RRB-87-40

THE CONCEPT OF ONSHORE COLONIZATION EFFICIENCY IN EVALUATING THE IMPACT ON MARSHLANDS OF PERSISTENT WATER LEVEL INCREASES

by

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NWRI Contribution #88-98

ABSTRACT

Historical airborne imagery has been used with a recently developed mathematical model to evaluate the range of impact of increases in ambient persistent water level on the areal extent of shoreline marshes in the Georgian Bay/North Channel region of the Great Lakes. As an extension of that work, two methods that significantly improve the predictive capabilities of the model are presented. A regression equation is determined that relates the natural logarithm of predicted marsh area minus the natural logarithm of measured marsh area to the product of the coincident ambient water level and onshore slope. The regression indicates that discrepancies between predicted and measured marsh areas increase as the impacted onshore area increases. Introducing the concept of onshore colonization efficiency, a simplistic algorithm, based upon the duality of onshore and offshore marsh vegetation response, is developed. This algorithm leads to the determination of an "effective water level", which is less than the coincident ambient level, and which indicates the state of progression of onshore vegetation colonization. For the Georgian Bay/North Channel marshlands during the time interval 1935-1973, this "effective water level" is shown to be about +0.4 m.

RÉSUMÉ

On a utilisé des images aériennes d'archives avec un modèle mathématique récemment mis au point afin d'évaluer toute la gamme des répercussions causées par les augmentations du niveau constant de l'eau dans le milieu ambiant sur la superficie des marécages littoraux de la région des Grands Lacs constituée par la baie Georgienne et le North Channel. Comme prolongement de ces travaux, on présente deux méthodes permettant d'améliorer de façon significative les capacités de prévision du modèle. On détermine une équation de régression qui établit une relation entre le logarithme népérien de la superficie prévue des marécages moins le logarithme népérien de la superficie mesurée et le produit du niveau d'eau correspondant du milieu et de la pente litorale. La régression indique un accroissement des écarts entre les superficies prévues et mesurées des marécages avec l'augmentation de la superficie côtière touchée. En introduisant la notion de colonisation côtière efficace, on a mis au point un algorithme très simplifié, basé sur la dualité de la réaction de la végétation poussant dans les marécages du littoral et du large. Cet algorithme permet de déterminer un "niveau d'eau efficace" qui est inférieur au niveau correspondant du milieu et qui indique la progression de la colonisation végétale côtière. Dans le cas des marécages de la baie Georgienne et du North Channel durant la période allant de 1935 à 1973, on a montré que ce "niveau d'eau efficace" était d'environ + 0,4 m.

MANAGEMENT PERSPECTIVE

This is the third in a series of communications dealing with the prediction of resulting shoreline marsh area subsequent to a persistent change in the ambient water level. The first communication presented a mathematical model based primarily on the geometric parameters defining the containing basin. The model provides predictions of marsh areas for two extremes of environmental conditions. The first condition assumes that the dynamic nature of the chemical/biological/physical inter-relationships, although ignored, are nonetheless acting in such a manner as to allow total metamorphic transformation between marsh and onshore regimes. The second condition assumes that no such metamorphism is possible. Consequently, the marsh model is designed to predict the maximum and minimum marsh areas which could result from a change in the persistent ambient water level.

The second communication applied this mathematical model to the marshes along the Georgian Bay/North Channel shoreline from the St. Mary's River to the Wingfield basin of the Bruce Peninsula.

This third communication is a logical extension of the second communication, wherein both the need to relate a particular water level to a coincident marsh area, as well as the difficulties encountered in arriving at such a relationship, are discussed. Two methods of estimating such a relationship are presented. The first method employs a mathematical regression among various parameters historically recorded for the Georgian Bay/North Channel marshes. The resulting regression shows that the difficulties encountered in obtaining an unambiguous relationship between measured marsh areas and coincident water levels increase significantly with increasing impacted onshore distance. This observation logically suggests the second method which assumes that, whereas offshore impacted regions may readily, and with 100% efficiency, participate in the offshore/onshore metamorphism processes, the onshore impacted regions may participate with efficiencies that may vary between 0 and 100%. A model is presented wherein such a principle is applied to the Georgian Bay/North Channel marsh regions. Such a model, while still open to further refinement, provides a valuable basis for estimations of lag-times required for marshes to respond to, adapt, and stabilize to fluctuating environmental conditions.

PERSPECTIVE-GESTION

Cette communication est la troisième d'une série concernant les prévisions de la superficie des marécages côtiers à la suite d'un changement du niveau de l'eau du milieu ambiant. La première communication présentait un modèle mathématique essentiellement fondé sur les paramètres géométriques définissant le bassin de retenue. Le modèle permet de prévoir les superficies des marécages dans deux conditions environnementales extrêmes. La première suppose l'influence de la nature dynamique des inter-relations chimiques, biologiques et physiques, même si on n'en tient pas compte, de façon à permettre la transformation métamorphique totale entre les régimes en milieu marécageux et en milieu littoral. La deuxième condition suppose qu'aucun métamorphisme semblable n'est possible. Par conséquent, le modèle de marécages est destiné à prévoir les superficies maximales et minimales qui pourraient résulter d'une modification du niveau d'eau constant du milieu.

La deuxième communication applique ce modèle mathématique aux marécages situés le long de la côte de la baie Georgienne et du North Channel, de la rivière St. Mary vers le bassin Wingfield de la péninsule Bruce.

Cette troisième communication est la suite logique de la deuxième. On y examine la nécessité d'établir une relation entre un niveau d'eau particulier et la superficie correspondante des marécages, ainsi que les difficultés rencontrées pour établir une telle relation. On y présente aussi deux méthodes permettant d'estimer cette relation. La première méthode emploie une régression mathématique parmi divers paramètres, enregistrés dans le passé, s'appliquant aux marécages de la baie Georgienne et du North Channel. La régression qui en résulte indique que les difficultés rencontrées pour obtenir une relation non équivoque entre les superficies mesurées des marécages et les niveaux d'eau correspondants augmentent de façon significative avec la distance par rapport au littoral touché. Cette observation conduit logiquement à la deuxième méthode qui suppose que les régions touchées du large peuvent facilement, avec une efficacité de 100 %, participer aux processus métamorphiques au large et vers le littoral, tandis que l'efficacité de participation des régions côtières touchées varie de 0 à 100 %. On présente un modèle où ce principe est appliqué aux marécages de la baie Georgienne et du North Channel. Ce modèle peut être encore amélioré, mais il est bien utile si on veut estimer le temps de réponse des marécages pour s'adapter et se stabiliser face à des fluctuations de l'environnement.

INTRODUCTION

Recently we have presented (Bukata and others, 1988 (a)) a mathematical model whereby the impact on synoptically-observable shoreline marsh area, produced by changes in persistent (long-term) ambient water levels can be predicted primarily on the basis of the geometric parameters describing the basin containing the impacted wetland. The basic premise of the model is that, despite the biological, chemical, and physical complexities of wetland vegetation dynamics, a non-catastrophic change in persistent ambient water level must result in a marsh area within the limits defined by the model. Mathematical expressions were developed relating the areal extents of marshlands to coincident ambient water levels in terms of the onshore and offshore terrain slopes, geometrical configuration of the shoreline, and the maximum depth beyond which bottom-anchored emergent vegetation can no longer be discerned synoptically. For increases in ambient water level, the upper limit of the model is defined by the assumption that all inundated onshore terrain is colonized by marsh vegetation, whereas the lower limit assumption is that onshore marsh vegetation colonization is totally inhibited.

This mathematical model was then applied (Bukata and others, 1988 (b)) to shoreline marshes in the Georgian Bay/North Channel region of the Great Lakes basin. Historical airborne imagery pertinent to long-term water level increases was obtained within the time interval 1935-1985, and marsh area predictions resulting from the use of the mathematical model, operating in each of its extreme modes, were compared with actual marsh areas determined by Ecoplans Ltd. (1986).

A summary of these results is presented in Table 1, which lists the marsh regions considered, their geometric shoreline configurations, the onshore and offshore slope angles, initial and final water levels, initial and final measured marsh areas and predicted maximum and minimum marsh areas. The predicted marsh areas in Table 1 assume, as the initial and final water levels, the existing daily water levels measured at the time the aerial surveys were conducted. Figure 1 illustrates the monthly mean water level history from 1936-1985 for the Lake Huron/Lake Michigan area.

It can be seen from Table 1 that, excluding the Sturgeon Bay (a) region, and after allowing for a ±1 acre measurement inaccuracy, the actual measured final marsh areas do fall within the prediction limits of the model. The Hog Bay (a), Mile 386, Sydney Bay, and Wingfield Basin regions are known to have rocky shorelines, which are not conducive to onshore marsh vegetation development. For these marshes, only the model's minimum predictions are appropriate, and indeed these predictions are quite close to the actual measured final marsh areas. It was this result that suggested a possible method to refine the model predictions.

MODEL REFINEMENTS: a) REGRESSION EQUATION

To illustrate the impact of a rise in persistent water level on both offshore and onshore marsh regions, Figure 2 presents a simplified sketch of a linear shoreline marsh regime. The offshore slope angle α and the onshore slope angle β (both measured on the assumption that the strand line corresponds to zero water level datum) are shown, as is the water depth d which defines the offshore extent of synoptically-observable principal marsh area. This depth d corresponds to the maximum depth at which bottom-anchored emergent marsh vegetation can be discerned in an aerial image. The dashed line in Figure 2 illustrates the situation for a persistent ambient water level R_n above zero water level datum. For the case of $0 \leq R_n \leq d$ it is seen that the marsh dimension b_n perpendicular to the shoreline comprises a distance x_n associated with the offshore (relative to the original strand line) slope angle α and a distance y_n associated with the onshore (relative to the original strand line) slope angle β. Thus for $0 \leq R_n \leq d$,

$$b_n = x_n + y_n$$

$$= (d - R_n) \cot \alpha + R_n \cot \beta. \qquad (1)$$

For $R_n = 0$ (zero water level datum), the marsh dimension b_0 is associated entirely with the offshore slope angle α, ($b_0 = d \cot \alpha$).

If the alongshore extent of the marsh is L, then the linear marsh areas corresponding to b_o and b_n are b_oL and b_nL, respectively.

Good agreement between predicted and measured marsh areas was observed for the regions Hog Bay (a), Mile 386, Sydney Bay, and Wingfield Basin where the onshore reaches are not conducive to marsh vegetation development. For these regions the term $R_n \cot \beta$ of equation 1 can be ignored. Comparable agreement, however, was not observed for the other marsh regions where $R_n \cot \beta$ cannot be ignored.

To investigate the departure of maximum predicted marsh areas from measured marsh areas for those regions where $R_n \cot \beta$ is non-zero, Figure 3 displays a plot of $\log_e$ (Predicted Area) - $\log_e$ (Measured Area) as a function of $R_n \cot \beta$ for fourteen of the marsh regions listed in Table 1.

Figure 3 shows that, in general, the larger the $R_n \cot \beta$ term, the greater is the departure between measured and maximum predicted marsh areas. Thus, a gently sloping onshore terrain, when inundated to a given water level R_n above zero datum, presents a situation in which onshore marsh vegetation colonization is considerably more unpredictable than is the situation for a much more steeply sloping terrain. The correlation therefore suggests a mathematical relationship among the maximum predicted marsh area P_{max}, the actual measured marsh area M, the coincident persistent water level R_n, and the onshore slope angle β, of the form

$$\log_e P_{max} - \log_e M = k R_n \cot \beta \qquad (2)$$

where k is a constant.

Excluding the two very small measured marsh regions, Sturgeon Bay (a) and Hog Bay (a), as well as Echo Bay, which apparently requires a more sophisticated approach than that suggested by equation 2, a statistical regression between ($\log_e P_{max} - \log_e M$) and $R_n \cot \beta$ for the other fourteen marsh regions listed in Table 1 (and shown in Figure 3) yields a k value of 0.0156 with a coefficient of determination $r^2 = 0.80$. For the Georgian Bay/North Channel marshlands considered here, equation 2 may be rewritten to yield the regression predicted marsh area P_{reg} (anticipated at coincident persistent water level R_n) in terms of the onshore slope angle β and P_{max} (the upper limit prediction of the mathematical marsh model). Thus,

$$P_{reg} = \exp \left[\log_e P_{max} - 0.0156 R_n \cot \beta\right]. \qquad (3)$$

Equation 3 was used to calculate P_{reg} for each of the seventeen Georgian Bay/North Channel shoreline marsh regions. These values of P_{reg} together with the corresponding values of P_{max} are listed in Table 2. The use of equation 3, on the average, results in predicted marsh areas that are significantly closer to the actual measured marsh areas than are the values of P_{max}. Whereas the total of the P_{max} predictions for the seventeen marshes overestimates the total measured area by 254%, the corresponding total area as predicted by equation 3 underestimates the actual total area by only 44.3%. It should be noted, however, that this underestimation of total marsh area resulting from the regression equation is due almost entirely to the Echo Bay marsh region. Removing Echo Bay from consideration reduces the difference between the P_{reg} area total and M area total to a mere -2.8%. Such an improvement is understandable since Echo Bay data were not included in the regression determination.

It must, of course, be emphasized that any statistical regression such as equation 3, which arises from the analysis of spatially and temporally restricted environmental data sets, should be regarded as strictly relevant only for the regions and time intervals specific to the study. To minimize mathematical complexity, such regressions ignore explicitly many physical, chemical, and biological influences as well as details of their spatial and temporal variations. For the Georgian Bay/North Channel marshes such influences serve to modify the regression-determined values of k (0.0156) and r^2 (0.80). Although these numerical values could be considerably different for other locales and/or time intervals, the functional form of the correlation, as expressed by equation 2, should remain valid. The significance of the regression is that it reveals a positive relationship between inundated onshore distance and the extent to which actual measured marsh areas depart from the maximum theoretically attainable areas predicted by the model. The regression indicates that, at least for the conditions specific to this study, the rate of onshore colonization by marsh vegetation is much slower than the rate of rise of the ambient water levels, resulting in substantial inundated onshore areas devoid of marsh vegetation. Nevertheless, the fact that most of the measured final marsh areas coincident with R_n are greater than the minimum predicted areas, P_{min}, indicates that onshore colonization is indeed progressing, although with less than 100% efficiency. For a given water level rise R_n, onshore colonization efficiency may then be defined as the ratio of the actual amount of onshore marsh vegetation to the maximum attainable amount of onshore marsh vegetation.

In the following section, the concept of an effective water level, which is less than the coincident water level, is introduced in the mathematical model in order to refine predictions of marsh areas and onshore colonization efficiency.

MODEL REFINEMENTS: b) EFFECTIVE WATER LEVEL

In order to more rigorously quantify marsh area predictions and onshore colonization efficiency, a simple algorithm was developed. This algorithm uses the mathematical marsh model and some reasonable assumptions to estimate the marsh areas expected for suboptimal conditions of onshore colonization efficiency. It should be re-emphasized here that, in the subsequent discussions, the use of the terms "onshore" and "offshore" refers to directions from the strand line at zero water level datum, as shown in Figure 2. If it is assumed that marshes can be destroyed with considerably greater ease and speed than they can be created, then, for a rising water level, the original offshore extent of marshland should be controlled by the coincident persistent water level R_n, whereas the resulting onshore extent of marshland should be controlled by an effective persistent water level R_{eff}. This R_{eff} would be less than the coincident persistent water level R_n. This duality of response displayed by offshore and onshore vegetation requires a separate marsh area calculation procedure for each regime. For the Georgian Bay/North Channel marshes the details of the calculation methodology are as follows:

For the thirteen Georgian Bay/North Channel marsh regions that could be expected to display some degree of onshore marsh vegetation colonization (no recalculations were required for the other four rocky shoreline marsh regions), the marsh model presented in Bukata and others (1988(a)) was first used to determine the areal extent of marshland A_0 associated with zero water level datum. This was accomplished by considering the initial water level R_1 to be as listed in Table 1, and the final water level to be $R_2=0$. It is reasonable to assume that for minor water level fluctuations about the zero water level datum, both the creation and destruction of marshland may proceed at 100% efficiency (i.e., destruction and/or creation may be completed within one seasonal cycle). Consequently, we have assumed that the range of initial water levels listed in Table 1 (-0.07 m $\leq R_1 \leq +0.26$ m) is sufficiently close to zero water level datum to allow such an assumption of 100% creation/destruction efficiency. Thus A_0 was confidently taken to be the upper limit prediction P_{max} of the marsh model. P_{max} may therefore be expressed as a function of R_1, $R_2 = 0$, and A_1, and the explicit functional dependence of A_0 may be written as

$$A_0 = P_{max} (R_1, 0, A_1). \quad (4)$$

The efficiency of vegetation response was taken to be 100% in the offshore region for all water levels. Onshore, the efficiency was taken to be 100% from the zero datum level to some assumed maximum effective water level R_{eff}. Above R_{eff} and extending to the final coincident water level, R_2, the efficiency was taken as being zero. The +1.27 m final water level appropriate to about one-half of the marsh regions considered is 0.02 m over the estimated d value of 1.25 m (Bukata and others, 1988 (b)). This inundation over the d value would result in a systematic removal of observable onshore marsh area at or near the original strand line. This effect, however, was not considered to be significant and the 1.27 m value was taken, for the purpose of these calculations, to be 1.25 m.

Onshore marsh areas P_{on} were determined for each of the marsh regions by taking the initial water level to be $R_1 = 0$, the final water level to be R_{eff}, and using the model in both of its extreme modes. Thus, $P_{on} = P_{max} - P_{min}$, and when the functional dependencies are explicitly shown, P_{on} is defined by

$$P_{on} = P_{max} (0, R_{eff}, A_0) - P_{min} (0, R_{eff}, A_0). \quad (5)$$

Offshore marsh areas P_{off} were then determined for each of the marsh regions by taking the initial water level to be $R_1=0$, the final water level to be the actual water level R_2 (from Table 1) at the time of aerial observation, and using the model in its lower limit mode. Thus,

$$P_{off} = P_{min}\ (0,\ R_2,\ A_0). \tag{6}$$

The predicted final marsh area P_{alg} resulting from the use of this algorithm is then given as

$$P_{alg} = P_{on} + P_{off}. \tag{7}$$

P_{alg} marsh area predictions for R_{eff} values of +0.3 m, +0.4 m, and +0.5 m are presented in Table 2. Also listed in Table 2 are the totals of the marsh areas as directly observed and as predicted by the P_{max}, P_{reg}, and P_{alg} methodologies. These prediction totals are also presented as a percentage of the directly measured marsh area total. Linear ($y = mx$) regressions were performed between the natural logarithm of the directly measured individual marsh areas (x) and the natural logarithm of the corresponding various predicted marsh areas, (y). The slopes m and coefficients of determination r^2 resulting from these regressions are also listed in Table 2. Hog Bay (a), Mile 386, Sydney Bay, and Wingfield Basin data were excluded from the regressions since these regions do not support onshore marsh vegetation. Also excluded was the Sturgeon Bay (a) region as its zero measured final marsh area is not usable in a logarithmic calculation.

From Table 2, it is seen that very good agreement between predicted and synoptically-determined marsh areas is obtained for average effective onshore persistent water levels of +0.3 to +0.5 m. Although an R_{eff} of +0.3 m results in only a -6.7% departure from the total measured marsh area compared to a +19.7% departure for an R_{eff} of +0.4 m, the regression parameters m and r^2 for R_{eff} = +0.3 m are 0.93 and 0.92, respectively compared to the somewhat better values of m = 1.01 and r^2 = 0.93 for R_{eff} of +0.4 m.

For the condition of increased water level considered in this analysis, the working definition of onshore colonization efficiency, OCE, is given by the value of P_{on} at the effective water level R_{eff} divided by the value of P_{on} at the coincident water level R_n. The OCE for a linear marsh may be calculated readily using the onshore term of equation 1. Thus,

$$\frac{P_{on}\ (R_{eff})}{P_{on}\ (R_n)} = \frac{L \bullet R_{eff} \cot\beta}{L \bullet R_n \cot\beta} = \frac{R_{eff}}{R_n}. \qquad (8)$$

For R_{eff} = +0.4 m and R_n = 1.25 m the OCE of a linear marsh is 32%. In general, for marshes having the same water level histories and onshore/offshore slopes, a concave geometry marsh will have an OCE less than the corresponding linear marsh, and a convex geometry marsh will have an OCE greater than the linear value. In terms of the P_{max} and P_{min} area predictions of the model, the OCE may be calculated for all geometries as

$$OCE = \frac{P_{max}\ (0,R_{eff},A_0) - P_{min}\ (0,R_{eff},A_0)}{P_{max}\ (0,R_n,A_0) - P_{min}\ (0,R_n,A_0)}. \qquad (9)$$

DISCUSSION

As an extension of the recently developed mathematical marsh model (Bukata and others 1988 (a)), which relates long-term changes in ambient water levels to marsh area for both maximum and minimum onshore vegetation colonization, this paper has presented two approaches that can be used to significantly refine the model predictions for rising water levels.

The generation of a regression equation that relates the difference between maximum predicted marsh area and directly measured marsh area to the basin geometry, has both limited usability and restricted geographical scope. Nevertheless, it does distinctly illustrate that the discrepancies between predicted and measured marsh areas are directly related to impacted onshore distance, indicating the significance to marsh area response of the vegetation colonization efficiency of the onshore terrain.

The implications of the regression led to the development of an algorithm that expanded the applicability of the mathematical marsh model to include marshlands characterized by suboptimal onshore colonization efficiencies. This revealed that, despite the fact that the ambient persistent water level in the Georgian Bay basin varied between -0.5 m and +1.3 m throughout the period 1935-1973, the onshore marsh areas observed in 1973 were equivalent, on average, to that expected for a persistent water level of approximately +0.4 m and a vegetation colonization efficiency of 100%.

Examining the water level history of Figure 1, it can be seen that for the 38 year period from 1936 to 1973, nineteen of the years displayed an average annual water level above +0.4 m and nineteen years had an average annual water level below +0.4 m. This average water level is delineated by the dashed line in Figure 1. Thus, over this time span, +0.4 m represents a good estimate of the long-term average water level of the Georgian Bay/North Channel basin. It is thus possible that for a rising water level, marsh vegetation may readily colonize the onshore reaches up to this long-term average water level but encounter greater difficulty above this level. It may be argued, however, that the marsh areas observed in 1973 are primarily the result of the water level rise from the low of 1964 to the high of 1973, and that the advance of onshore marsh vegetation is proceeding at a rate that lags the water level rise by several years. The magnitude of the difference between R_n and R_{eff} clearly depends upon the rate of rise of the water level. It could be expected that a sufficiently slow rate of rise would allow onshore colonization to keep pace with the advancing water level. A very rapid rise would result in an even larger discrepancy between R_n and R_{eff}. Expressed mathematically, this discrepancy becomes a function of the time derivative of the ambient water level. Thus,

$$R_n - R_{eff} = f\left(\frac{\partial R_n}{\partial t}\right). \tag{10}$$

Other possible reasons for the discrepancy between R_n and R_{eff} may involve the topography of the basin, human encroachment, and/or the nature of the onshore soils. Acting alone or together these parameters may severely limit marsh vegetation colonization beyond some onshore point, regardless of the coincident water level or its long-term rate of increase. Although it is doubtful that these other factors are of prime significance for the majority of the marshes considered here, they could certainly be factors for any individual marsh, and could explain values of R_{eff} significantly different from +0.4 m.

In conclusion, the results of this analysis confirm the hypothesis that a response duality is displayed by offshore and onshore marsh vegetation subjected to a rising water level. Whereas the offshore marsh vegetation is directly responsive to the coincident persistent water level R_n, the onshore vegetation is responsive to an effective persistent water level R_{eff} that is less than R_n. However, the specific governing mechanisms responsible for this suboptimal rate of onshore colonization are not immediately obvious and could be expected to vary considerably from marsh region to marsh region.

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FIGURE CAPTIONS

Figure 1: Monthly mean water levels for the Lake Huron/Lake Michigan area throughout the time interval 1936 to 1985.

Figure 2: Simplified onshore/offshore geometric configuration of a linear shoreline marsh regime.

Figure 3: A plot of the calculated parameter $\log_e$ (predicted marsh area) $-\log_e$ (measured marsh area) versus the parameter $R_n \cot \beta$ for the Georgian Bay/North Channel marshes considered herein. As discussed in the text, the regression line is defined mathematically by the equation

$$P_{reg} = \exp \left[\log_e P_{max} - 0.0156\, R_n \cot \beta\right]$$

Table 1. Measured and mathematically predicted Georgian Bay/North Channel marsh areas (from Bukata and others, 1988(b))

Region	Geometry	Offshore slope angle α (degrees)	Onshore slope angle β (degrees)	Initial water level R_1(m)	Final water level R_2(m)	Measured initial area A_1(a)	Measured final area A_2(a)	Predicted final areas $P_{max(a)}$, $P_{min(a)}$
Echo Bay	Concave elliptical	0.0674;0.122	0.179;0.293	0.26	1.27	804	128	549, 0
Lake George (a)	Linear	0.220	1.22	0.26	1.27	508	42.6	111, 0
Lake George (b)	Linear	0.143	0.431	0.25	1.27	118	4.9	45.3, 0
Lake George (c)	Linear	0.220	3.67	0.25	1.27	100	8.4	7.4, 0
Opposite Shoal Island	Linear	0.472	3.67	0.26	1.27	19	1.3	3.0, 0
Bruce Mines	Concave	0.413	1.40	0.25	1.27	60	8.4	24.1, 0
Garden Bay	Concave	0.472	1.05	-0.06	1.27	28	3.3	26.5, 0
Hay Bay	Concave elliptical	0.330;0.330	0.489;1.72	-0.06	1.27	90	4.6	52.1, 0
MacBeth Bay	Concave elliptical	0.367;0.413	4.89;1.05	-0.06	1.27	52	11.2	17.5, 0
Sturgeon Bay (a)	Linear	0.330	1.22	-0.07	1.14	98	0	32.0, 7.8
Sturgeon Bay (b)	Concave	0.141	0.611	-0.07	1.14	146	44.5	73.1, 18.5
Hog Bay (a)	Linear	1.65	90.0*	-0.07	1.14	9	0	- , 0.7
Hog Bay (b)	Concave	0.661	0.815	-0.07	1.14	43	7.4	44.7, 4.0
Hog Bay (c)	Concave elliptical	0.234;0.669	1.22;1.05	-0.07	1.14	52	19.3	37.8, 6.5
Mile 386	Linear	0.472	90.0*	-0.06	1.14	14	1.5	- , 1.1
Sydney Bay	Concave elliptical	0.661;0.661	90.0;90.0*	-0.06	1.14	55	5.0	- , 4.9
Wingfield Basin	Concave	1.34	90.0*	-0.06	1.14	14	1.0	- , 1.3

*Rocky Shoreline (onshore slope angle β set equal to 90°).

Table 2. Comparison between measured and predicted marsh areas assuming partial onshore marsh vegetation colonization

Region	M (acres)	P_{max} (acres)	P_{reg} (acres)	P_{alg} (R_{eff}=+0.3 m) (acres)	P_{alg} (R_{eff}=+0.4 m) (acres)	P_{alg} (R_{eff}=+0.5 m) (acres)
Echo Bay	128.0	549.0	3.3	119.3	160.7	203.0
Lake George (a)	42.6	111.0	43.7	26.5	35.4	44.2
Lake George (b)	4.9	45.3	3.3	10.9	14.5	18.1
Lake George (c)	8.4	7.4	5.4	1.8	2.4	3.0
Opposite Shoal Island	1.3	3.0	2.2	0.7	1.0	1.2
Bruce Mines	8.4	24.1	10.7	5.6	7.5	9.4
Garden Bay	3.3	26.5	9.0	5.6	7.6	9.6
Hay Bay	4.6	52.1	11.7	11.9	15.9	20.0
MacBeth Bay	11.2	17.5	9.1	4.1	5.5	6.9
Sturgeon Bay (a)	0.0	32.0	13.9	15.0	17.1	19.2
Sturgeon Bay (b)	44.5	73.1	13.8	33.7	38.3	43.0
Hog Bay (a)	0.0	0.7	0.7	0.7	0.7	0.7
Hog Bay (b)	7.4	44.7	12.8	14.2	17.6	21.1
Hog Bay (c)	19.3	37.8	15.3	14.7	17.4	20.0
Mile 386	1.5	1.1	1.1	1.1	1.1	1.1
Sydney Bay	5.0	4.9	4.9	4.9	4.9	4.9
Wingfield Basin	1.0	1.3	1.3	1.3	1.3	1.3
Total area	291.4	1031.5	162.2	272.0	348.9	426.7
Percent of total M		+254.0	-44.3	-6.7	+19.7	+46.4
m		1.35	0.77	0.93	1.01	1.08
r^2		0.92	0.80	0.92	0.93	0.93

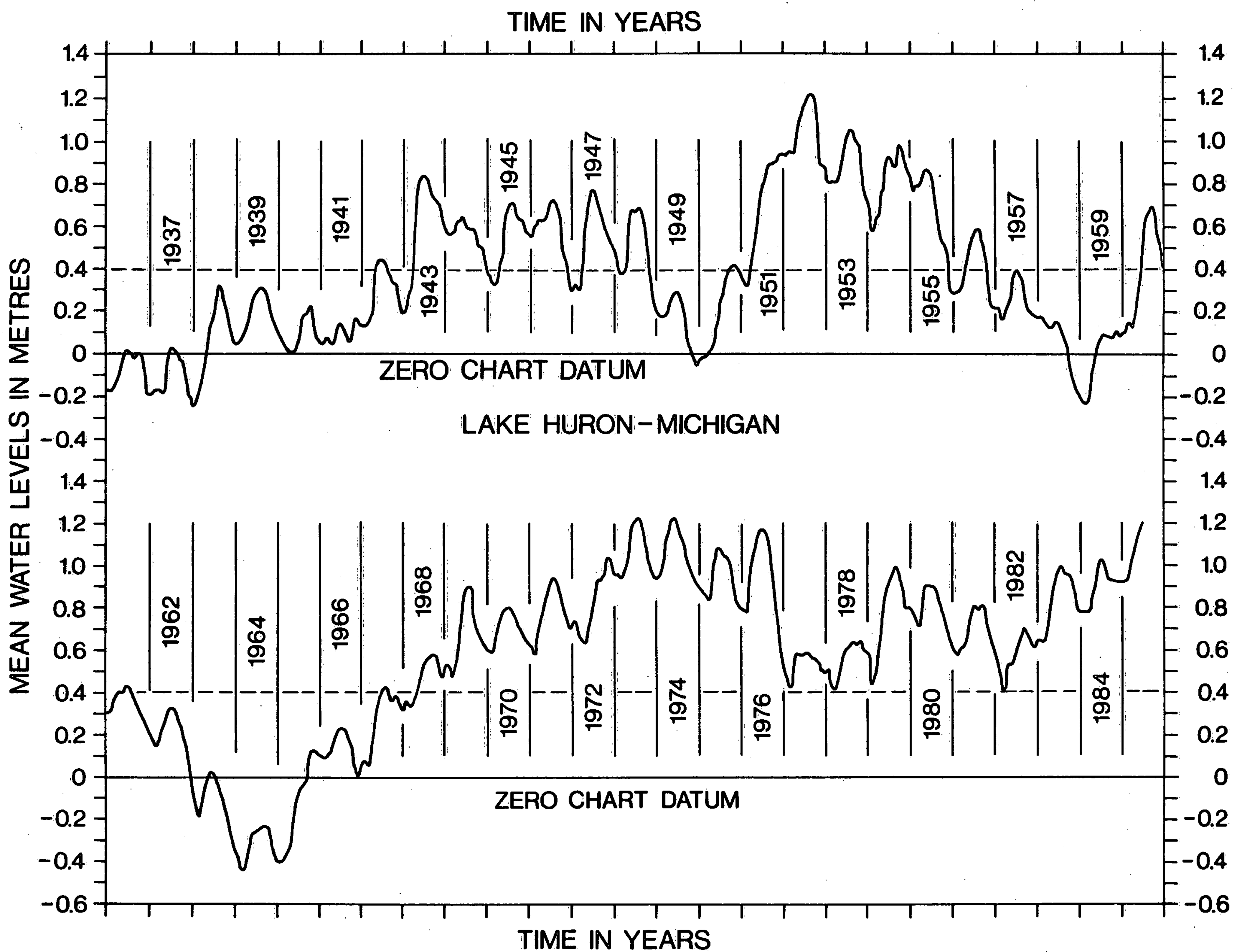
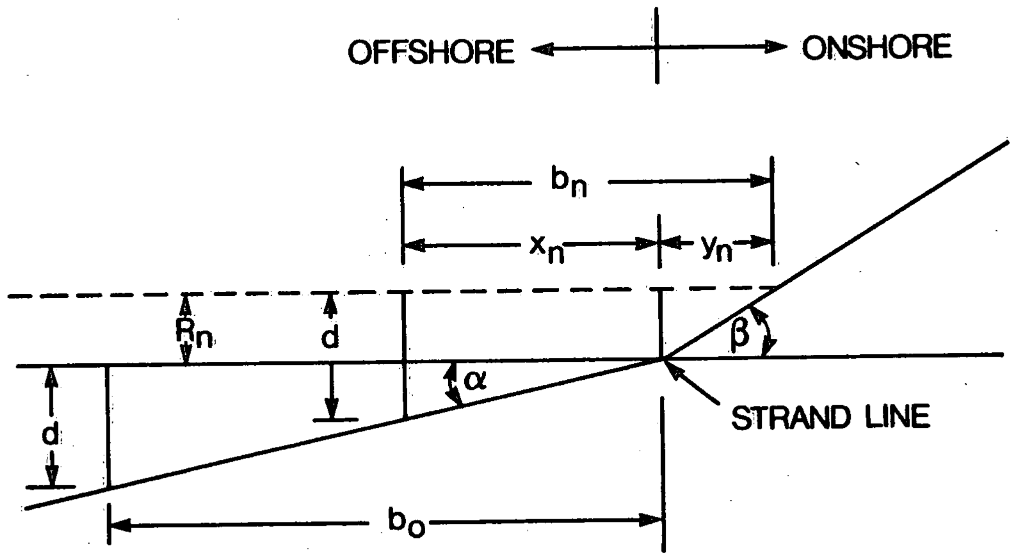

TIME IN YEARS
MEAN WATER LEVELS IN METRES
1937
1939
1941
1943
1945
1947
1949
1951
1953
1955
1957
1959
ZERO CHART DATUM
LAKE HURON-MICHIGAN
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
ZERO CHART DATUM
TIME IN YEARS

Figure 1



for $O \leq R_n \leq d$

$$b_n = x_n + y_n$$
$$= (d - R_n) \cot \alpha + R_n \cot \beta$$

Figure 2

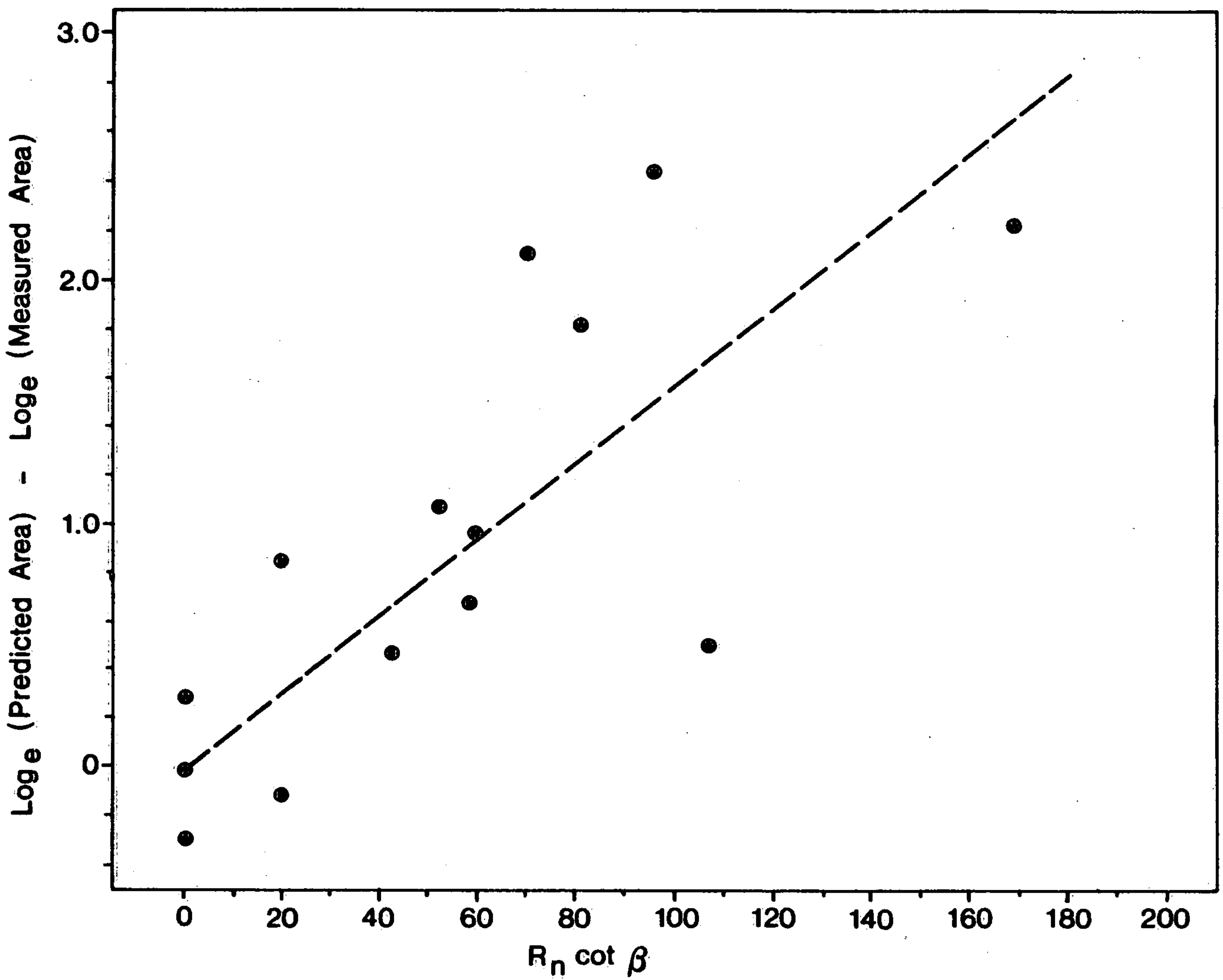

3.0
2.0
1.0
0
Log e (Predicted Area) - Loge (Measured Area)
0
20
40
60
80
100
120
140
160
180
200
R n cot β

Figure 3