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AN EVALUATION OF THE IMPACT OF PERSISTENT WATER LEVEL CHANGES ON THE AREAL EXTENT OF GEORGIAN BAY/NORTH CHANNEL MARSHLANDS

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ABSTRACT

A recently-developed geometric model and associated computerized predictive methodologies designed to evaluate the impact of persistent changes in the ambient water level on the areal extent of marshlands were tested by a consideration of shoreline marshes in the Great Lakes basin. Historical airborne data dating from 1935 to 1985 and collected in a quasi-continual manner over reaches of Georgian Bay and the North Channel in Ontario, Canada were used, along with recorded values of ambient water levels during this period to compare the predicted marsh acreages of the conceptual mathematical model with the actual marsh acreages as measured from the aerial photography.

The appropriateness of the mathematical marsh model operating in its extreme modes (the first mode assuming that a vegetative equilibrium might be readily established allowing uninhibited metamorphic transformation between marsh and onshore terrain and the second mode assuming that no such vegetative equilibrium may be established) is illustrated and discussed.

RÉSUMÉ

Un modèle géométrique récemment mis au point et des méthodes provisionnelles informatisées connexes conçues pour évaluer l'impact des changements persistants du niveau ambiant de l'eau sur la superficie des terres marécageuses ont été testés dans le cadre d'un programme d'observation des marais côtiers dans le bassin des Grands Lacs. Les données historiques des relevés aériens de 1935 à 1985 recueillies de façon quasi continuelle sur certaines parties de la baie Georgienne et du chenal Nord en Ontario, Canada, ont été utilisées, ainsi que les valeurs enregistrées du niveau ambiant de l'eau au cours de cette période, afin de comparer la superficie couverte par les marais prévus par le modèle mathématique conceptuel avec la superficie réele mesurée à l'aide de photographies aériennes.

Le présent document illustre et examine la valeur de modèle mathématique des marais qui opère dans ses modes extrêmes: le premier suppose qu'un equilibre végétatif peut être établi facilement, permettant une transformation métamorphique non refrénée entre le marais et le terrain côtier, et le second suppose qu'aucun équilibre végétatif ne peut être établi.

MANAGEMENT PERSPECTIVE

Coastal wetlands provide an essential liaising interface between the natural recharge and discharge regions of river and lake basins. As such, they are dynamic and vulnerable ecosystems which support a delicately balanced vegetation/fishstock/waterfowl population by providing locales which simultaneously harbour spawning, nursing, and feeding activities. Such activities, along with the continual chemical, biological, and physical evolution of wetlands, are dependent upon not only the quality, but also the quantity, of available water. Fluctuations in ambient water levels, both short term (seasonal) and long term (substantially greater than seasonal), may dramatically alter the areal extents of the impacted wetlands.

A conceptual mathematical description of the impact of persistent changes in ambient water levels on the synoptically observable areal extents of shoreline marshes has recently been presented. This conceptual model considers the impact of such persistent water level changes primarily in terms of the basin geometry, both onshore and offshore, characterizing the basin under study. While the chemical and biological soil/water/vegetation interrelationships are disregarded from consideration <u>per se</u>, such complex interactions are taken to be contained within two extreme cases. The first extreme case assumes that the soil/water/vegetation interrelationships are acting in such a manner as to allow, subsequent to an appropriate lag time, complete metamorphic transformation between marsh and onshore regimes. That is, the first extreme considers that a vegetative equilibrium among wetland classification types may be readily established. The second extreme case considers that no such vegetative equilibrium may be readily established. Consequently, these two extremes may be confidently taken to represent the philosophical view that (a) apart from the water itself, the ultimate limiting factor controlling the areal extent of marshland acreage in a basin or watershed is the geometrical configuration of that basin or watershed, and (b) irrespective of the favourable or unfavourable consequences of the interrelated physical, chemical and biological forcing functions, acting in concert with the persistent change in water level, these forcing functions can neither generate through wetland metamorphism more marshland area than the geometrical containment factors of the basin can accommodate, nor permanently remove from the existing marshland acreage any more area than the geometrical containment factors of the basin are willing to relinquish. Short-term catastrophic episodes are, of course, excluded from this philosophy.

This conceptual mathematical marsh/water level model is applied to a stretch of shoreline marshes in the Georgian Bay/North Channel region in Ontario, Canada. Historical airborne data dating from 1935 to 1985 and collected in a quasi-continual manner over these marsh reaches, along with recorded values of ambient water levels during this period, were used to compare the predicted marsh acreages of the model with the actual marsh acreages as measured from the aerial photography. Calculations, graphs, and discussions are presented describing the appropriateness of the marsh model in anticipating the consequences to existing shoreline marsh acreage of persistent changes in the ambient basin water levels.

PERSPECTIVE - GESTION

Les terres humides côtières constituent une interface de liaison essentielle entre les zones de réalimentation et les zones d'émergence des bassins des rivières et des lacs. Comme telles, ces zones sont des écosystèmes dynamiques et vulnérables qui supportent une population de végétation, de poisson et de sauvagine dont l'équilibre est fragile étant donné qu'elles lui fournissent un milieu propice pour les activités de frai, d'élevage et d'alimentation. Conjointement à l'évolution chimique, biologique et physique continuelle des terres humides,, ces activités dépendent non seulement de la qualité, mais également de la quantité d'eau disponible. Les fluctuations du niveau ambiant de l'eau, aussi bien à court terme (saisonnières) qu'à long terme (sensiblement plus longues que saisonnières), peuvent modifier considérablement la superficie des terres humides touchées.

On a récemment présenté une description mathématique théorique de l'impact des changements persistants du niveau ambiant de l'eau sur la superficie synoptiquement observable des marais côtiers. Ce modèle théorique considère l'impact de ces changements persistants du niveau de l'eau principalement en termes de géométrie du bassin, aussi bien sur le rivage qu'au large, en caractérisant le bassin à l'étude. Bien que les interactions chimiques et biologiques du sol, de l'eau et de la végétation ne soient pas considérées comme telles, elles sont toutefois prises en considération dans les deux cas extrêmes. Le premier cas extrême suppose que les interactions entre le sol, l'eau et la végétation agissent de façon à permettre, après un certain délai, une transformation métamorphique complète entre les régimes des marais et les régimes côtiers. C'est-à-dire que le premier cas extrême considère qu'un équilibre végétatif peut facilement s'établir entre les différents types de classes de terres humides. Le second cas extrême considère qu'aucun équilibre végétatif ne peut s'établir facilement. On peut donc supposer à bon droit que ces deux cas extrêmes représentent le point de vue théorique selon lequel a) l'eau mise à part, le facteur limitatif ultime régissant la superficie des terres marécageuses dans un bassin ou un bassin hydrographique est sa configuration géométrique, et b) qu'indépendemment des conséquences favorables ou défavorables des fonctions de constrainte physiques, chimiques et biologiques agissant de concern avec le changement persistant des niveaux de l'eau, ces fonctions de constrainte ne peuvent ni produire par métamorphisme des terres humides plus de terres marécageuses que ne le permettent les facteurs de retenue géométriques du bassin, ni retirer de façon permanente de la superficie existante de terres marécageuses une superficie plus importante que ne le permettent les facteurs de retenue géométriques du bassin. Ce concept ne tient évidemment pas compte des épisodes catastrophiques à court terme.

Ce modèle mathématique théorique marais/niveau de l'eau est appliqué à une section de marais côtiers dans la région de la baie Georgienne/chenal Nord en Ontario, au Canada. Les données historiques des relevés faits par avion de 1935 à 1985 et recueillies de façon quasi continuelle dans ces zones marécageuses, ainsi que les valeurs enregistrées des niveaux ambiants de l'eau au cours de cette période, ont été utilisées afin de comparer la superficie couverte de marécages prévue par le modèle avec la superficie réele des terres marécageuses à partir de photographiques aériennes. Des calculs, des graphiques et des analyses sont présentés pour décrir l'aptitude du modèle des marais à prévoir les conséquences des changements persistants du niveau ambiant de l'eau des bassins sur la superficie existante des marais côtiers.

INTRODUCTION

It has long been recognized that wetlands, particularly those of the shallow open water and marsh type, play an essential role in the environmental life cycle by providing nutrients, shelter, spawning and nursery sites for a wide variety of fish and wildlife species. As such, wetlands are both dependent upon and a natural consequence of the inter-relationships existing among the flora, fauna, terrain, and climatic parameters indigenous to the specific region under consideration. Freshwater wetlands are, therefore, dynamically complex natural resources, which may co-exist in a variety of distinguishable classification types (swamps, marshes, bogs, and fens, for example). These wetland classification types may, in fact, display metamorphic transformations from one classification type into another, depending upon both the abilities of the wetland to adapt to changing aquatic and/or environmental conditions and the willingness of the environmental parameters to allow such adaptation.

The inter-relationships existing among the various physical, chemical, and biological parameters governing the status of the flora, fauna, and sustaining aquatic and soil regimes of wetlands have been very actively pursued in recent years. As a consequence, much valuable literature has emerged dealing with both the destructive and regenerative processes governing the behavioural fate of wetlands. While the precise forms of many of these physical/chemical/biological inter-relationships (as well as their spatial and temporal variability) still lack the desired state of readily verifiable and reproducible mathematical expression, these inter-relationships are rapidly becoming both more fully appreciated and more fully understood.

Coastal wetlands in large-lake basins form, in part, a natural liaison between the very obvious discharge areas delineated by the lakes and interconnecting and/or drainage rivers, and the perhaps somewhat less obvious recharge areas defined by a water table located substantially more distant from the surface. Acting in the capacity of such a liaison , coastal wetlands may be characterized by either the presence or absence of readily-discernible standing water, as well as an associated vegetative cover dictated to a large degree by such standing water conditions. Clearly, therefore, such coastal wetlands are under direct influence of the ambient water levels characterizing the lake basins or watersheds. Keddy and Reznicek (1986) present a convenient model for Laurentian Great Lakes coastal wetlands that divides shoreline vegetation into five broad classifications: aquatic (e.g. submersed vegetation), marsh (e.g. emergent vegetation), strand, wet meadow, and forest/shrub thicket. Marsh vegetation is considered to dominate the zone extending from the current strand line offshore to a maximum depth of approximately 1.5 m (generally corresponding to the recent historical minimum water level), while the wet meadow zone is considered to develop onshore (where conditions permit) between the current strand line and the recent historical maximum water level. The impact of water level fluctuations on the physical, zoological, botanical, and chemical dynamics of such wetlands has been discussed by a number of workers (see, for example, Gosselink and Turner, 1978; Burton, 1985; Jaworski and others, 1979; Whillans, 1982; Lyon, 1981; Lyon and others, 1986; Bedford and others, 1976; Geis, 1985; Geis and Kee, 1977; Keddy and Reznicek, 1986; Quinlan and Mulamoottil, 1987; Herdendorf and others, 1986; Herdendorf, 1987; amongst others). Seasonal, or short-term water level fluctuations are required to enable shoreline marshes to continue, in an uninterrupted manner, the growth and life cycles so essential to their development and productivity. Periodic short-term floodings are needed to simultaneously provide nutrient inputs and flush away waste materials. Extended periods of high or low water levels can compound these short-term effects of fluctuating water levels, and thereby induce effects which may or may not be desirable. Shifts in indigenous plant communities and corresponding shifts in fish and wildlife status and health may ensue (Harris and Marshall, 1963; van der Valk and Davis, 1978; Keddy and Reznicek, 1982; Keddy and Reznicek, 1986; Jaworski and Raphael, 1978; amongst others).

In an attempt to mathematically quantify the effects of prolonged water level changes on the areal extent of shoreline marshes, a conceptual mathematical model has recently been presented (Bukata and others, 1987). The complete details of this conceptual model will not be re-iterated here. Suffice it to say that the salient considerations of the model may be summarized as follows:

a) Despite the full awareness of the complex interdependencies governing the biological, chemical, and physical attributes of the marshland ecology, the model attempts to relate marshland area as determined from synoptic overviews (using the presence or absence of identifiable emergent vegetation as a means of indicating the hydrological characteristics of the regions being remotely-sensed) to persistent changes in water levels based solely upon the geometric variables defining the morphology of the marsh and its confining basin.

b) A shoreline marsh is considered to assume the geometrical shape of the shoreline with which it is associated. The model divides the principal shoreline marsh configurations into linear, concave, convex, concave-elliptical, and convex-elliptical.

c) The principal mathematical parameters considered include offshore slope angle α, onshore slope angle β (both measured from the strand line at zero water level datum), the change in water level R_n reckoned from the zero water level datum, the maximum marsh water depth d beyond which no emergent vegetation may be synoptically observed, the ellipticity factor γ of the shoreline marsh, the principal marsh areal extent A_o existent at zero water level datum, and the principal marsh areal extent A_n existent at water level R_n.

d) The mathematical model predicts the impact of persistent water level changes on shoreline marsh areal extent for two general and mutually contradictory conditions. The first condition tacitly assumes that both the offshore and onshore reaches of the wetland under study are capable of supporting a phreatophytic vegetative canopy which, subject to sufficient regeneration time, can transform into either marsh or onshore vegetation. That is, a dynamic equilibrium may be established between marsh and onshore configurations. The second condition tacitly assumes that no such dynamic equilibrium may be established on the onshore reaches. Consequently, the model considers the two extreme cases of maximum and minimum marsh areas resulting from a particular change in persistent ambient water level. Reality, it is assumed, is contained within these two extremes.

In essence, therefore, the conceptual marsh model presents the philosophical view that, apart from the water itself, the ultimate limiting factor which controls the areal extent of marshland acreage in a basin or watershed is the geometric configuration of that basin or watershed. That is, irrespective of the favourable or unfavourable consequences of the interactive physical, chemical, and biological forcing functions acting in tandem with the sustained change in ambient water level, these forcing functions cannot regenerate, through wetland metaphorism, more marshland area than the geometrical containment factors of the basin can accommodate. Similarly, these interactive multidisciplinary forcing functions cannot conspire to permanently remove from the marshland acreage any more than the containment factors of the basin will relinquish for a particular circumstance of persistent change in ambient water level. The possibility of catastrophic destruction of marshland, of course, still exists, wherein short-lived natural disasters such as severe storms, hurricanes, earthquakes, etc. or direct human interventions such as diking, draining, dredging and filling may wreak havoc in excess of the maximum loss of marshland predicted by the mathematical marsh model operating in its totally non-regenerative mode. These catastrophic disturbances may also impact the geometrical configurations of the wetlands as well. Obviously, such short-term catastrophic destructions and basin modifications are excluded from immediate consideration. However, marsh regeneration (or temporary-to-permanent non-regeneration) subsequent to such catastrophic impact should proceed over a long term in the manner described by the mathematical marsh model and the original or modified basin parameters.

PHOTOGRAPHIC ESTIMATES OF MARSH-AREA DEPENDENCE ON WATER LEVEL

In order to evaluate the application of the mathematical marsh model (Bukata and others, 1987) to an estimation of the effect of long-term changes on Great Lakes marsh dynamics, a search was initiated for pertinent historical synoptic data. In particular, airborne photographic and satellite digital formats were considered. The current work was restricted to the former for three basic reasons:

a) It was felt that the evaluation of both the areal extents of marsh regions as well as the applicability of the conceptual geometric marsh model required the use of higher resolution data than were available on much of the satellite imagery.

b) Satellite data of sufficient resolution prior to the year 1972 are non-existent.

c) Interpretation facilities (both hardware and software components) are currently being developed at NWRI, and the application of satellite technology to this problem will be deferred to a future communication.

Aerial photography was obtained over the North Channel/Georgian Bay shoreline from the St. Mary's River to the Wingfield basin of the Bruce Peninsula in central Ontario, Canada (the enclosed region shown in the Great Lakes map of Figure 1). While these historical data covered the time period 1935-1985, particularly concentrated data sets included:

a) 1935, 1950, and 1965 data which formed part of various Great Lakes aerial surveys performed during periods of low ambient water level. These data were a component of the Lake Huron Task Force shoreline and wildlife habitat inventory conducted under the auspices of the International Joint Commission for the International Great Lakes Level Board and were utilized to compile extensive low water level maps of Lake Huron/Georgian Bay/North Channel marshlands (Department of Public Works of Canada, 1970).

b) 1973 data obtained during a period of high water level. These data formed part of the Canada/Ontario Great Lakes Shore Damage Survey. Some of these data have been incorporated into the Coastal Zone Atlas resulting from this survey (Haras and Tsui, ed., 1976).

c) 1985 data obtained during a period of prolonged high water level. These data formed part of the Canada/Ontario Flood Damage Reduction Program directed towards the mapping of flood-prone areas.

The calculation of existing marsh areas as synoptically depicted on the 1973 and 1985 data sets was performed by means of a contract issued to Ecoplans Ltd. of Waterloo, Ontario. The methodologies utilized (which included the use of mirror stereoscopes, mylar overlays, and digital planimetry) and the ensuing determinations are discussed and compiled in their report (Ecoplans Ltd., 1986). The criterion for marshland delineation was the obvious appearance in the photography of marshland vegetation of the emergent type. The presence of this emergent vegetation defined the "basic" marsh area of the type considered in the conceptual mathematical marsh model of Bukata and others (1987). The presence of standing shallow water devoid of observable emergent vegetation, but nonetheless possessing image tones suggestive of the presence of submerged vegetation, was considered to be indicative of a "fringe" marsh area. The substantially more subjective nature of methods available to convincingly delineate "fringe" marsh areas from synoptic overviews caused such "fringe" areas to be excluded from the conceptual mathematical marsh model. For the 1935, 1950, and 1965 data sets similar calculations of "basic" and "fringe" marsh areas had been previously compiled as part of the International Great Lakes Level Board study and these "basic" marsh areas were utilized for comparison with the 1973 and 1985 data.

As an indication of the temporal history of the water levels throughout most of the period of concern in this study, Figure 2 illustrates the monthly mean water levels for the Lake Huron/Lake Michigan area throughout the time interval 1936-1985. The water level data are plotted in metres above or below the zero water level datum (International Great Lakes Datum, 1955) and were provided by the Canadian Hydrographic Service.

The principal conclusions of the marshland delineation exercise may be briefly summarized as follows:

a) The North Channel/Georgian Bay shoreline from St. Mary's River to the Wingfield Basin of the Bruce Peninsula was divided into 58 marsh areas. Although data were not available for all these areas for all overflight surveys (in fact only 6 areas were included within the 1985 flight corridor, for example), it was generally observed that the higher water levels existing in 1973 had eliminated a very large percentage of the marshland visible in the pre-1973 imagery. Less than 10% of the historical marsh acreage survived to 1973.

b) Although the 1985 and 1973 ambient water levels were almost directly comparable (see Figure 2), the limited amount of 1985 photographic data suggests that the marsh acreage in some areas approximately doubled (Echo Bay, Little Lake George, St. Mary's River) between 1973 and 1985. This re-emergence of marsh acreage, however, still only accounted for about 33% of the historical marsh acreage. Such re-emergence of marsh acreage could, in part, be explained (see Figure 2) by the fact that 1977 and 1978 were characterized by comparatively low ambient water levels, and while both 1973 and 1985 were characterized by high ambient water levels, the decade prior to 1975 was characterized by a relatively rapid rise to and sojourn at high water level marks, while the decade subsequent to 1975 was characterized by a relatively rapid descent to and sojourn at a comparatively lower water level mark. This slight recession in persistent water level could have resulted in some marsh vegetation grow-back.

Following the photographic estimations of marshland areal extents on the available historical data, an attempt was made to evaluate changes in marsh area within the framework of the conceptual geometric marsh model. Such an attempt, however, requires very refined determinations of the appropriate slopes comprising the marsh boundaries, both onshore and offshore. Unfortunately, such precise topographical information exists at only a very limited number of locations. Existing topographical maps, while certainly of value, were very often insufficient for the desired application and testing of the geometric model.

From the historical data available, 17 marsh data sets were selected, based on the concurrent criteria of reliability of unambiguous marsh acreage delineation from aerial imagery, the availability of reliable terrain slopes, and the availability of reliable flight corridor imagery over the same site on more than one occasion. The selected marsh sites, along with their pertinent geometric parameters are listed in Table 1.

As an aid to clarifying the entries in Table 1 as well as the mathematical manipulations which were performed upon those entries, Figure 3 schematically illustrates a hypothetical stretch of lacustrine or riverine shoreline with associated marsh acreage pertinent to a persistent ambient zero water level datum. The shoreline is taken to be comprised of a continuum of the five basic geometric shapes considered within the conceptual model (convex, concave, and linear are depicted in Figure 3). The radius of curvature of the shoreline (taken to be the strand line at zero water level datum) is represented at zero water level datum by S_o. The centre of curvature is considered to lie on the land for convex shoreline marshes (indicative of headlands, islands, etc.) and is considered to lie in the water for concave shoreline marshes (indicative of bays, bights, etc.). E_o represents the radius of curvature from the centre of curvature to the offshore edge of the basic shoreline marsh. The offshore extent of a linear shoreline marsh at zero water level datum is designated as b_o. Similarly, the associated values of these parameters for persistent ambient water level R_n (reckoned from the zero water level datum) are designated as S_n, E_n and b_n, respectively. Since ellipses are characterized by both major and minor axes, two such (S, E) pairs of values are required to describe both the convex-elliptical and concave-elliptical shoreline marshes.

Consider the simplified marsh diagram of Figure 4. Herein is depicted a rectangular marsh along a linear shoreline as seen in plan view. The total marsh area is taken to be comprised of a basic marsh area B (offshore portion of the marsh, the maximum extent of which is determined by the limit of observable emergent vegetation) and a fringe marsh area F (offshore extension of the basic marsh to accommodate the non-directly observable submerged vegetation). Only the basic marsh area B is considered in this model.

Figure 4 also illustrates a vertical cross-section of the basic marsh configuration under two distinct water level conditions. The initial condition assumes that the water level is at the zero water level datum (International Great Lakes Datum, 1955) and that the basic marsh area originates at the strand line, with the strand line separating an aquatic regime of offshore slope α and onshore slope β. The initial length, b_o, of the basic marsh at zero water level datum is taken as the offshore distance to the water depth d (corresponding to that depth beyond which there is no further emergent vegetation). The dotted water level represents the condition subsequent to a water level increase R_n above the zero water level. The offshore length of the basic marsh (again taken to the depth d which is assumed invariant to the fluctuating water levels) associated with this new water level is taken to be b_n.

If $0 \leq R_n \leq d$, it may be readily seen that

$$b_n = x + y$$

$$= \frac{d - R_n}{\tan\alpha} + \frac{R_n}{\tan\beta} \qquad (1)$$

and $$\frac{b_n}{b_o} = 1 - \frac{R_n}{d}\left(1 - \frac{\tan\alpha}{\tan\beta}\right) \qquad (2)$$

If the alongshore extent of the marsh is L, then the plan view areas of the new and initial marshlands are b_nL and b_oL, respectively. Equation (2) thus equivalently expresses the ratio of new basic marsh area (at water level R_n above zero water level datum) to initial basic marsh area (at zero water level datum) in terms of the offshore and onshore slopes of the marsh region, the water depth d beyond which there is no observable emergent vegetation and the ambient water level R_n.

As detailed in Bukata and others (1987), the governing equations for determining the ratio of marsh areal extent, A_n, at ambient water level R_n to marsh areal extent, A_o, at zero water level datum, assuming that a vegetative equilibrium is established may be written as:

<u>For $R_n < 0$</u>

<u>Linear Shoreline</u>

$$\frac{A_n}{A_o} = 1 \qquad (3)$$

<u>Concave Shoreline</u>

$$\frac{A_n}{A_o} = 1 + \frac{2R_n \cot \alpha}{2S_o - d \cot \alpha} \qquad (4)$$

<u>Convex Shoreline</u>

$$\frac{A_n}{A_o} = 1 - \frac{2R_n \cot \alpha}{2S_o + d \cot \alpha} \qquad (5)$$

<u>Concave Elliptical Shoreline</u>

$$\frac{A_n}{A_o} = 1 + \frac{2R_n \cot \alpha_u \cot \alpha_v}{S_{ou} \cot \alpha_v + S_{ov} \cot \alpha_u - d \cot \alpha_u \cot \alpha_v} \qquad (6)$$

<u>Convex Elliptical Shoreline</u>

$$\frac{A_n}{A_o} = 1 - \frac{2R_n \cot \alpha_u \cot \alpha_v}{S_{ou} \cot \alpha_v + S_{ov} \cot \alpha_u + d \cot \alpha_u \cot \alpha_v} \qquad (7)$$

<u>For $0 \leq R_n \leq d$</u>

<u>Linear Shoreline</u>

$$\frac{A_n}{A_o} = \left(1 - \frac{R_n}{d}\right) + \frac{R_n}{d} \frac{\tan\alpha}{\tan\beta} \qquad (8)$$

<u>Concave Shoreline</u>

$$\frac{A_n}{A_o} = \left[1 + \frac{R_n}{2S_o - d \cot\alpha} (\cot\alpha + \cot\beta)\right] \left[1 - \frac{R_n}{d} + \frac{R_n}{d} \frac{\tan\alpha}{\tan\beta}\right] \qquad (9)$$

<u>Convex Shoreline</u>

$$\frac{A_n}{A_o} = \left[1 - \frac{R_n}{2S_o + d \cot\alpha} (\cot\alpha + \cot\beta)\right] \left[1 - \frac{R_n}{d} + \frac{R_n}{d} \frac{\tan\alpha}{\tan\beta}\right] \qquad (10)$$

Concave Elliptical Shoreline

$$\frac{A_n}{A_o} = \left[\frac{-b_{nv} + (S_{ov} + R_n \cot\beta_v) + (S_{ou} + R_n \cot\beta_u)\left(\frac{b_{nv}}{b_{nu}}\right)}{-b_{ov} + S_{ov} + S_{ou}\left(\frac{b_{ov}}{b_{ou}}\right)}\right]\left(\frac{b_{nu}}{b_{ou}}\right) \qquad (11)$$

Convex Elliptical Shoreline

$$\frac{A_n}{A_o} = \left[\frac{b_{nv} + (S_{ov} - R_n \cot\beta_v) + (S_{ou} - R_n \cot\beta_u)\left(\frac{b_{nv}}{b_{nu}}\right)}{b_{ov} + S_{ov} + S_{ou}\left(\frac{b_{ov}}{b_{ou}}\right)}\right]\left(\frac{b_{nu}}{b_{ou}}\right) \qquad (12)$$

For $R_n > d$

Linear Shoreline

$$\frac{A_n}{A_o} = \frac{\cot\beta}{\cot\alpha} \qquad (13)$$

Concave Shoreline

$$\frac{A_n}{A_o} = \left[\frac{2S_o + (2R_n - d)\cot\beta}{2S_o - d\cot\alpha}\right]\left[\frac{\cot\beta}{\cot\alpha}\right] \qquad (14)$$

Convex Shoreline

$$\frac{A_n}{A_o} = \left[\frac{2S_o - (2R_n - d)\cot\beta}{2S_o + d\cot\alpha}\right]\left[\frac{\cot\beta}{\cot\alpha}\right] \qquad (15)$$

Concave Elliptical Shoreline

$$\frac{A_n}{A_o} = \frac{S_{ou}\cot\beta_v + S_{ov}\cot\beta_u + (2R_n - d)\cot\beta_u\cot\beta_v}{S_{ou}\cot\alpha_v + S_{ov}\cot\alpha_u - d\cot\alpha_u\cot\alpha_v} \qquad (16)$$

Convex Elliptical Shoreline

$$\frac{A_n}{A_o} = \frac{S_{ou}\cot\beta_v + S_{ov}\cot\beta_u - (2R_n - d)\cot\beta_u\cot\beta_v}{S_{ou}\cot\alpha_v + S_{ov}\cot\alpha_u + d\cot\alpha_u\cot\alpha_v} \qquad (17)$$

where S_o, R_n, and d are as defined above, S_{ou} and S_{ov} are the semi-axial lengths along the u and v principal axes of an elliptical shoreline at zero water level datum, S_{nu} and S_{nv} represent these shoreline semi-axial lengths at persistent ambient water level R_n, b_{ou} and b_{ov} represent the linear offshore extent of the elliptical marsh along each principal axis at zero water level datum, b_{nu} and b_{nv} represent the linear offshore extent of the elliptical marsh along each principal axis at ambient water level R_n, α and β are the respective offshore and onshore slope angles for the linear, concave, and convex shorelines, while α_u, β_u, α_v, and β_v are the offshore and onshore slope angles appropriate to the principal axes of elliptical shoreline marshes.

While equations (3) to (17) define the re-emergence of marsh areal extent subsequent to change in persistent ambient water level assuming that a regenerative vegetation equilibrium may be readily established, they are not indicative of the opposite situation in which no such vegetation equilibrium may be established. Such an inability to sustain a vegetative equilibrium may be a consequence of an excessively steep shoreline or inhospitable soil conditions. This situation, however, may be mathematically described by merely setting β=90° (either or both of β_u and β_v may be set equal to 90° depending on the inability of one or both of the principal axes to sustain a regenerative equilibrium).

The derivations of equations (3) to (17) along with numerous illustrations of the implications of their parametric variations are presented in considerable detail in the report by Bukata and others (1987).

APPLICATION OF THE GEOMETRIC MARSH MODEL

The marsh regions listed in Table 1 were used in conjunction with equations (3) to (17) (and their counterparts describing the situations wherein no vegetative equilibrium may be established) to estimate the impact on principal marsh areal extent of a persistent change in ambient water level. Since nearly the entire decade of the 1930's was characterized by near-zero-datum water levels (the latter stage of this low water era is indicated in Figure 2), the year 1935 was a valuable standard to use as a comparative starting point. Equations (3) to (17) compare the areal extents of marshes associated with a persistent ambient water level R_n to the areal extents of those marshes that would be associated with a persistent ambient water level at zero datum. Very rarely, if ever, do historical aerial records contain such zero-datum data, and equally rarely is it convenient to wait for zero-datum water level to obtain such data. It is considerably more convenient to obtain (as has been done in this investigation) two or more synoptic data sets over the same marsh region at distinct water levels, none of which is at zero water level datum. As shown in Bukata and others (1987), for a linear marsh geometry these two synoptic data sets may be used to estimate both A_o (the marsh areal extent associated with zero water level datum) and d (the maximum water depth at which emergent bottom-anchored vegetation may be synoptically observed) from the relationships:

a) For the case of regenerative equilibrium

$$A_o = \frac{A_1R_2 - A_2R_1}{R_2 - R_1} \tag{18}$$

$$d = \frac{R_2A_1 - R_1A_2}{A_1 - A_2} \left(1 - \frac{\tan\alpha}{\tan\beta}\right) \tag{19}$$

b) For the case of total non-regeneration

$$A_o = \frac{A_1R_2 - A_2R_1}{R_2 - R_1} \tag{20}$$

$$d = \frac{R_2A_1 - R_1A_2}{A_1 - A_2} \tag{21}$$

where A_1 is the basic marsh area corresponding to water level R_1 (measured from zero water level datum) and A_2 is the basic marsh area corresponding to water level R_2 (measured from zero water level datum). The offshore and onshore slopes are characterized by $\tan\alpha$ and $\tan\beta$, respectively.

It is interesting to note that equations (18) and (20) are identical and independent of the marshland slopes. Thus, if the appropriate linear marsh areal extents may be accurately determined and related to two known ambient water levels, the expected marshland area corresponding to zero water level datum may be readily calculated without precise knowledge of the basin topography irrespective of whether or not the region is capable or totally incapable of sustaining a vegetative metamorphism. The determination of the maximum basic marsh depth d from such synoptic data sets, as seen from equation (19), however, does require precise topographical knowledge for the case of a basin displaying vegetative equilibrium capabilities.

For the seven linear marsh regions listed in Table 1, equation (19) was used in conjunction with the corresponding areal, water level, and slope parameters to arrive at an average value of d = 1.25 metres with a standard deviation of 0.10 metres. This mean value of d was then considered to be invariant over time and space for the Georgian Bay/North Channel marsh region, and used in the computer program "MARSHMODEL" given in Bukata and others (1987) to predict final marsh areas (for both the assumptions of total marsh regeneration and total marsh non-regeneration) for the 17 historical marsh data sets. Table 2 lists the results of this application of the geometric marsh model, tabulating the initial and final persistent water levels specific to each area, and the measured initial and measured final areas determined from the historical airborne data existing for each data collection period. The predicted final marsh areas for the situations of total marsh regeneration and total marsh non-regeneration comprise the final two columns. The results of Table 2 are displayed in Figure 5 wherein are plotted the predicted marsh area in acres against the measured marsh area in acres. The open circles represent the predicted marsh area assuming that marsh regenerative metamorphism is allowed to flourish, while the open triangles represent the predicted marsh area assuming that marsh regenerative metamorphism is partially to totally inhibited.

Several points should be noted regarding Table 2 and Figure 5, viz:

a) The water levels associated with the various regions are those recorded for the actual day or days on which the photographic imagery was taken. Considerably different predictions could arise from a consideration of water levels or average of water levels of previous years. Most importantly, since the 1973 aerial photography was recorded near the peak water level, the resulting measured marsh areas, must,of course, underestimate the potentially realizable marsh areas which would ensue given a sufficient time for total vegetative regeneration.

b) Three predicted final marsh areas are considered for the non-regenerative situation for elliptical marshes. These three predictions correspond to the assumptions of non-regeneration occurring solely in one of each of the principal axes and the assumption of non-regeneration occurring in both of the principal axes. This is reflected as the association of up to four predicted values with some of the measured values of marsh acreage.

c) The water levels considered cover the range from below zero water level datum to total inundation of existing emergent marsh vegetation. This $R_n > d$ condition results in the prediction of total elimination of marsh regions for situations in which the onshore slope is incapable of vegetative regeneration.

d) The vast majority of the Georgian Bay/North Channel marsh regions are of the linear and concave (or concave elliptical)geometries, and very little representation could be given to convex shoreline marshes in this study. This is due largely to the physical nature of the considered Great Lakes region. However, it is also due, in part, to an unavailability of appropriate data sets over those convex shoreline marshes which are present within the basin.

These above considerations notwithstanding, Figure 5 strongly suggests:

a) The conceptual mathematical marsh model may be appropriately applied to an estimation of the impact of persistent water level fluctuations to freshwater shoreline marshes such as comprise the Georgian Bay/North Channel region of the Great Lakes basin.

b) In the vast majority of cases the actual measured final marsh area was a value less than the maximum predicted regenerative marsh acreage but greater than the minimum predicted non-regenerative marsh acreage, indicating that reality does, in fact, lie somewhere between these two metamorphic extremes. Two obvious exceptions to these predictive model capabilities are designated by X and Y in Figure 5. X represents the linear shoreline marsh along a reach of Sturgeon Bay wherein no marsh acreage was remotely observable in the imagery associated with the 1.14 m water level. This linear marsh, as delineated in earlier imagery was characterized by significantly longer alongshore than offshore dimension. Consequently, several possibilities readily present themselves. Either, the linear marsh has, in fact, been destroyed for reasons that are not immediately apparent, insufficient time has elapsed to allow for vegetative regeneration, or because of the elongated nature of the Sturgeon Bay linear shoreline marsh, the actual offshore extent of the marsh could be so small as to be aerially undetectable even though the conceptual mathematical model anticipates a marsh area in the range 8-32 acres. Another possibility is that the actual value of d for this region is closer to 1.1 m than the average 1.25 m assumed which would readily allow an R_n of 1.14 m to completely eliminate the marsh as observed. Y represents the linear shoreline marsh in the rocky shore area along Hog Bay. Here, too, no measureable acreage was recorded corresponding to the 1.14 m water level. However, the accuracy of the aerial delineation in the majority of instances was considered as ~ ± 1 acre. Since the anticipated final acreage according to the mathematical marsh model was 0.7 acres, it is conceivable that the linear shoreline Hog Bay marsh was simply beneath the detection limit of the synoptic delineation methodology, and that aerial estimations of marsh regions should be restricted to marshes larger than 1 acre. Of course, as discussed above, a local value of d close to 1.1 m would also explain the total disappearance of the marsh.

c) Clearly, Figure 5 illustrates that less marsh acreage has consistently re-emerged subsequent to a persistent change in ambient water level than would have been allowed to re-emerge solely on the basis of basin geometrics. This partial non-regeneration is more clearly seen in Figure 6 wherein are plotted the maximum predicted marsh acreage (assuming either total vegetative regeneration, or, for those few marshes where rocky shorelines are known to exist assuming that vegetative non-regeneration controls the maximum re-emergence of marsh acreage) against the actual measured marsh acreage. The open circles in Figure 6 are taken from the data points plotted in Figure 5 and the dashed line represents the relationship to be expected for 100% marsh vegetative regeneration. Open circles above this line represent those instances in which less marsh acreage was observed than the basin geometry would permit. The open circles are based, as discussed before, on a consideration of the actual water levels existing at the time the aerial photography was acquired. No serious consideration was given to the establishment of a suitable "grow-back" time-lag for the wetlands in question to establish (or not establish) a vegetative equilibrium. As an example of how such a time-lag consideration might impact the predictions of the marsh model, the solid circles on Figure 6 consider as the associated water levels for each aerially determined marsh acreage, the average water level recorded at that location for the 24 month interval preceding the synoptic data acquisition. The solid circles, like the open circles, assume the basin is capable of total vegetative regeneration. Clearly, the solid circles for each marsh region show a larger predicted marsh acreage than do the corresponding open circles for that marsh region, suggesting that the measured loss of marshland is more severe than the loss of marshland indicated by a consideration of the water level present near the time of aerial survey. This could certainly be possible, viz. that the anticipated totally regenerated marsh acreage for the coastal wetlands could be larger than the values listed in Table 2. These predicted marsh acreage values, are certainly a function of the initial and final persistent water levels R_1 and R_2. However, if it is assumed (a) that no on-shore vegetative equilibrium may be established (corresponding to the open triangles of Figure 5) and (b) that the appropriate water levels are those utilized in generating the closed circles of Figure 6, the ensuing predicted marsh acreages also exceed the actual measured marsh acreages. This would suggest that not only did the measured marsh acreage fall short of the maximum acreage that the basin geometry was capable of sustaining, but that the loss in marsh acreage also exceeded the maximum acreage that the basin geometry was willing to relinquish. Such a suggestion is clearly untenable. Consequently, for the case of the Lake Huron/Georgian Bay shoreline marshes considered herein, utilizing the mean water level values for the two-year period preceding the synoptic data collection activity is an inappropriate method of obtaining R_1 and R_2. This refuting of the validity of the closed circles, understandably, does not automatically validate the use of the open circles in Figures 5 and 6. It does, however, indicate that the water levels used in their generation are certainly more appropriate than the water levels used in the generation of the closed circles. The precise method of ascribing an associated persistent water level to a particular observed extant marsh acreage is not necessarily an immediately obvious and/or intuitive technique that can be casually applied. Such factors as the rapidity with which a persistent water level has advanced or retreated, the realization that marsh vegetation may be destroyed in a much shorter time period than marsh vegetation may be generated or metamorphosed, the precise time during the onset or retreat of persistent water level fluctuations during which synoptic observations are taken, amongst other numerous factors must be seriously considered. Further discussions of this relationship between water levels R_n and associated marsh acreages A_n will be deferred to a later time.

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FIGURE CAPTIONS

TABLE 1. Selected marsh sites and their pertinent geometric parameters

Region	Geometry	Offshore Slope (Expressed as one in _)	Onshore Slope (Expressed as one in _)
Echo Bay	Concave Elliptical	851;469	320;195
Lake George (a) (Bar River to Echo Bay)	Linear	260	47
Lake George (b) (Pumpkin Point to Bar River)	Linear	399	133
Lake George (c) (Birch Point to Pumpkin Point)	Linear	261	16
Opposite Shoal Island	Linear	122	16
Bruce Mines	Concave	139	41
Garden Bay	Concave	122	55
Hay Bay	Concave Elliptical	174;174	117;33
MacBeth Bay	Concave Elliptical	156;139	12;55
Sturgeon Bay (a)	Linear	174	47
Sturgeon Bay (b)	Concave	405	94
Hog Bay (a)	Linear	35	0 (Rocky Shoreline)
Hog Bay (b)	Concave	87	70
Hog Bay (c)	Concave Elliptical	243;86	47;55
Mile 386	Linear	122	0 (Rocky Shoreline)
Sydney Bay	Concave Elliptical	87;87	0 (Rocky Shoreline)
Wingfield Basin	Concave	43	0 (Rocky Shoreline)

Table 2. The measured marsh areas associated with specific persistent water levels and the marsh areas determined from the conceptual mathematical model

Region	Initial Water Level R_1(m)	Date	Final Water Level R_2(m)	Date	Measured Initial Area (acres)	Measured Final Area (acres)	Predicted Final Area Regeneration (acres)	Predicted Final Area Non-regeneration (acres)
Echo Bay	0.26	5/50	1.27	6/73	804	128	549	270;245;0
Lake George (a)	0.26	5/50	1.27	6/73	508	42.6	111	0
Lake George (b)	0.25	5/50	1.27	6/73	118	4.9	45.3	0
Lake George (c)	0.25	5/50	1.27	6/73	100	8.4	7.4	0
Opposite Shoal Island	0.26	5/50	1.27	6/73	19	1.3	3.0	0
Bruce Mines	0.25	5/50	1.27	6/73	60	8.4	24.1	0
Garden Bay	-0.06	9/35	1.27	6/73	28	3.3	26.5	0
Hay Bay	-0.06	9/35	1.27	6/73	90	4.6	52.1	36.1;12.5;0
MacBeth Bay	-0.06	9/35	1.27	6/73	52	11.2	17.5	15.1;2.0;0
Sturgeon Bay (a)	-0.07	5/65	1.14	5/73	98	0	32.0	7.8
Sturgeon Bay (b)	-0.07	5/65	1.14	5/73	146	44.5	73.1	18.5
Hog Bay (a)	-0.07	5/65	1.14	5/73	9	0	-	0.7
Hog Bay (b)	-0.07	5/65	1.14	5/73	43	7.4	44.7	4.0
Hog Bay (c)	-0.07	5/65	1.14	5/73	52	19.3	37.8	25.8;15.6;6.5
Mile 386	-0.06	5/65	1.14	5/73	14	1.5	-	1.1
Sydney Bay	-0.06	5/65	1.14	5/73	55	5.0	-	4.9
Wingfield Basin	-0.06	5/65	1.14	5/73	14	1.0	-	1.3

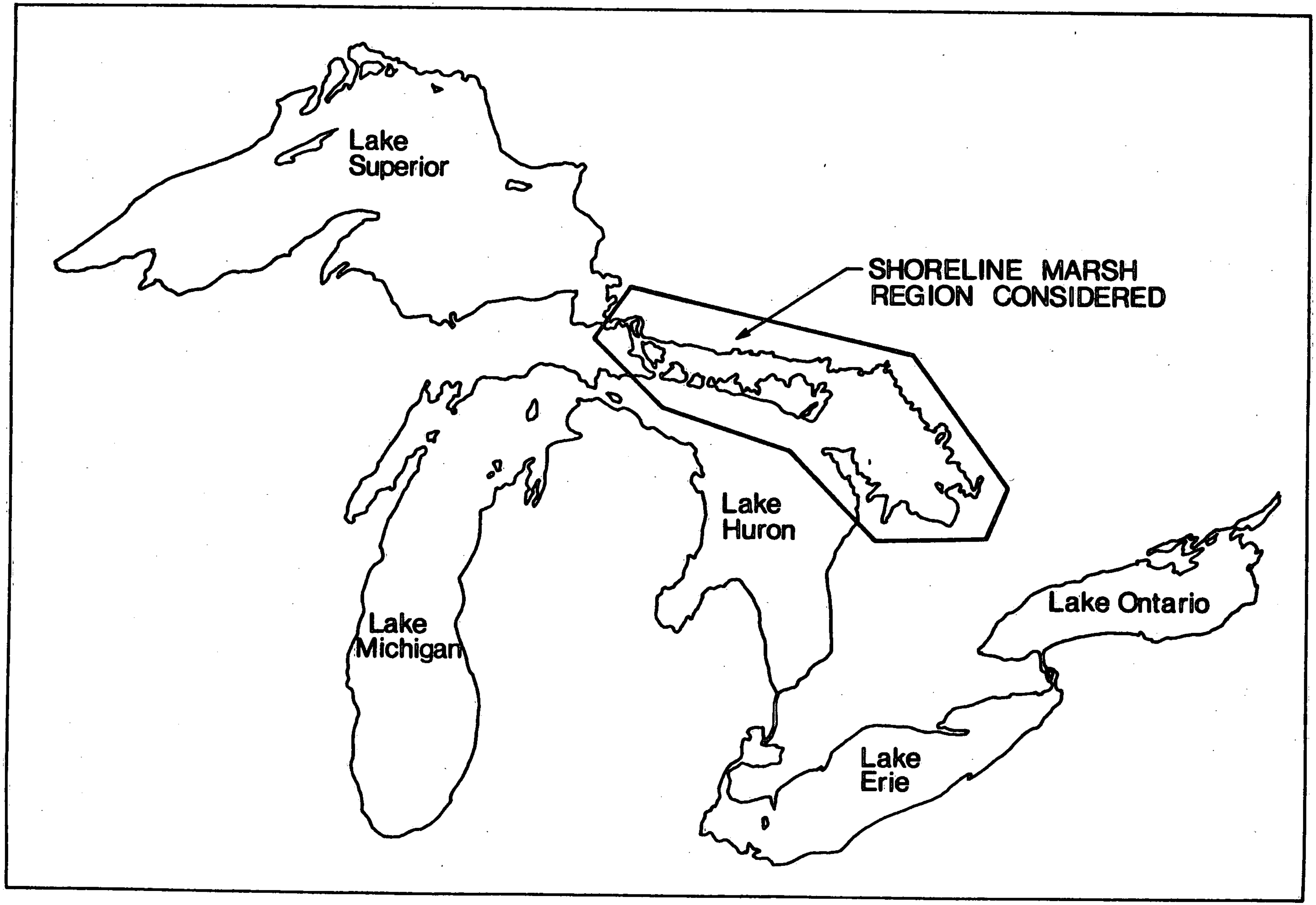
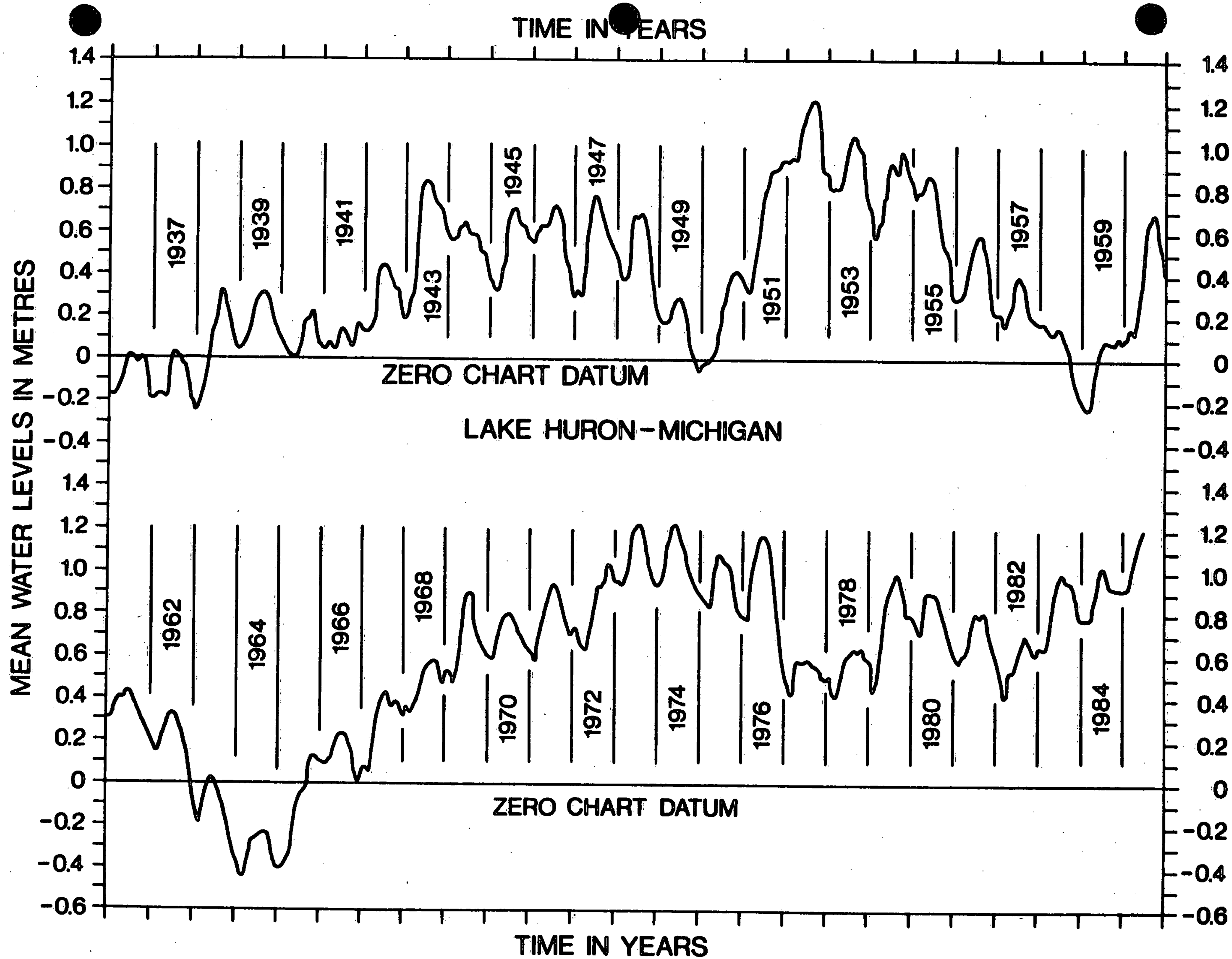

Lake Superior
SHORELINE MARSH REGION CONSIDERED
Lake Huron
Lake Michigan
Lake Ontario
Lake Erie

FIG. 1



TIME IN YEARS
MEAN WATER LEVELS IN METRES
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
1937
1939
1941
1943
1945
1947
1949
1951
1953
1955
1957
1959
ZERO CHART DATUM
LAKE HURON-MICHIGAN
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
ZERO CHART DATUM
TIME IN YEARS

FIG. 2

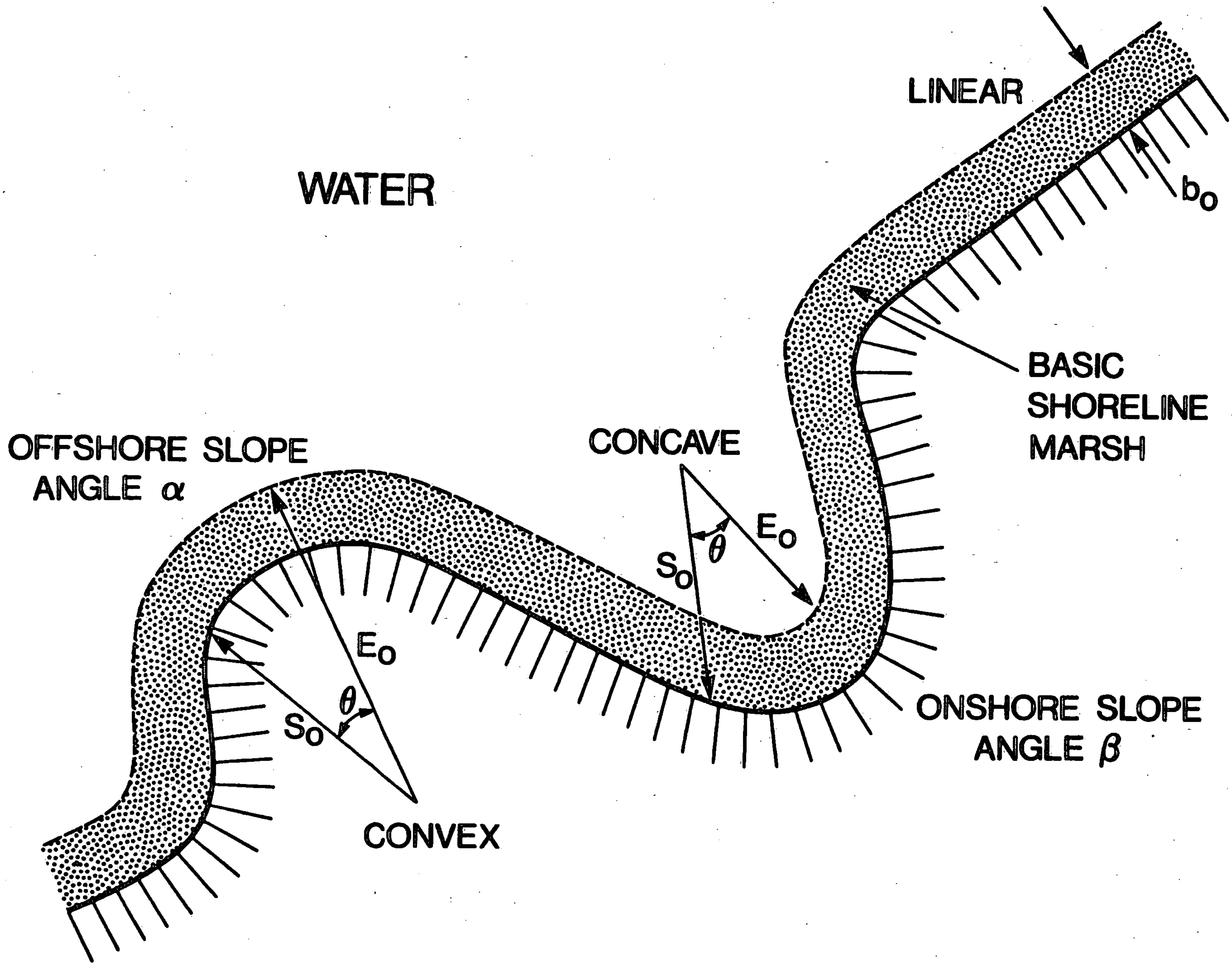

WATER
LINEAR
b_o
BASIC
SHORELINE
MARSH
CONCAVE
E_o
S_o
θ
OFFSHORE SLOPE
ANGLE α
ONSHORE SLOPE
ANGLE β
E_o
θ
S_o
CONVEX

FIG. 3

LINEAR MARSH

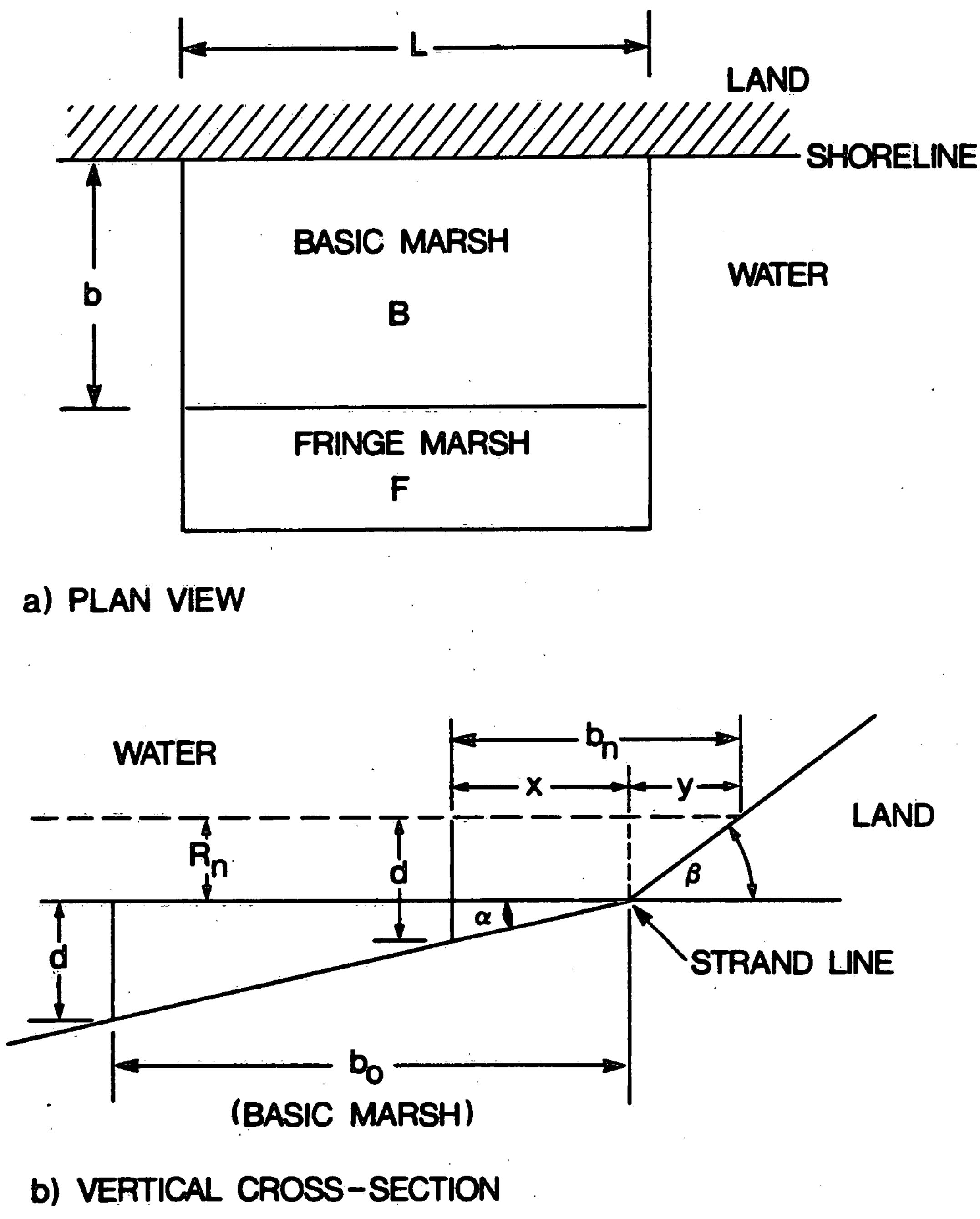


FIG. 4

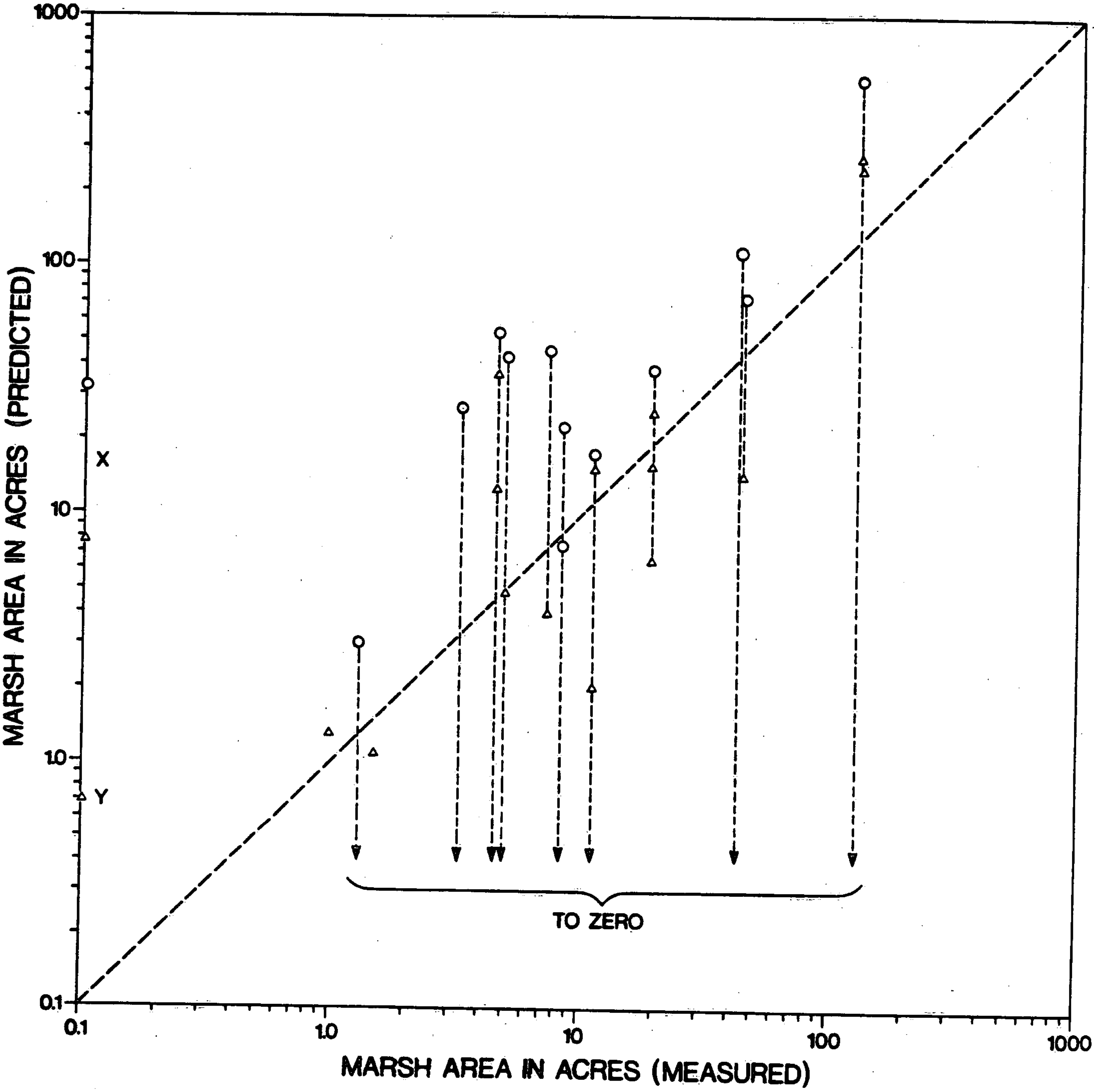

1000
100
10
1.0
0.1
MARSH AREA IN ACRES (PREDICTED)
X
Y
TO ZERO
0.1
1.0
10
100
1000
MARSH AREA IN ACRES (MEASURED)

FIG. 5

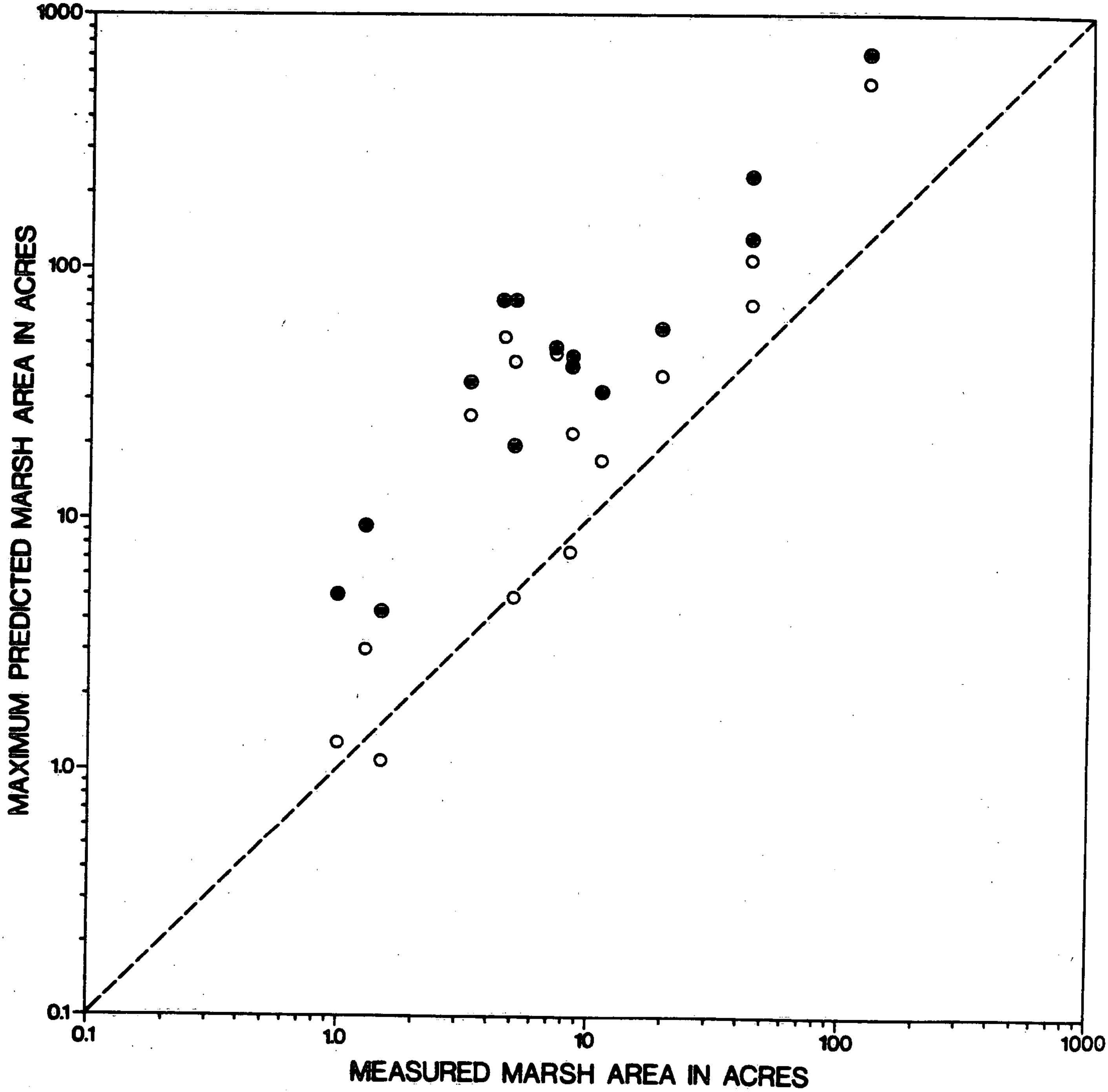

1000
100
10
1.0
0.1
MAXIMUM PREDICTED MARSH AREA IN ACRES
0.1
1.0
10
100
1000
MEASURED MARSH AREA IN ACRES

FIG. 6