results were based on statistical averages derived from transect data and, thus, his results might have suffered from under-sampling. Another possible reason for the large increase in rivers/canals indicated by the Landsat data might be the cell size of the digitized data. All digitized rivers or canals entered into the data base were represented by a 50m width. In reality, such water bodies observed by Chabreck might have been narrower, which may partially explain the difference in the two sets of results.

C. DISTANCE MEASUREMENT RESULTS

The operation of DIST on the Landsat data for the study area resulted in 168 classes of distance measurements

Table 4. Area and Percent of Basic Water Body Types and Specific Water Body Types Derived from WBOD. The amount of land in the study area was about 61%.

Basic Water Body Class	Area (Ha)	%	Specific Water Body Class	Area (Ha)	%
(4 Classes)			(12 Classes)		
OPEN WATER	604,579	19.922	estuarine open water	604,579	19.922
TOTAL RIVERS/ CANALS	259,876	8.556	fresh rivers/caals not adjoining open water	154,531	5.088
			estuarine rivers/ canals not adjoining open water	26,822	.883
			fresh rivers/ canals adjoining open water	60,953	2.007
			estuarine rivers/ canals adjoining open water	17,570	.578
TOTAL LAKES	319,073	10.505	fresh lakes not adjoining open water	11,730	.386
			estuarine lakes not adjoining open water	75,388	2.482
			fresh lakes adjoining open water	176	.006
			estuarine lakes adjoining open water	231,779	7.631
TOTAL PONDS	13,443	.442	fresh ponds not adjoining open water	1,611	.053
			estuarine ponds not adjoining open water	11,545	.380
			estuarine ponds adjoining open water	287	.009

Table 5. A Comparison of Results for Landsat-derived Vs. Field-derived Water Body Types. The comparison is made for hydrologic unit II of Chabreck's data.[11] Landsat data were for 1977, that of Chabreck for 1968.

Class	Landsat Results Area (Ha)	Chabreck's Results Area (Ha)
Lakes and Ponds	20230	20047
Rivers/Canals	9439	5248
Land	71982	70174

ranging from 50m to 5150m. The distance classes were grouped to effect an image with discernible gray levels, shown in figure 5.

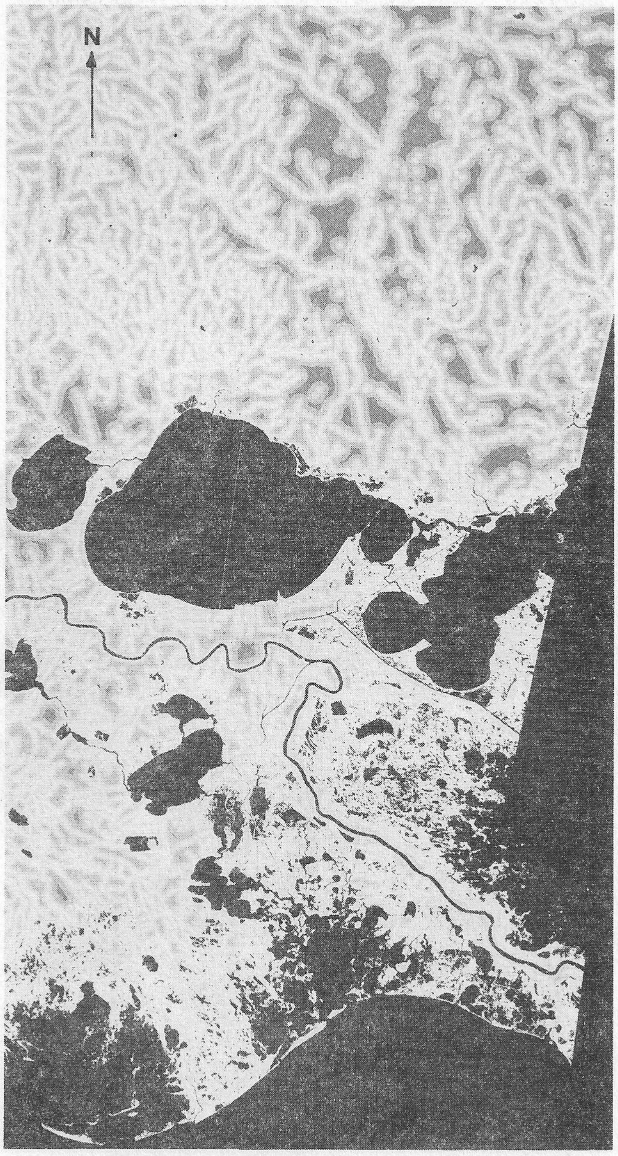

Figure 5. Distance-to-Nearest-Water Measurements. The distance values (D) computed for the southeast La./Ms. study area were grouped into four classes: $0<D\leq 150$m is white, $150<D\leq 300$m is light gray, $300<D\leq 600$m is medium gray, and $600<D\leq 5150$m is dark gray. Water is black.

The accuracy of the distance measurement depends on the inherent accuracy of program DIST, as well as the accuracy of the land/water classified input data. It has already been established that when using the index table discussed earlier, the computer program generated true distances for those up to 750m. Beyond 750m, the accuracy of the program depends on how closely the true value approached the round-off value. This source of error will vary with the choice of an index table. Table 6 quantifies the maximum possible error in the distance measurements calculated for the study area. About 67.3% of the land in figure 5 was no more than 750m from the nearest water. There was no appreciable measurement error due to DIST for these cells. For any distance greater than 750m and less than or equal to 1800m, the maximum possible error in the distance measurement approximated 25m, or 3.3%. The area of land described by this distance represented 23.4% of the total. Similarly, for any distance greater than 1800m and less than or equal to 5150m, the maximum possible measurement error was 50m, or 2.8%. About 9.2% of the land had distance measurements in the last category.

Table 6. Analysis of Maximum Error in the Distance Measurements Calculated by DIST for the Study Area. One notes that for any cell with a distance to nearest water measurement of less than or equal to 750m, there was no error in the measurement due to DIST alone.

		Maximum Measurement Error	
Distance	% Area	Distance	%
$D\leq 750$m	67.3	0	0
750m $D\leq 1800$m	23.4	25m.	3.3
$1800\text{m}<D\leq 5150$m	9.2	50m.	2.8

Productive Capacity Model Results. Development of DIST and the water body identification technique supported the PC model data needs. Model variables representing production (fB) and export (fD and fW) were quantified from Landsat MSS data and related to the model via the georeferenced data base for a marsh test site. The test site was located in the southeast portion of the study area and included about 230,000 Ha.

Figure 6 shows three levels of production derived from the land cover classification by assigning known production data to the species classes. The production term of the model was calculated from these data. The percent area of the test site accounted by each terrestrial plant production level was as follows: high production - 8.7%, mid-production - 27.6%, low production - 12.3%.

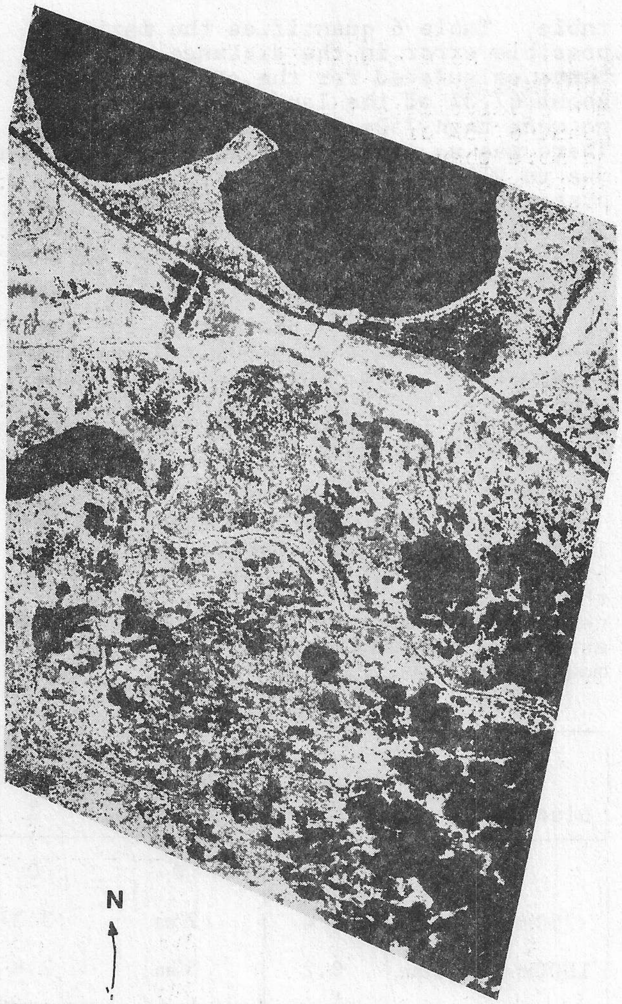

Figure 6. Classification of Plant Production in the La. Marsh Test Site. Areas of high production (about 3500 g. dry vegetation/m^2/yr.) are dark gray, medium production (about 2300 g. dry vegetation/m./yr.) are medium gray and low production (1200 g. dry vegetation/m^2/yr.) are light gray, water is black and non-marsh is white. The test site includes about 230,000 Ha. All open water adjoins the Gulf of Mexico.

Figure 7 is a result of DIST and represents the marsh test site values for D in the distance term, $1000e^{D(-.005)}$, of the PC model. DIST also recorded the importance value of the water body to which each distance was measured, providing values for W in the PC model. The basic water body type classification from which importance values were derived for the test site is shown in figure 8. Figures 7 and 8 were extracted and enlarged from figures 5 and 3, respectively.

Table 7 indicates the nearest-distance-to-water measurements and their relative percent of occurrence calculated for the test site. It also gives the relative percent distribution of the water body importance values recorded for the data base cells in each distance class. About 32% of the marsh area lay within 50m of the nearest body of water, which was most frequently an estuarine lake or pond not adjoining water contiguous with the Gulf and having a relatively low importance value. Distance measurements greater than 650m occurred in negligible frequency, less than 0.1%. As distance measurements increased, the relative frequency for which those measurements were made to water bodies with high importance values diminished. Not all the specific water body types were represented in the test site. Thus, only importance values of 1, 4, 5, 6, 10, and 12 from a possible range of one to 13 were recorded.

Figure 7. Distance-to-Nearest-Water Measurements for the La. Marsh Test Site. Distance Measurements (D) were grouped according to: $0<D\leq150$m. - black, $150<D\leq300$m - dark gray, $300<D\leq600$m - medium gray, $600<D\leq1000$m - light gray. Water is white.

Using DBAS to combine values for the three independent variables according to equation 1, the productive capacity was computed for each marsh cell. The value of PC could potentially range from 135 to 29097, defined by the range of values determined for the independent variables.

Figure 8. Classification of Four Types of Water Bodies for the La. Marsh Test Site. Categories are river/canal and pond - white, lake - dark gray, open water - light gray, land is black.

The resulting values for PC were rescaled to accommodate the representation of PC on the image display device. Consequently, the PC values generated were integers less than or equal to 255. The PC values were grouped into three equally separated levels to aid the analysis of the product, shown in figure 9. The relative frequencies of the three levels of productive capacity for the test site were: high PC - 10%, mid-PC - 58%, low PC - 32%.

The validity of the PC model and of the results generated for the marsh test site in this study remains to be tested. Upon acceptance of the model assumptions, the accuracy of PC depends on the accuracy of the input data.

V. CONCLUSION

The productive capacity model was formulated for the wetlands of the Gulf and southeast Atlantic coasts to quantify the detrital contribution any point in the marsh makes to the estuary. A major benefit of the model is its applicability in evaluation procedures for permitting and other management decisions in coastal areas.

Table 7. % Relative Frequency of Water Body Importance Values Recorded for Each Distance Class. The importance values are associated with the following specific water body type class: 1 - fresh ponds and lakes not adjoining open water, 4 - estuarine lakes and ponds not adjoining open water, 5 - estuarine lakes and ponds adjoining open water, 6 - estuarine rivers/canals not adjoining open water, 10 - estuarine rivers/canals adjoining open water, 12 - open estuarine water.

DISTANCE CLASS IN METERS	% RELATIVE OCCURRENCE	% RELATIVE FREQUENCY OF WATER BODY IMPORTANCE VALUES					
		1	4	5	6	10	12
$D \le 50$	32.3	0	41.0	14.4	31.1	5.2	8.3
$50 < D \le 100$	22.7	0	44.2	11.2	33.1	4.7	6.8
$100 < D \le 150$	17.4	0	47.5	8.8	33.9	4.5	5.2
$150 < D \le 200$	9.5	0	48.2	6.6	36.7	4.7	3.8
$200 < D \le 250$	4.3	0	45.6	4.5	41.1	6.2	2.6
$250 < D \le 300$	2.7	0	43.7	3.0	44.4	7.4	1.4
$300 < D \le 350$	2.5	0	40.1	1.7	46.9	10.7	0.6
$350 < D \le 400$	1.6	0	35.4	0.9	50.1	13.5	0.1
$400 < D \le 450$	1.0	0	33.0	0.4	52.4	14.1	0
$450 < D \le 500$	0.9	0	32.9	0.3	48.1	18.7	0
$500 < D \le 550$	0.6	0.1	31.8	0.1	47.9	20.1	0
$550 < D \le 600$	0.5	0.1	33.9	0	43.3	22.7	0
$600 < D \le 650$	0.1	0.1	37.4	0	43.8	18.8	0
$650 < D \le 700$	<.1	0.4	42.7	0	50.6	6.2	0
$700 < D \le 750$	<.1	1.3	48.7	0	50.0	0	0
$750 < D \le 800$	<.1	2.5	50.0	0	47.5	0	0
$800 < D \le 850$	<.1	6.8	52.3	0	40.9	0	0
$850 < D \le 900$	<.1	4.2	45.8	0	50.0	0	0
$900 < D \le 950$	<.1	14.3	21.4	0	64.3	0	0
$950 < D \le 1000$	<.1	11.1	22.2	0	66.7	0	0

In consideration of the technical aspects of the model we feel the assumptions we have made are rational. Further experimentation to substantiate the assumptions would be desirable. We believe the accuracy of the measurements of the model independent variables can be improved and offer these recommendations:

1. Investigate the use of MSS data to measure plant production directly from radiance, rather than infer it from a species classification. The Thematic Mapper may prove to be an instrument more sensitive to vegetation density or biomass than the Landsat MSS.

2. Develop a more specific understanding of the physical influences causing water bodies to differ in their effect on detrital export. Such information will substantiate the water body importance value.

The use of the computer programs initially written to support the productive capacity model extends to other applications, such as are described below.

1. The results of the technique to identify types of water bodies, based on WBOD, may integrate beneficially into current efforts to classify wetland systems.[10] In a general analysis, the program will identify isolated, homogeneous neighborhoods of cells which may assist in change detection studies.

2. The mechanics of program DIST allow distance measurements to be made between any two classes and do not limit the maximum obtainable measurement in a data file.

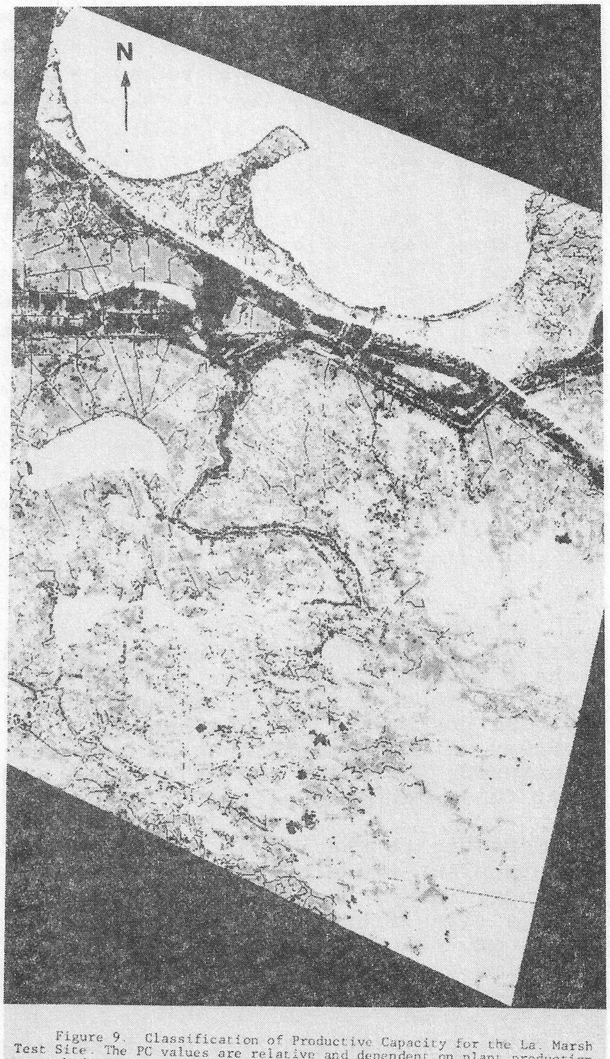

Figure 9. Classification of Productive Capacity for the La. Marsh Test Site. The PC values are relative and dependent on plant production, water body type, and distance to nearest water for each Landsat cell identified as marsh. Areas of high PC are light gray, medium PC are medium gray, and low PC are dark gray. Water is white and non-marsh is black.

The productive capacity model demonstrates a sophisticated use of Landsat MSS data and the Landsat georeferenced digital data format. Given a flexible software system such as ELAS, large quantities of diverse data can be stored in and retrieved from a data base. Data can be mathematically manipulated to characterize large geographical areas, as well as the smallest data base unit. The system offers consistency and efficiency, assets to the practical implementation of any model.

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