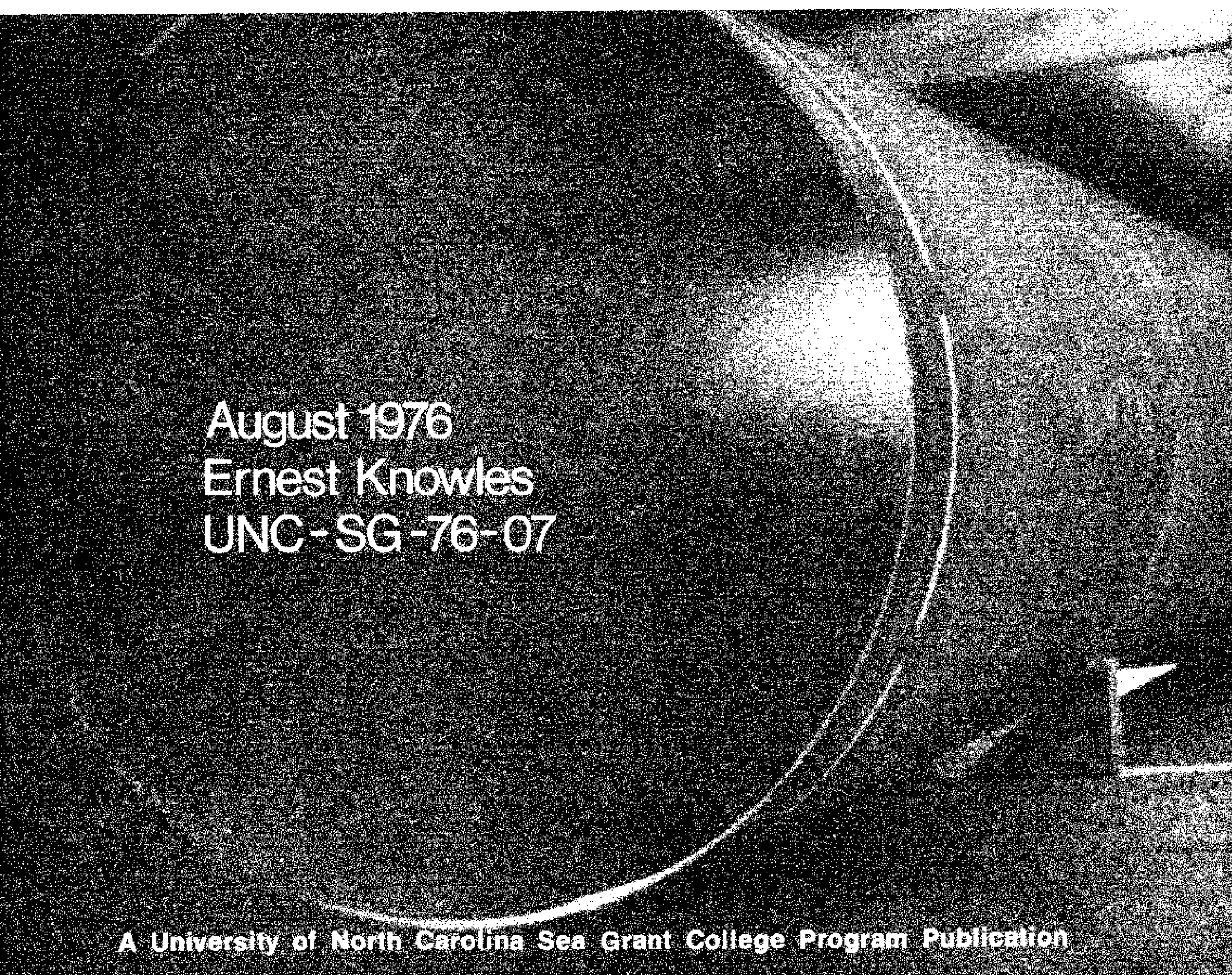
A Simple Diagnostic Model To Determine The Feasibility of Salinity Contol of Eurasian Watermilfoil



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Ernest Knowles

UNC-SG-76-07

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Errata to UNC-SG-76-07

Model I

1. After Eq. (22) should read

   "Conditions on (22):"

2. After Eq. (24) should read

   "From (17) $\Delta s = Q - \sigma$,"

3. After Eq. (28) should read

   "from (1) and (14), (28) becomes"

Model II

1. Q_T should be defined as

   "volume of water entering or leaving basin through inlet during one-half tidal cycle".

2. Eq. (42) should read

   "$\Gamma = Q_T + \gamma$,"

A SIMPLE DIAGNOSTIC MODEL TO DETERMINE THE FEASIBILITY OF SALINTIY CONTROL OF EURASIAN WATERMILFOIL

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INTRODUCTION

Eurasian Watermifoil is an exotic species of freshwater aquatic plant, rooted and submersed and growing primarily in quiet waters and as deep as sufficient light for photosynthetic activity penetrates. It forms a dense floating mat on the water surface and it is for this reason that its presence in inshore waters has become an ever increasing problem. Not only does watermilfoil hamper or effectively eliminate all forms of recreational use of the water area, it may also adversely affect the water quality as well. Wind waves (and their associated and critical vertical mixing) and wind set up (with its associated horizontal circulation) are both damped by milfoil. Indeed, it may make the normal horizontal circulation, usually present due to freshwater inflow and necessary for the flushing of the water body, to be so sluggish that anaerobic conditions develop.

There are several methods proposed for the control of Eurasian Watermilfoil, including the application of herbicides, the use of mechanical harvesting and the increase of salinity of the water body. It is with this last method that this paper is concerned.

The level of salinity required to use this method as a control mechanism is probably about one-half sea strength (Bailey and Haven, 1963). To raise the salinity level of even small bodies of water to that level by other than storm-induced overwash requires the movement (either by pumping or by cutting an inlet) of large amounts of seawater and either method is costly.

The two models developed here are deficient mainly in their assumption of non-stratified circulation, i.e., uniform salinity throughout the basin at any time τ or after any number of tidal cycles n. This is particularly true for large bodies of water, but if used to obtain initial cost/time estimates by policy-makers which can be compared with other alternatives, they can provide at least a good starting point for discussion. For instance, the models show that to achieve a basin salinity of one-half sea-strength, the freshwater inflow must always be considerably less than the salt water inflow. If it is near or greater than the salt water inflow, the basin will probably not reach the desired salinity in any finite time, e.g., in Back Bay, Virginia, the freshwater inflow is nearly five times greater than the saltwater pumping rate and after eight years the salinity had been raised to only about 8% of sea-strength.

Questions such as whether it is ecologically desirable to change the characteristics of a body from fresh to salt water are not addressed here (those are questions others in policy-making positions need to decide). Neither am I necessarily promoting the man-induced salinity control method over any others. The only purpose of these models are to provide a diagnostic tool that will help someone weight the cost/time benefits of this method; had someone done this in Back Bay then either a larger pump would have been used or no pumping at all would have been attempted.

SUMMARY AND CONCLUSIONS

The diagnostic models developed in this paper are simple and limited in application by some of their assumptions, but do provide valuable information in evaluating the method of salinity control of Eurasian Watermilfoil. They can be particularly valuable in estimating the amount of saltwater that would be needed to be introduced if the freshwater input is known, i.e., saltwater input must be greater than the freshwater input. As stated earlier, the pumping rate in Back Bay is about five orders of magnitude too small to achieve one-half sea-strength.

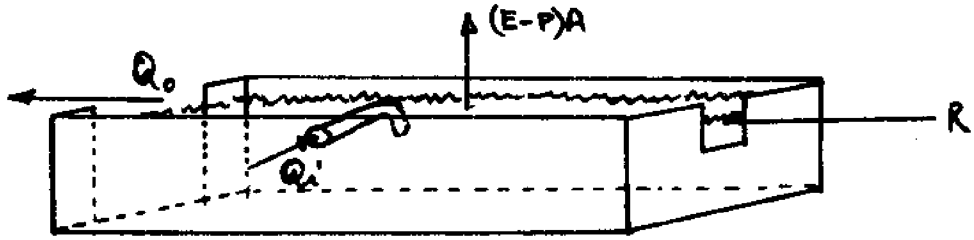
It is not clear whether these models underestimate or overestimate the time required to actually kill the milfoil (though the analysis for Back Bay indicates an underestimate in the time required to raise the salinity level). In some locales the more dense saltwater moving nearer the bottom may actually control the milfoil, before the whole basin's salinity level is raised, by killing the roots. The question of where on the plant the increased salinity actually does harm (i.e., roots, stem, etc.) is not clearly known and must be evaluated by aquatic biologists. If better estimates are needed of where the saltwater will go once introduced into the water body, then more sophisticated density-stratified circulation models must be used.

It is apparent from this analysis that cutting an inlet to control the salinity level of a basin may be unrealistic if keeping the level at a desired point is important. If, on the other hand, the decision is made to permanently change the basin from brackish to saltwater (i.e., as in case of Core Sound and Drum Inlet) the inlet may be the best salinity control alternative. Pumping is the most reliable "controlled" way to raise and then maintain the salinity level, but as can be seen by the cost analysis, the initial costs are very high.

MODEL DEVELOPMENT

Two models are developed below; the first assumes that saltwater is pumped into the basin, the second that an inlet is cut. Time, flow rate, and cost data are included for the application of both models to Currituck Sound.

I. Salinity control by pumping salt water into basin



Let:

Q_i	$\left[\frac{L^3}{T}\right]$	-	volume flux of seawater pumped into Basin
Q_o	$\left[\frac{L^3}{T}\right]$	-	volume flux of basin water leaving Basin
S_o	$[0/00]$	-	initial salinity of basin water
S	$[0/00]$	-	salinity of seawater
$\bar{S}(t)$	$[0/00]$	-	mean salinity of basin water at any time t
V	$[L^3]$	-	volume of basin
R	$\left[\frac{L^3}{T}\right]$	-	river runoff entering basin
$(E-P)\ A$	$\left[\frac{L^3}{T}\right]$	-	volume flux through surface
γ	$\left[\frac{L^3}{T}\right]$	-	R-(E-P)A (freshwater flux)

Assumptions

1. Volume of basin remains constant
2. Basin water mixes uniformly with seawater and freshwater, i.e, $\bar{S}(t)$ is uniform throughout basin at any time (t)
3. There are no tides in basin

Model Equations

<u>Conservation of Volume</u>

$$Q_o = \gamma + Q_i \tag{1}$$

<u>Salt Equation</u>

$$V \frac{d\bar{S}(t)}{dt} = Q_i S - Q_o \bar{S}(t) \tag{2}$$

<u>Initial Condition</u>

$@\ t = o$

$$\bar{S}(0) = S_o \tag{3}$$

<u>Problem Solution</u>

Eq. (2) can be rewritten

$$\frac{d\bar{S}(t)}{dt} + f\bar{S}(t) = r \tag{4}$$

and has solutions of form

$$\bar{S}(t) = rf^{-1} + ce^{-ft} \tag{5}$$

where

$$f = \frac{Q_o}{V} \tag{6}$$

$$r = \frac{Q_i}{V} S. \tag{7}$$

Using (3), (5) becomes

$$\bar{S}(t) = rf^{-1} - (rf^{-1} - S_o)\, e^{-ft} \tag{8}$$

The term f^{-1} is a time parameter, rf^{-1} a salinity parameter in (8). From (1), (6) becomes

$$f = \frac{\gamma + Q_i'}{V} = \frac{\Gamma}{V} \tag{9}$$

and

$$rf^{-1} = \frac{Q_i' S}{Q_i' + \gamma} = \frac{Q_i' S}{\Gamma} \tag{10}$$

Where $\Gamma = Q_i' + \gamma$. (11)

Eq. (8) is, therefore,

$$\bar{S}(t) = \frac{Q_i' S}{\Gamma} - \left[\frac{Q_i' S}{\Gamma} - S_o \right] e^{-ft} \tag{12}$$

or

$$\frac{\bar{S}(t)}{S} = \frac{Q_i'}{\Gamma} - \left[\frac{Q_i'}{\Gamma} - \frac{S_o}{S} \right] e^{-ft} \tag{13}$$

Let the <u>desired salinity ratio</u>

$$\frac{\bar{S}(t)}{S} \equiv \varphi \quad , \tag{14}$$

The <u>initial salinity ratio</u>

$$\frac{S_o}{S} \equiv \sigma \quad , \tag{15}$$

The <u>effective flow</u>

$$\frac{Q_i'}{\Gamma} \equiv Q, \tag{16}$$

and

$$\Delta S \equiv Q - \sigma. \tag{17}$$

Then (13) becomes

$$\varphi = Q - \Delta S e^{-ft} \tag{18}$$

or $e^{-ft} = \frac{1}{\Delta S}(Q - \varphi).$ (19)

Let

$$\Delta L \equiv Q - \varphi \tag{20}$$

then (19)

$$e^{-ft} = \frac{\Delta L}{\Delta S} \tag{21}$$

and at some future time τ, the non-dimensional time parameter

$$\tau f = \ln \left[\frac{\Delta S}{\Delta L}\right]. \tag{22}$$

Conditions on (20):

A. For $\tau > 0$, (22) must satisfy

$$\ln \left[\frac{\Delta S}{\Delta L}\right] > 0 \tag{23}$$

i.e. $\Delta L < \Delta S$ or

$\bar{S} > S_o$.

(a condition of the problem)

B. For argument of ln in (22)

$$\frac{\Delta S}{\Delta L} > 0. \tag{24}$$

From (18) $\Delta S = Q - \sigma$,

so if $\Delta S > 0$

then $Q > \sigma$,

also a condition of the problem.

Therefore,

$$\Delta L > 0 \tag{25}$$

or

$$Q = \frac{Q_i'}{Q_i' + \gamma} > \varphi. \tag{26}$$

If there is no γ, then Q = 1 so Q must fall within the limits

$$\varphi < Q < 1 \tag{27}$$

C. <u>Steady State Solution</u> to (2)

$$Q_i' S = Q_o \bar{S} \tag{28}$$

from (1) and (10), (28) becomes

$$Q = \frac{Q_i'}{Q_i' + \gamma} = \varphi, \tag{29}$$

i.e. as (26) and (29) show, the effective flow rate, Q, must always be greater than the steady state value to achieve φ in any finite time.

To get an explicit expression for τ for a given Q_i', (22) is written

$$\tau = f^{-1} \ln \left[\frac{Q - \sigma}{Q - \varphi} \right]. \tag{30}$$

Also, from (25)

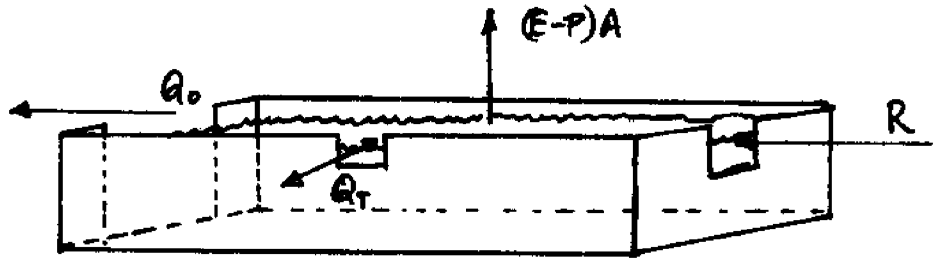
$$\frac{Q_i'}{Q_i' + \gamma} > \varphi$$

or

$$Q_i' > \gamma \left[\frac{\varphi}{1 - \varphi} \right]. \tag{31}$$

The conditional relationship between Q_i' & γ.

II. SALINITY CONTROL BY CUTTING INLET



Q_T $[L^3]$ - volume of water leaving basin during tidal cycle

Q_o $[L^3]$ - volume of water leaving basin during tidal cycle

S_o $[0/00]$ - initial salinityof basin water

S $[0/00]$ - salinity of seawater

$\bar{S}(n)$ $[0/00]$ - mean salinity of basin water after any number of tidal cycles

V $[L^3]$ - volume basin

R $[L^3]$ - volume of river runoff during tidal cycle

$(E-P)\ A [L^3]$ - evaporation flux during tidal cycle

A $[L^2]$ - surface area of basin

$n = \left[\frac{\tau}{T}\right]$ - number of tidal cycles

<u>Assumptions</u>

1. Volume of water in basin is constant
2. Over one tidal cyle, Q_o can be considered a sink for water with salinity $\bar{S}(n)$ when $\gamma > Q_o$, and a source when $\gamma < Q_o$.
3. During a flood tide, the basin water mixes uniformly with the seawater and freshwater; during an ebb tide it mixes uniformly only with the freshwater
4. Tidal flux through the inlet is equal during ebb and flood, i.e., there is no net volume flux over one tidal cycle

Conservation of volume (one tidal cycle)

$$Q_o = \gamma \tag{32}$$

Salt Equation (per tidal cycle)

$$\frac{dV\bar{S}(n)}{dn} = Q_T S - Q_T \bar{S}(n) - Q_o \bar{S}(n) \tag{33}$$

where any future time τ is given by:

$$\tau = nT, \tag{34}$$

and where n is an integer, n = 0, 1, 2, . . ., N representing the number of tidal cycles; T is the tidal period.

Initial Condition at $\tau = 0$, n = 0

$$\bar{S}(0) = S \tag{35}$$

Problem Solution:

$$V\frac{d\bar{S}(n)}{dn} + (Q_T + Q_o)\bar{S}(n) = Q_T S$$

or

$$\frac{d\bar{S}(n)}{dn} + f\bar{S}(n) = r, \tag{36}$$

which is identical in form with (4), except that (36) is a function of n rather than t, and f and r are defined as

$$f = \frac{Q_T + Q_o}{V}, \tag{37}$$

$$r = \frac{Q_T S}{V} \tag{38}$$

Using (35), (36) becomes

$$\bar{S}(n) = rf^{-1} - (rf^{-1} - S_o)\, e^{-fn}. \tag{39}$$

Mean salinity for basin after any number of tidal cycles, n.

Now, since (from (32))

$$Q_o = \gamma$$

$$\text{then} \quad f = \frac{Q_r + \gamma}{V} = \frac{\Gamma}{V}, \tag{40}$$

and

$$rf^{-1} = \frac{Q_r S}{\Gamma}, \tag{41}$$

where

$$\Gamma = Q + \gamma, \tag{42}$$

and (39) becomes

$$\varphi = Q - \Delta S e^{-fn}$$

or

$$e^{-fn} = \frac{\Delta L}{\Delta S}, \tag{43}$$

where φ, σ, ΔS and ΔL are given by (14), (15), (17) and (20) respectively, but where

$$Q \equiv \frac{Q_T}{\Gamma}. \tag{44}$$

Now at some future number of tidal cycles, n,

$$fn = \ln \left[\frac{\Delta S}{\Delta L}\right]. \tag{45}$$

Eqs. (45) and (22) are identical in form so the conditions (23), (24), (26) and (27) are satisfied for this model also.

The steady state solution to (33) is

$$Q_T S = Q_T \bar{S} + Q_o \bar{S} \tag{46}$$

and from (32)

$$Q_T S = \bar{S}(Q_T + \gamma) = \bar{S}\Gamma$$

so

$$Q = \frac{Q_T}{\Gamma} = \varphi . \tag{47}$$

Effective flow through inlet to maintain φ once it is achieved must always be greater than the steady state value to arrive at φ in finite time.

$\therefore$ analogous to (22)

$$nf = \ln \left[\frac{Q - \sigma}{Q - \varphi}\right] . \tag{48}$$

For the explicit n, expressions analogous to (30), and (31) are

$$n = f^{-1} \ln \left[\frac{\Delta S}{\Delta L}\right] \tag{49}$$

and

$$Q_T > \gamma\left[\frac{\varphi}{1-\varphi}\right] \tag{50}$$

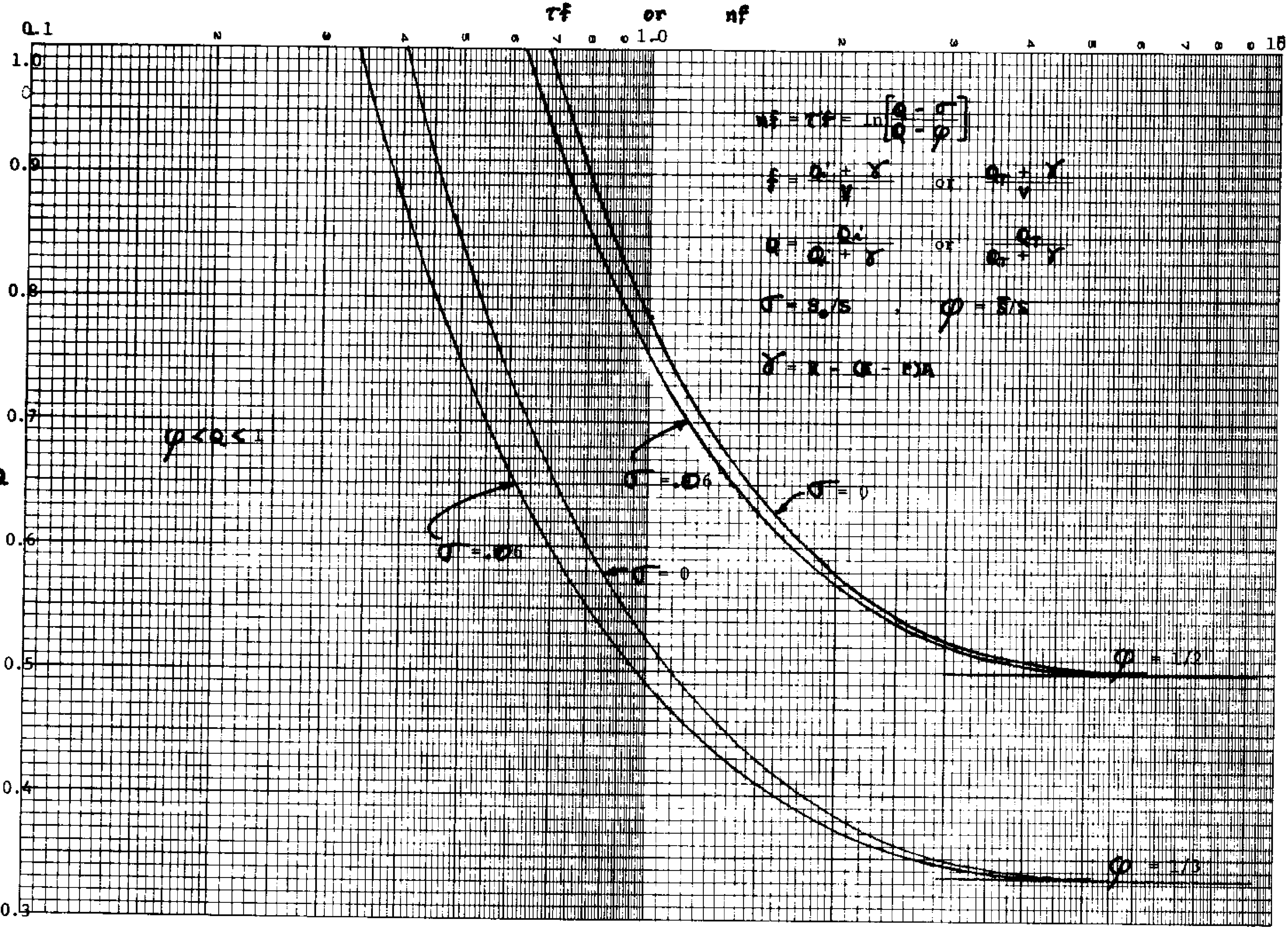
where $\dfrac{\Delta S}{\Delta L}$ in (49) is given by

$$\frac{\Delta S}{\Delta L} = \frac{Q_T(1-\sigma) - \sigma\gamma}{Q_T(1-\varphi) - \varphi\gamma} \tag{51}$$

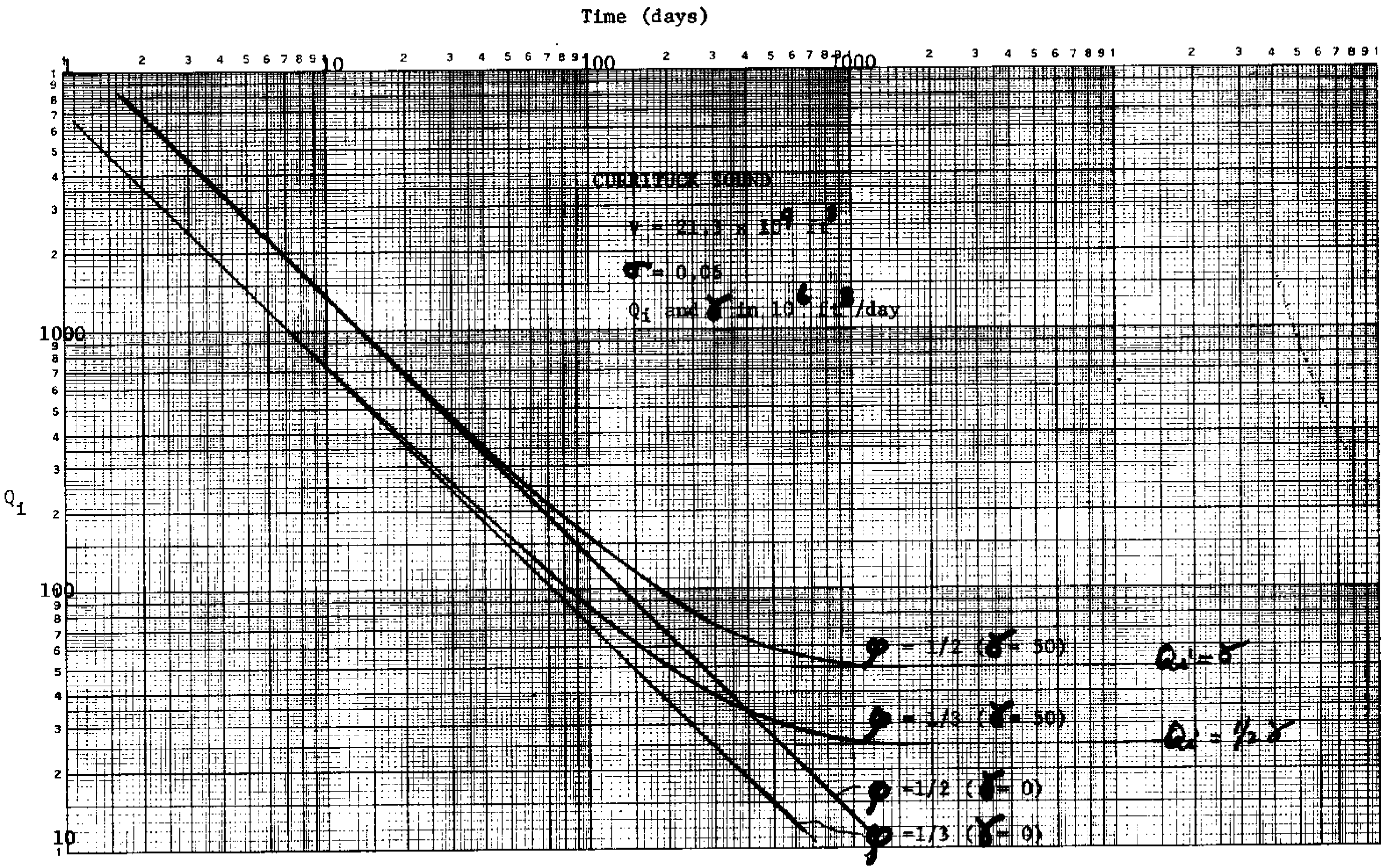
$\therefore$ The non-dimensional curves of (22) and (48) are identical in shape and can be used for either model as long as the definitions of of the various parameters for each model are kept in mind.

Figure 1. Non-dimensional curves of effective flow, Q, versus time parameters f and nf.

Figure 2. Time versus saltwater pumping rate, Q_1, for Currituck Sound.



τf or nf
Q
0.1
1.0
10
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
φ < Q < 1
σ = .06
σ = 0
σ = .06
σ = 0
φ = 1/2
φ = 1/3
σ = S₀/S


Time (days)
Q_1
CURRITUCK SOUND
V = 21.3 x 10⁹ ft³
σ = 0.05
Q_i and γ in 10⁶ ft³/day
φ = 1/2 (γ = 50)
φ = 1/3 (γ = 50)
φ = 1/2 (γ = 0)
φ = 1/3 (γ = 0)
Q_i = γ
Q_i = ½ γ

Model Test - Back Bay

Data Source: γ U.S. GEOLOGICAL SURVEY, Dec. 1970
Q_i, φ NER ENVIRONMENTAL IMPACT STATEMENT, April 1974
V, A BACK BAY - CURRITUCK SOUND DATA RPT(3) May 1966

$$\left.\begin{array}{l} R = 9.94 \times 10^6 \text{ ft}^3/d \\ (E-P)A = -1.1 \times 10^6 \text{ ft}^3/d \end{array}\right\} \quad \gamma = R-(E-P)A = 11 \times 10^6 \text{ ft}^3/d$$

$V = 3.87 \times 10^9 \text{ ft}^3$
$Q_1 = 2 \times 10^6 \text{ ft}^3/d$
$\sigma = 0$

$$\left.\begin{array}{l} f = \frac{Q_i}{V} = .52 \times 10^{-3} d^{-1} \\ t = 8 \text{ yrs} = 2.92 \times 10^3 d \end{array}\right\} \quad tf = 1.51$$

$e^{-ft} = .221$

$$Q = \frac{Q_i}{Q_i + \gamma} \quad ; \quad \Delta S = Q - \sigma = Q$$

From equation (18)

$$\varphi = Q - \Delta S e^{-ft} = Q(1 - e^{-ft})$$

$$\varphi = .15(1 - .221) = .15(.779)$$

$$\varphi = .12$$

$\varphi = .08$ Actual salinity ratio

The actual value is 33% less than the predicted, i.e., the model underestimates the time required to achieve any desired salinity or overestimates the salinity after any given time. This discrepancy is most certainly due to the assumptions used, primarily the non-stratified condition, but it may be due to the freshwater inflow as well. The freshwater inflow, R, is an estimate based on 1 ft^3/sec per sq. mi for the drainage area and (E-P)A a net gain of 4 inches of precipitation (P) over evaporation (E) over the water surface area of Back Bay. They are based on annual averages and may not be constant from year to year.

Cost and Performance Figures for Currituck Sound

I. PUMP

	$(\times 10^6)$
Pump and installation	\$5 ea.
Pipe	\$4 per mi.
Operation and maintenance	\$2100 per 12×10^6 ft^3/day

Pumping Rate 3.5 to 190 $\times 10^6$ ft^3/day

75% capacity = 145 $\times 10^6$ ft^3/day

Operation and maintenance @ 75% = \$25,200/day

Operation and maintenance @ γ = \$ 8,750/day

II. INLET

Dredging Costs	\$1/yd^3 of sand moved
Rocking	\$12/yd^3 of rock used

Cost Analysis - Currituck Sound

$V = 21.3 \times 10^9\ ft^3$ $\qquad \varphi = 1/2$ $\qquad \gamma = 50 \times 10^6 ft^3/d$

I. PUMPING

$Q_i = 145 \times 10^6\ ft^3/d$ (75% capacity of pump)

$Q = \frac{145}{195} = .743$; $\qquad f^{-1} = \frac{21.3x10^9}{.195x10^9} = 109$

From non-dimensional curve (Figure 1) for Q value:

$\tau f = 1.03$

$\tau = 109(1.03) = 112$ days to attain $\varphi = 1/2$

1st year and initial costs	$(x10^6)$
1 pump @ \$5	\$5
2 mi. pipe @ \$4/mi.	\$8
Op. & Maint. for 112 days @\$25,200/d	\$2.8
Op. & Maint. for 253 days @\$8,750/d (where $Q_i = \gamma$)	\$2.2
	\$18

Other years

Op. & Maint. for 365 days @\$8,750/d \$3.2

II. INLET

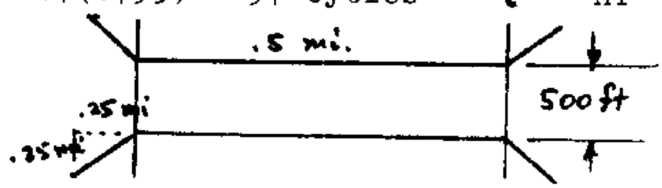
$\gamma = 25 \times 10^6\ ft^3/12$ hrs.
$Q_T = 150 \times 10^6\ ft^3/6$ hrs (1/2 Drum Inlet rate)
$A_c = 3000\ ft^2$ (500 ft wide)
$h = 6$ ft

$Q = .857$; $\qquad f^{-1} = 121.7$

From nondimensional curve (Figure 1) for Q value:

$nf = .795$

$n = 121.7(.795) = 97$ cycles $\qquad \tau = nT = 97(12) = 48.5$ days



Total volume sand to be dredged (3 yds deep) = $2 \times 10^6\ yd^3$
Total volume rock to be placed (1 yd thick) = $.68 \times 10^6\ yd^3$

	$(x10^6)$
Dredging costs @ \$1/yd³ sand	\$2
Rocking costs @ \$12/yd³ rock	\$8.2
	\$10.2

Would have to narrow width to about 170 ft to maintain $\varphi = 1/2$, i.e., $Q_T = \gamma$.

REFERENCES

Bailey, Robert S. and Dexter S. Haven. Milfoil, a frilly weed that ruins your sport. Virginia Wildlife, 3 pp., March 1963.

Acknowledgements

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