Eutrophication Analysis of Embayments in Prince William Sound, Alaska

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Abstract: Fertilizers were used in the summer of 1989 to accelerate bacterial growth in a bioremediation effort to clean up the beaches following the EXXON *Valdez* oil spill. Mathematical models were used to quantify the eutrophication potential in two selected embayments in Prince William Sound: Passage Cove and Snug Harbor. First, mass transport in these two embayments was determined. Next, eutrophication models were developed for these two embayments to simulate the seasonal algal concentrations prior to fertilizer application. Finally, a series of nutrient-loading scenarios based on different fertilizer and other chemical application rates were developed to investigate the impact. Model results and the data available indicated that the rapid exchange between embayments and the open water limits algal growth and buildup of concentrations of other chemicals applied to beaches. The exception is the potential for some ammonia toxicity at high application rates. Despite the limited data available it is clear that no significant increased algal growth would be expected following fertilizer application.

INTRODUCTION

The EPA bioremediation program to investigate cleaning up the contaminated beaches following the EXXON *Valdez* oil spill involved a field demonstration project conducted to determine whether nutrient addition to contaminated beaches would stimulate hydrocarbon breakdown by indigenous bacteria (McCutcheon 1989). One of the concerns associated with nutrient application was whether the added nutrients would cause excessive algal growth during the growing season in the embayments where the study was conducted. The concern was raised by the federal and state agencies on the Shoreline Committee during the planning of the bioremediation experiments and later when EXXON proposed to apply nutrients on a wide scale. Another concern was whether there would be an adverse long-term quality impact after the fertilizer application was completed and discontinued.

Because of limited data in the study area, a modeling approach was chosen to address these questions by simulating the eutrophication potential. Two embayments in Knight Island: Passage Cove and Snug Harbor (Fig. 1) were modeled. The modeling analysis consists of first determining the mass transport in these two systems using measured salinity. The mass-transport patterns developed were then incorporated into the eutrophication models of Passage Cove and Snug Harbor. Model sensitivity analyses were performed to better quantify the algal biomass levels and productivity rates, and also serve as important checkpoints for the model calculations. The eutrophication models were then used to evaluate the short-term and long-term impacts of fertilizer application. The model results were intended to quantify the incremental impact of nutrient applications on eutrophication. They

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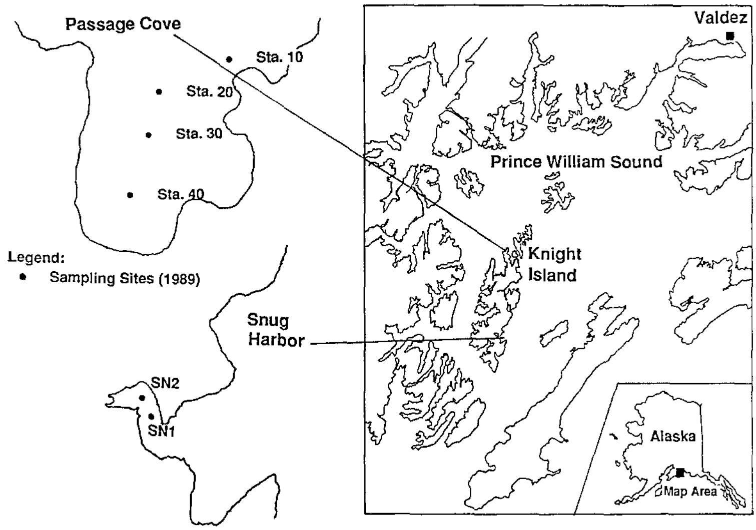


FIG. 1. Passage Cove and Snug Harbor, Knight Island, Prince William Sound

should not be viewed as actual predictions for algal biomass levels in the embayments.

STUDY AREA

Snug Harbor is located on the southeastern side of Knight Island (Fig. 1). Major sources of freshwater runoff are from precipitation and snowmelt, which is typical of islands in Prince William Sound. Although some shorelines in Snug Harbor were heavily contaminated with oil, it appeared that little oil was being released to the water, thus minimizing the prospect of reoiling on the beaches chosen for treatment and reference plots. In the bioremediation project, the moderately oiled beaches of Snug Harbor were selected to serve as a beach on which the degree of contamination was that expected to be found after a heavily oiled beach had been physically washed.

A second site chosen for treatment was Passage Cove, which is located just northwest of the northern tip of Knight Island (Fig. 1). Even after physical washing with hot water, considerable amounts of oil remained at this site, mostly spread uniformly over the surface of rocks and in the beach material below the rocks.

MODELING APPROACH

Simulation of phytoplankton growth in an estuarine or a coastal system is complicated by many factors. A number of biochemical, biological, and chemical processes interact and the reaction rates vary with time. In addition, the freshwater flow and associated circulation and mass-transport patterns also are functions of time, with time scales ranging from minutes to weeks. External inputs (forcing functions) and other parameters further complicate the time-variable nature of a phytoplankton population in an estuarine system. In general, phytoplankton modeling analyses for estuarine systems may employ time-variable calculations in either real-time (intratidal) or tidally averaged, time-variable mode. Time-variable phytoplankton modeling is resource demanding and computationally intensive, often resulting in complex models. In addition, the amount of data required to calibrate and verify a real-time model is formidable. Data on hour-to-hour changes in tidal stage, velocity, freshwater inflow, and nutrient loads must be available for model calibration.

In many northern systems like the Prince William Sound, phytoplankton growth is a seasonal event. Thus, approximations of the phytoplankton-nutrient dynamics on a seasonal steady-state basis are quite appropriate. The approximation is particularly valid for the Alaskan study area under a summer-low, steady-flow condition. In addition, steady-state approximations have a modest data requirement and provide a significant amount of insight into eutrophication in the system to support decision making.

To assess the eutrophication potential in Snug Harbor and Passage Cove under seasonal steady-state conditions, the modeling framework EUTRO4 (Ambrose et al. 1988) was adapted for these two systems. Site-specific information on mass transport, kinetics, and loading rates was employed to support the calculations. In addition, limited chlorophyll *a* and nutrient data collected in the open water of these two systems were utilized to evaluate the model applications.

DATA ANALYSIS

Freshwater runoff from small streams into the embayments could only be estimated. On a seasonal average basis, the freshwater flows from the watersheds were estimated to be about 0.9 m^3/s (30 cfs) and 2.8 m^3/s (100 cfs) in the Passage Cove and Snug Harbor, respectively. These estimates were based on one or two observations of the approximate surface velocities and on crude estimates of cross-sectional areas of the major streams. The freshwater flows to these two embayments are primarily from snowmelt runoffs. Meteorological data from the study area were used to develop the light intensity and photoperiod for modeling use.

National Oceanic and Atmospheric Administration (NOAA) navigation charts for Knight Island were examined to calculate average depth, volume, and surface area of the two embayments. Hydrodynamic information such as tidal range near Passage Cove was obtained from tide measurements collected in August 1989 (SAIC, unpublished report, 1989). Tidal ranges for other periods in Passage Cove and for Snug Harbor were obtained from locally published fisherman's guides and NOAA (*Tide Tables* 1989) reports for Cordova, just outside Prince William Sound. Corrections for amplitude and delay in tide arrival at Passage Cove and Snug Harbor were available in the fisherman's guide and NOAA reports. Maximum tidal fluctuation reaches 4.57 m (15 ft) in the two embayments.

A number of water-quality surveys were conducted in Passage Cove and Snug Harbor during the bioremediation study in 1989. Fig. 2 shows the vertical profiles of temperature, pH, salinity, and dissolved oxygen in Passage Cove measured on July 18, 1989. A similar summary for Snug Harbor is presented in Fig. 3. The temperature and salinity profiles indicate that the water column is partially mixed in both embayments. Higher temperatures and lower salinity levels in the surface layers (up to 10 m deep) are due to the freshwater inflows. pH levels show little vertical variation. Dissolved oxygen profiles show progressive increase from the surface to the thermocline, probably due to decreased temperature. Below the thermo-

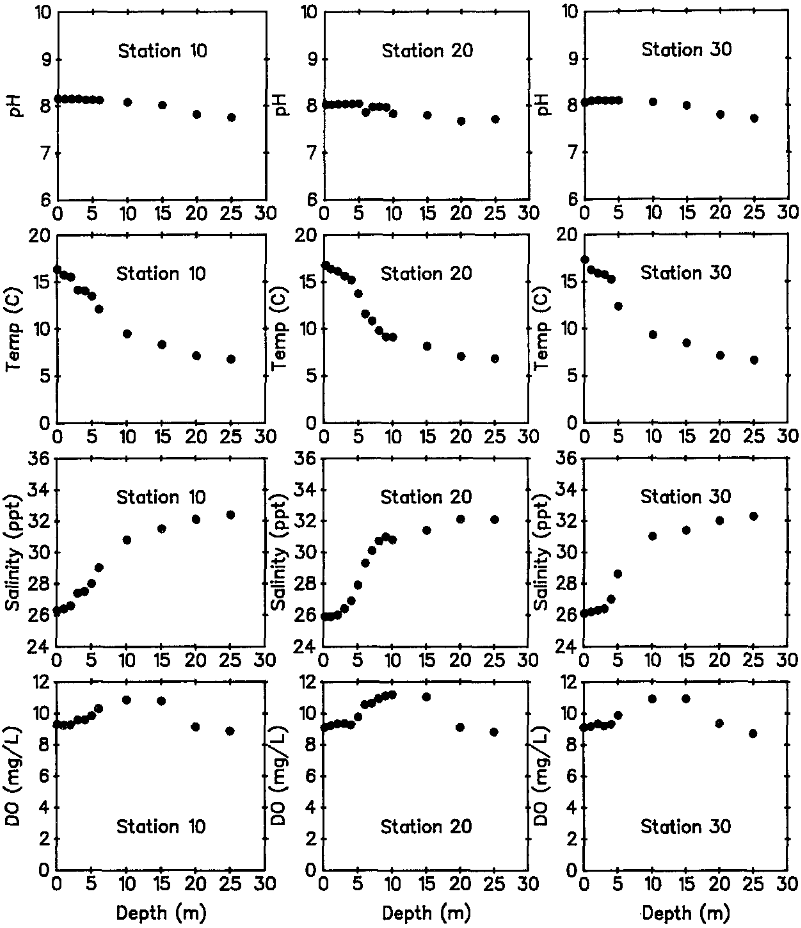


FIG. 2. Measured pH, Temperature, Salinity, and Dissolved Oxygen in Passage Cove, July 18, 1989

cline, bacterial and algal respiration and biomass decomposition reduce the dissolved oxygen concentration in the water column (Figs. 2 and 3).

Chlorophyll *a* concentrations measured in the summer of 1989 in the surface waters of Passage Cove and Snug Harbor range from less than 1 μg/L to slightly over 2 μg/L (Pritchard et al. 1989) with the maximum values being observed immediately following the fertilizer application. These chlorophyll *a* levels are considered to be insignificant from the standpoint of eutrophication (Mills et al. 1985; Vollenweider and Kerekes 1981). Algal productivity rates observed during the same period in these two systems are below 1.0 mg C/m^3/hr prior to the treatment and up to 3.0 mg C/m^3/hr after the treatment (Pritchard et al. 1989). These are relatively low productivity rates, another indication of insignificant eutrophication.

Only limited data are available from analyses of water samples from Passage Cove for ammonia, nitrite, nitrate, and phosphorus. A review of the nutrient data in the study area suggests nitrogen limitation for algal

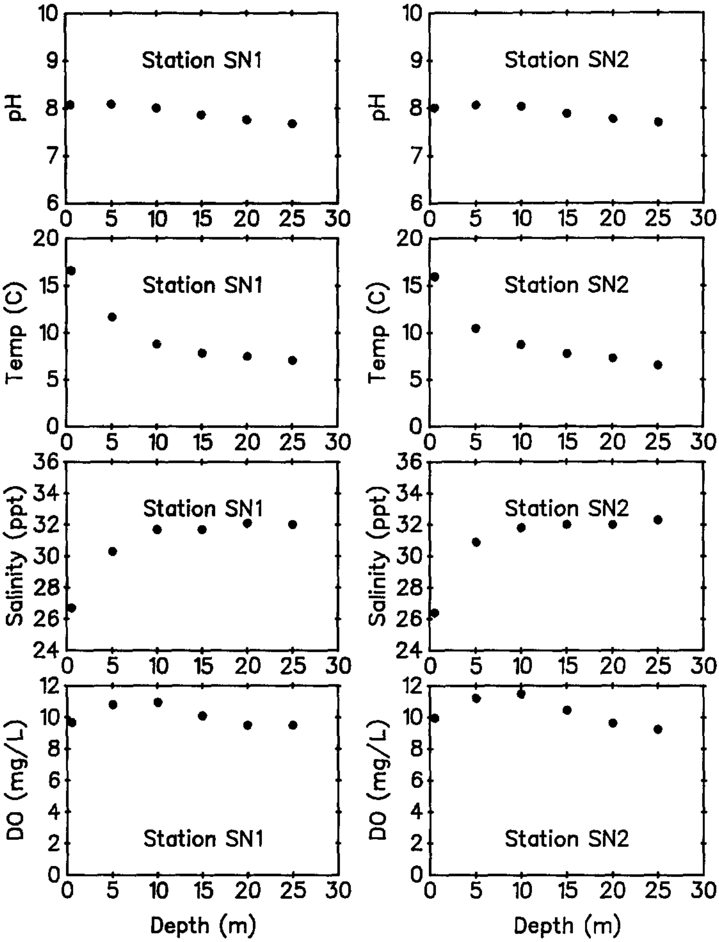


FIG. 3. Measured pH, Temperature, Salinity, and Dissolved Oxygen in Snug Harbor, July 11, 1989

growth in both embayments, which is consistent with the general observation that many coastal waters are nitrogen limited. Nitrate concentrations are about 0.012–0.025 mg/L; orthophosphate concentrations range 0.009–0.012 mg/L.

Preliminary Mixing Analysis

Mixing and circulation play a major role in determining the eutrophication potential of these small embayments. Flushing time and residence time of a conservative substance are good indicators of how long a contaminant would remain in the embayment. Two methods were utilized to determine the flushing times: the fraction of freshwater and the tidal prism methods (Dyer 1973). Table 1 presents the results using these two methods to calculate the flushing time in Passage Cove and Snug Harbor. Based on the small freshwater inflows, the flushing times are long (slow flushing rates). On the other hand, strong tides provide efficient mixing, resulting in very

TABLE 1. Flushing Time Calculation for Passage Cove and Snug Harbor

Parameter (1)	Passage Cove (2)	Snug Harbor (3)
Tidally averaged volume (m^3)	4.017×10^6	143.421×10^6
Tidal range (m)	4.57	4.57
Surface area (m^2)	0.188×10^6	5.961×10^6
Tidal prism (m^3)	0.860×10^6	27.263×10^6
Low tide volume (m^3)	3.586×10^6	129.790×10^6
Freshwater flow (m^3/tidal cycle)[a]	38,379.6	127,932.8
Open-sea salinity, S_i (ppt)	32.3	32.3
Salinity in embayment, S (ppt)	30.0	30.0
Flushing time (tidal cycles):[a]		
fraction of freshwater method	108.7	8,974
tidal prism method	1.72	5.76

[a]1 tidal cycle = 12.54 hr.

short flushing times (about two to five tidal cycles). It should be pointed out that the salinity in Figs. 2 and 3 suggest incomplete mixing. Thus, the results in Table 1 serve as a bounding analysis for mixing in these two coastal systems. It is expected that the actual mixing falls between these bounds and must be estimated using a more rigorous analysis.

MODELING MASS TRANSPORT AND MIXING

The methodology developed by Lung and O'Connor (1984) and Lung (1986) was used to calculate the two-layer mass transport in the two embayments. First, vertical profiles of tidally averaged longitudinal velocities were calculated based on the two-dimensional salinity distributions (Figs. 2 and 3). Next, mass-transport coefficients such as longitudinal and vertical advective flows and vertical dispersion coefficients were determined. These values were then incorporated into a two-layer salinity model (with four segments all together). Fig. 4 shows the mass-transport coefficients in a four-segment configuration for Passage Cove and Snug Harbor. Note that the freshwater flow rates are small compared with the two-layer flows.

The average salinity calculated for each segment is compared with the measured salinity (derived from Figs. 2 and 3). Subsequent model sensitivity analysis through iterations of this procedure fine-tuned the mass-transport coefficients to match the measured salinity data (Table 2). Based on the mass-transport coefficients (advective and dispersive flows) in this four-segment model, the flushing times in these two systems were calculated to be 5.6 and 28.4 tidal cycles for Passage Cove and Snug Harbor, respectively. The flushing times are slightly longer than those determined by the tidal prism method but substantially shorter than those determined solely by freshwater dilution (see Table 1). In summary, the flushing times for both embayments are relatively short, resulting from the tidal actions.

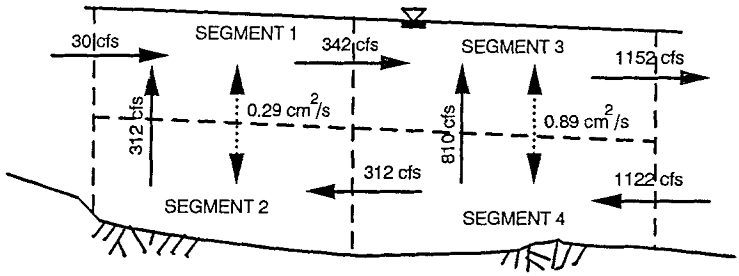
EUTROPHICATION ANALYSIS USING EUTRO4

Modeling Framework

The EUTRO4 model, which is distributed and supported by EPA's Center for Exposure Assessment Modeling in Athens, Ga., was used in this analysis (Ambrose et al. 1988). EUTRO4 has been used in a wide range of regulatory

PASSAGE COVE

SEG. NO.	1	2	3	4
DEPTH (m)	9.10	9.10	10.7	10.7
VOL. (10^6 m^3)	0.87	0.87	1.18	1.18



SNUG HARBOR

SEG. NO.	1	2	3	4
DEPTH (m)	10.0	11.0	10.0	36.0
VOL. (10^6 m^3)	3.21	7.20	16.2	116.8

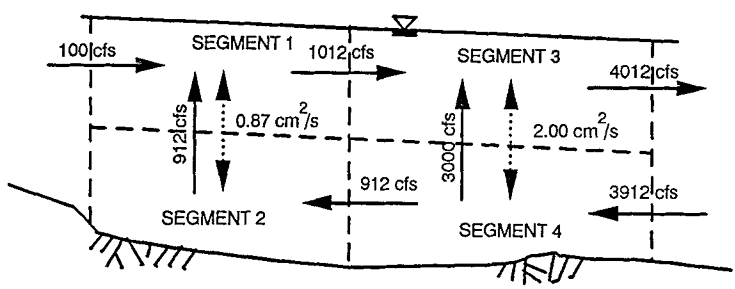


FIG. 4. Two-Layer Mass Transport in Passage Cove and Snug Harbor

applications by EPA and many model applications of eutrophication analysis have been reported (Thomann and Fitzpatrick 1982; Lung and Paerl 1988; Lung 1990). The program simulates the transport and transformation of up to eight water-quality constituents associated with eutrophication in the water column and sediment bed, including carbonaceous biochemical oxygen demand, phytoplankton carbon and chlorophyll *a*, ammonia, nitrate, organic nitrogen, organic phosphorus, orthophosphate, and dissolved oxygen. Algal growth is subject to nutrient and light limitations. EUTRO4 calculates time-variable concentrations for every segment in a specialized

TABLE 2. Mass Transport Calculation for Passage Cove and Snug Harbor

Model segment (1)	Calculated salinity (ppt) (2)	Measured salinity (ppt) (3)	Calculated residence time (tidal cycles) (4)
	(*a*) Passage Cove		
Segment 1	29.47	28.75(26.01–30.76)[a]	1.93
Segment 2	32.29	32.01(30.80–32.33)[a]	2.12
Segment 3	31.46	29.79(26.00–30.45)[a]	0.78
Segment 4	32.30	32.12(30.80–32.40)[a]	0.80
Total	—	—	5.63
	(*b*) Snug Harbor		
Segment 1	29.07	29.75(26.75–31.33)[a]	2.26
Segment 2	32.20	32.04(32.00–32.32)[a]	5.57
Segment 3	31.50	—	2.45
Segment 4	32.26	—	18.07
Total	—	—	28.35

[a]Range.

TABLE 3. Kinetic Coefficients for Passage Cove and Snug Harbor

Parameter (1)	Unit (2)	Value (3)
Algal saturation growth rate (20°C)	day^{-1}	2.0
Temperature coefficient, θ	—	1.06
Optimum light intensity	langley/day	350
Light extinction coefficient	m^{-1}	0.2
Algal respiration rate (20°C)	day^{-1}	0.125
Temperature coefficient, θ	—	1.045
Algal death rate (20°C)	day^{-1}	0.02
Algal settling velocity	m/day	1.0
Michaelis constant (*P*)	μg/L	1.0
Michaelis constant (*N*)	μg/L	25.0
Carbon/chlorophyll *a*	mgC/mg Chl *a*	50.0
Organic N hydrolysis rate (20°C)	day^{-1}	0.075
Temperature coefficient, θ	—	1.08
Organic P mineralization rate (20°C)	day^{-1}	0.22
Temperature coefficient, θ	—	1.08

network that may include surface water, underlying water, surface bed, and underlying bed. Variable concentrations are reported at user-specified time intervals, along with calculated transformation and transfer rates.

Application of EUTRO4 to Passage Cove and Snug Harbor

EUTRO4 was adapted to the two embayments with site-specific data (such as the mass-transport coefficients developed and described in the preceding section) to simulate the seasonal steady-state water quality in the systems. Most kinetic coefficients for algal nutrient dynamics and nutrient recycling were derived from values reported for estuaries and embayments with similar characteristics and are listed in Table 3. A review of the literature did not yield any applicable studies in Prince William Sound. Environmental conditions such as light intensity, water temperature, photoperiod, and light extinction coefficient were estimated for the study area. Boundary conditions for algal biomass and nutrients were developed from data collected from ambient waters in Prince William Sound.

The calculated seasonal algal chlorophyll *a* concentrations and algal production rates in the surface layer of Passage Cove and Snug Harbor are shown in Table 4 along with measured values. Table 4 indicates that model results match the measured algal chlorophyll *a* concentrations and algal productivity rates very well.

Model Sensitivity Analyses

Model predictions using the EUTRO4 models for Passage Cove and Snug Harbor have uncertainty associated with some coefficients that affect algal growth. In the modeling analysis, literature values for these coefficients were used due to limited site-specific data. An analysis was performed to identify the key parameters and coefficients that have the greatest impact on model predictions in terms of algal biomass and algal productivity rate. The four parameters were identified—residence time, maximum algal growth rate, algal endogenous respiration rate, and light extinction coefficient.

The approaches whereby the residence times were computed are well established and are based on independent measurements, such as the amplitude of the tidal current and measured salinity and temperature profiles. However, other supporting data on which the estimates were based were limited, resulting in some uncertainty in the residence time estimates. In addition, localized differences in flows could result in differences in residence times from the computed average values. Advective flow rates (affecting mass transport) and resulting residence times were varied over a wide range for the models to compute the corresponding algal chlorophyll *a* concentrations and productivity rates. Results of this analysis are presented in Fig. 5. The analysis indicates that errors or localized differences in the computed residence time could have significant impacts on estimated algal chlorophyll *a* concentrations and productivity rates. It should be stressed that such a wide range of residence times illustrated is not considered reasonable for the water column as a whole. Unreasonable values of water-column–averaged residence times would not only result in unreasonable values of algal populations for the base case, prior to fertilizer addition, but would also result in unreasonable temperature and salinity predictions. In

TABLE 4. Model Calculation (Surface Layer) versus Field Data

Parameter (1)	Passage Cove (2)	Snug Harbor (3)
Chlorophyll *a* (μg/L):		
model	0.84–1.13	1.09–1.12
measured[a]	0.70–0.90	0.90–1.10
Productivity rate (mg C/m^3/hr):		
model	1.07–1.50	1.36–1.38
measured[a]	1.00–2.50	0.20–1.40

[a]Pritchard et al. (1989)

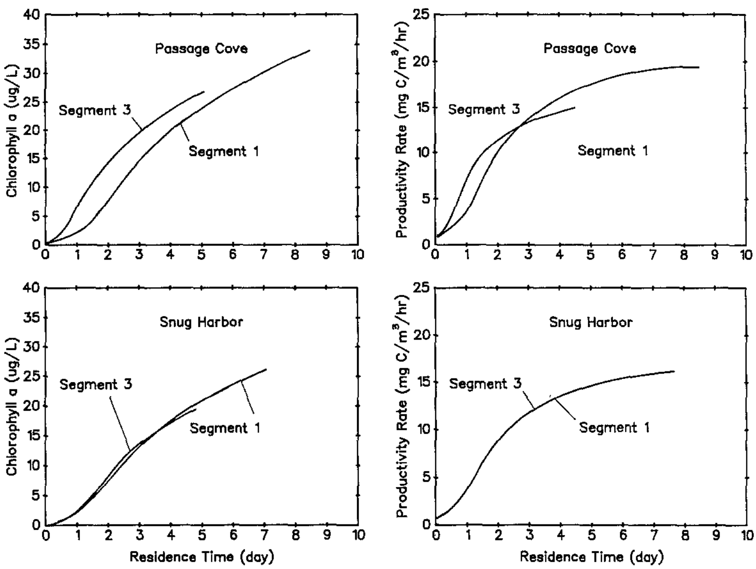


FIG. 5. Effect of Residence Time on Chlorophyll *a* Concentration and Productivity Rate in Surface Layer

fact, average residence times computed for the inner and outer portions of Passage Cove and Snug Harbor are not expected to vary by more than a factor of two.

The next step in the model sensitivity analysis was to evaluate the variability that could occur in model projections of the steady-state maximum eutrophication potential in terms of these kinetic coefficients. Since algal populations under a nutrient saturation condition represent the maximum eutrophication potential of the system, the uncertainty analyses were conducted by holding nutrient concentrations constant at a sufficiently high value so that algal growth was not limited by nutrients. This assumption also removed influences of assigned values of boundary conditions and coefficients affecting nutrient cycling.

Sensitivity analyses for the remaining three model parameters determined to have greatest impact on algal populations were performed by first selecting three values for each parameter. The three values are assumed to represent a best estimate, a maximum expected value, and a minimum expected value:

- Maximum algal growth rate at 20°C: 1, 2, and 3 day^{-1}.
- Algal endogenous respiration rate at 20°C: 0.063, 0.125, and 0.25 day^{-1}.
- Light extinction coefficient in water column: 0.05, 0.2, and 0.5 m^{-1}.

Simulations were performed for all of the 27 combinations of these parameters to generate the nutrient-saturated chlorophyll *a* concentrations and algal productivity rates. The results of this analysis were used to estimate the probability of occurrence of the chlorophyll *a* concentrations and the algal productivity rates, assuming that each of the three values for a given

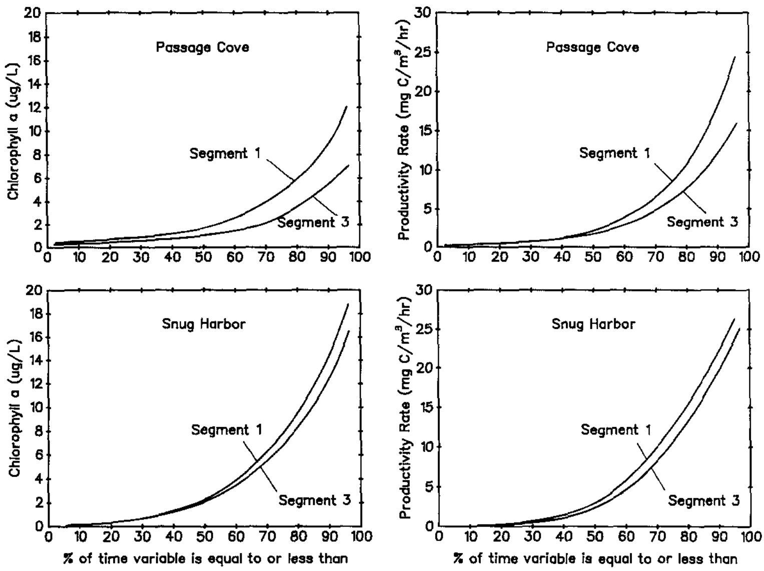


FIG. 6. Variations of Algal Chlorophyll *a* Concentration and Productivity Rate in Surface Layer due to Changes in Algal Kinetic Coefficients

kinetic coefficient had an equal chance to occur (a uniform distribution). This assumption results in overestimates of the probability of the more extreme (unlikely) occurrences or combinations. The cumulative probability of the estimated chlorophyll *a* concentrations and the algal productivity rates in the surface layer of Passage Cove and Snug Harbor are presented in Fig. 6. The results indicate that the medium values for maximum expected (nutrient-saturated) algal chlorophyll *a* concentrations for Passage Cove are 1.5 and 1.0 μg/L, and that those for Snug Harbor are 2.3 and 2.2 μg/L, for the inner and outer embayments, respectively.

Varying the kinetic parameters one at a time resulted in small differences in algal chlorophyll *a* levels, indicating strong influence of mass transport in these two embayments. As a result, the dilution and transport conditions generated by tidal actions in Passage Cove and Snug Harbor are significant enough to inhibit eutrophication in these embayments. This result supports the observation by Pritchard et al. (1989) that if primary productivity was enhanced along the shoreline due to nutrient input, the effect on algal growth was not sufficient to overcome dilution and transport due to tidal exchange. That is, algal growth in these coastal systems is flow limited.

Incremental Impacts under Various Nutrient-Loading Scenarios

A number of fertilizer types and application procedures were tested for application to Prince William Sound. A typical loading estimate for fertilizers sprayed on the test beaches was about 7.0 kg/day and 0.7 kg/day for nitrogen and phosphorus, respectively (S. C. McCutcheon, unpublished data 1990). For the loading analysis, this application rate was multiplied by factors ranging from 0 to 1,000 in order to evaluate all possible loading conditions. This loading was assumed to be applied directly to the water column and neglects losses that may have occurred due to uptake by organisms in the beach or nearshore zone.

Model results of nutrient addition are summarized in Fig. 7. Total algal chlorophyll *a*, ammonia nitrogen, nitrate nitrogen, and orthophosphate concentrations in the surface layer of Passage Cove and Snug Harbor are shown with increasing nutrient input (in terms of factors of base loading rates). Essentially, the model results indicate that the maximum chlorophyll *a* concentrations could reach only 1 to 2 μg/L in Passage Cove and about 2.9 to 3.3 μg/L in Snug Harbor.

Long-Term Impact

To determine how long it takes the embayments to recover after the nutrient treatment stops, the eutrophication models were run with constant nutrient loading rates for about 100 days when the algal biomass in the embayment approached equilibrium with the nutrient loads. The nutrient

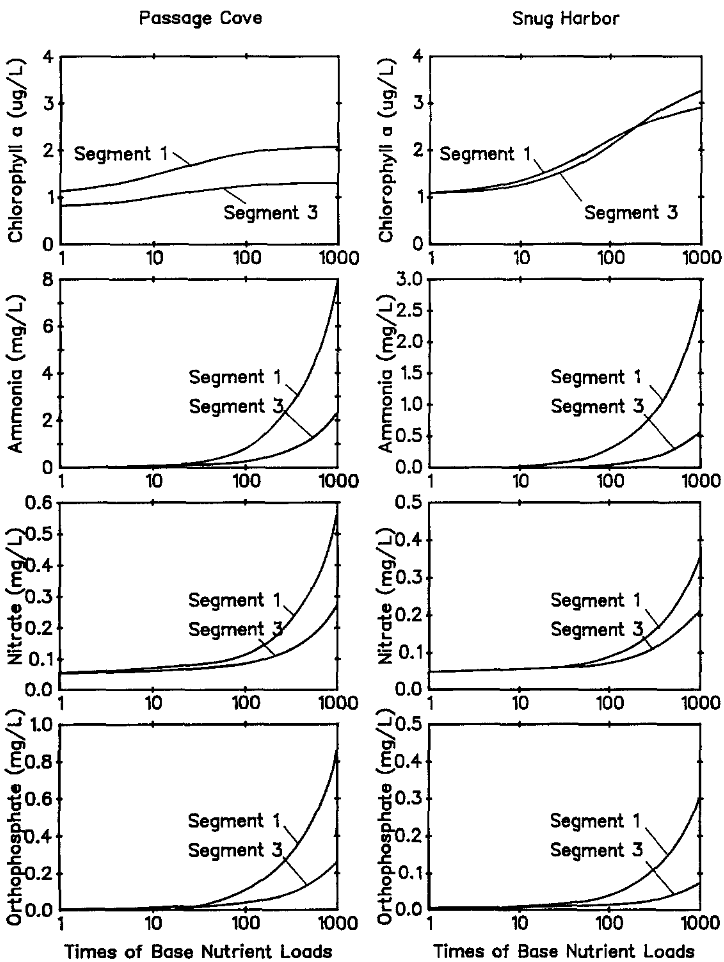


FIG. 7. Predicted Response to Nutrient Additions in Surface Layers of Passage Cove and Snug Harbor

loads were then discontinued. The model results showed that depending on the loading conditions (10, 100, and 1,000 times the base rate), Snug Harbor would take approximately 20–60 days to reduce the nutrient concentrations to the pretreatment levels. In comparison, the recovery time for Passage Cove is much shorter (no more than 15 days regardless of the loading factor) due to its small size.

Ammonia Toxicity

Significant concentrations of ammonia in the water column were predicted by the model under high application rates of fertilizer (Fig. 7). At a water temperature of 12.4°C and pH of 7.5 as used in the model calculation, about 0.75% of the ammonia is un-ionized. As such, the inner Passage Cove would violate the 0.02 mg/L un-ionized ammonia criterion at a loading factor of about 300. On the other hand, Snug Harbor is not expected to exceed this criterion with the maximum nutrient load rate (1,000 times of the base rate).

SUMMARY AND CONCLUSIONS

A modeling analysis was conducted to evaluate the eutrophication potential in two embayments in Prince William Sound in terms of nutrient addition from fertilizer application to clean up the oil-contaminated beaches. The analysis included a review of the existing data to support the modeling work, flushing time calculation, mass-transport calculation, and eutrophication modeling for these two systems.

The flushing time and mass-transport analyses indicated that the exchange between the embayments and the open water due to tidal actions was very significant. As a result, the algal growth potential was controlled by the strong circulation and mixing in the water column. Algal growth in these two embayments would be limited by strong tidal actions from the Prince William Sound which offer considerable flushing power. Model sensitivity analyses further substantiated this conclusion. Therefore, nutrient addition to the embayments would not be expected to generate much algal biomass in the water column. The possible eutrophication impact of fertilizer application would be minimal.

The model results also suggested that no lasting impact on the embayments would exist once the treatment stopped. That is, the recovery time for these coastal waters would be relatively short with a maximum period of 60 days for Snug Harbor under the maximum nutrient loading condition (1,000 times the base rate).

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