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Research Article

Quantifying septic nitrogen loadings to receiving waters: Waquoit Bay, Massachusetts

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Abstract. Waquoit Bay, a shallow bay on Cape Cod, Massachusetts, is exhibiting symptoms of eutrophication, largely attributed to septic nitrogen inputs. This study assessed septic nitrogen inputs by linking a three-dimensional ground-water model, a geographic information system (GIS), and a customized spatio-temporal nitrogen loading program. Owing to the slow speed of ground-water movement, the bulk of septic nitrogen entering the bay lags behind development by nearly a decade. Even if residential development is held at 1989 levels, nitrogen input from septic systems will increase by 36% over the current levels. At full residential build-out (i.e., development), septic nitrogen loading will eventually increase to more than twice the current levels.

1. Introduction

There is growing concern about nitrogen loading to coastal waters, predominately because primary production rates in coastal waters are nitrogen limited (Ryther and Dunstan 1971, Howarth 1988). Coastal waters are increasingly at risk of eutrophication because of higher loadings of anthropogenic nutrients to ground and surface water (Nixen and Pilson 1983, Lee and Olsen, 1985, Valiela and Costa 1988, Giblin and Gaines 1990). Waquoit Bay, a shallow coastal bay on the southwestern edge of Cape Cod (figure 1), is undergoing the process of eutrophication. In 1989, Waquoit Bay was chosen as one of the Land Margin Ecosystems Research (LMER) sites by the National Science Foundation. The Waquoit Bay LMER project team conducted interdisciplinary investigations into the relationship between changes in land use and responses in the nutrient dynamics and primary productivity of shallow estuarine ecosystems.

Residential septic systems are one of the principal sources of nitrogen input to Waquoit Bay because the drainage area is heavily populated and largely unsewered. Other nitrogen sources include atmospheric deposition and lawn and agricultural fertilizers; however, these sources are not addressed in this paper. Because the geology of the Waquoit Bay drainage area consists of highly permeable unconsolidated sand and gravel of glacial and marine origin (Oldale 1976, LeBlanc and Guswa 1977), rapid percolation of precipitation is favoured, making surface runoff a negligible contribution to receiving waters. As a result, nutrients from terrestrial sources, such as septic systems,

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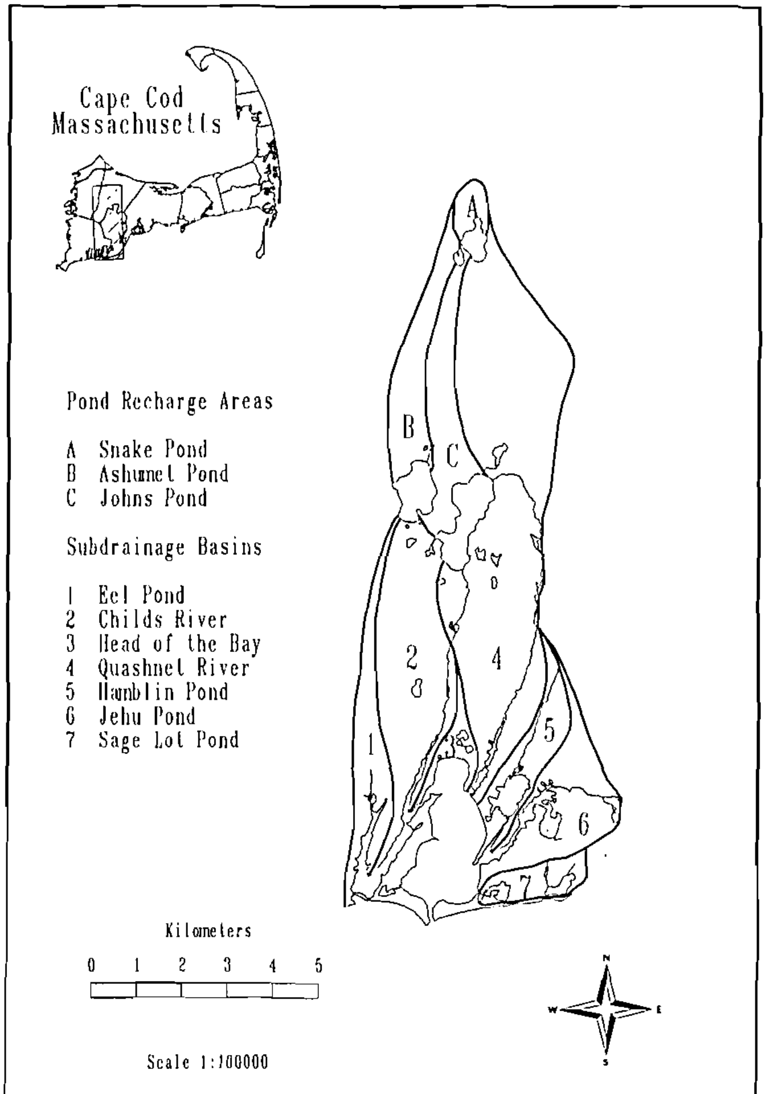

Figure 1. Waquoit Bay drainage area delineation: Sub-basins: (1) Eel Pond, (2) Childs River, (3) Head of the Bay, (4) Quashnet River, (5) Hamblin Pond, (6) Jehu Pond, and (7) Sage Lot Pond; Kettle Pond recharge areas: (A) Snake Pond, (B) Ashumet Pond, and (C) Johns Pond.

are transported primarily by ground water, through ground water-fed streams or by direct seepage along the coast.

The Waquoit Bay drainage area covers approximately 50 km^2 and is subdivided into seven sub-basins and three kettle pond contributing areas (figure 1). Residential housing density varies widely in the area, with a higher concentration along the coast. Increased nitrogen concentrations delivered to the bay are associated with at least three major ecological alterations: increased seaweed growth, reduced eelgrass growth, and adverse effects to the food web (Costa 1988, Valiela *et al.* 1990). Because of these ecological changes and the danger of further eutrophication, it is important to assess and quantify the rate of anthropogenic nitrogen loading to Waquoit Bay over time. Quantification of septic nitrogen input is essential to gain a better understanding of the ecological response to increasing nitrogen loading, and to implement responsible development strategies for the future in similar coastal environments.

This paper describes the methods, assumptions, and results of a unique approach to quantifying nutrient loading. Our study integrates both spatial and temporal characteristics of nitrogen loading to yield more reliable loading estimates. Due to the spatial variability of housing density and the relatively slow movement of ground water, we estimate nitrogen input rates to the bay using both ground-water travel time and the distribution of residential development.

2. Estimating septic nitrogen loading over time

A ground-water model has been used to delineate annual 'time bands' of ground-water flow, indicating the approximate number of years it takes for ground water to move from the point of recharge to the receiving waters of Waquoit Bay. Land parcel information stored in a geographical information system (GIS) is coupled with ground-water time bands to estimate the temporal and spatial distributions of nitrogen loading across the drainage area. Using a customized nitrogen loading calculation program written in C, these distributions are then processed to quantify the total amount and trend of nitrogen loading to Waquoit Bay.

2.1. *Ground-water modelling and delineation of time bands*

The assessment of ground-water flow characteristic within the Waquoit Bay drainage area was conducted using existing hydrogeological data, newly acquired field data, and ground-water flow modelling. A finite difference, three-dimensional ground-water flow model (MODFLOW from the US Geological Survey) and its particle-tracking module (MODPATH) were used to determine the ground-water dynamics within the drainage area. In addition, a pre- and post-processing package 'Processing MODFLOW' developed by Chaing and Kinzelbach (1991) on the personal computer platform was used to process model inputs and results.

In modelling the ground water flow in the Waquoit Bay drainage area, initial inputs to the model were based on surface (e.g., ponds) and well water levels observed during 17–21 December 1991 as documented by Cambareri *et al.* (1993). Assumptions regarding other hydrogeological conditions are: (1) the aquifer is homogeneous and horizontally isotropic; (2) the aquifer is composed of two geological units, an upper, coarse-grained permeable unit and a lower, fine-grained less permeable unit; (3) recharge to the aquifer, ground water flow rate, and water table levels remain constant over time; and (4) stream flow increases linearly with distance downstream. After varying the finite difference model grid during the early phase of the model building exercise, a model grid with 120×120 cells and three vertical layers was found to be optimal. The cell widths range from 53 to 120 m in the east-west direction and from 70 to 240 m in the north-south direction. The three vertical layers vary in thickness, but are approximately 20, 15, and 30 m for layers 1, 2 and 3, respectively. The top two layers simulate the upper, coarse-grained aquifer unit and the bottom layer simulates the underlying fine-grained, less permeable aquifer unit (Cambareri *et al.* 1993). Values for horizontal hydraulic conductivity of the upper coarse-grained aquifer units were set at 92·5 m per day (m/d), whereas the hydraulic conductivity of the lower fine-grained unit was set at 12·3 m/d. Vertical hydraulic conductivity values of the upper units and lower unit were estimated to be 24·7 and 0·07 m/d, respectively. Porosity for the entire model domain was set at 0·35. These hydrogeological parameters were derived from various projects conducted in the vicinity of the study area, that include LeBlanc (1984), LeBlanc *et al.* (1986), and Cambareri *et al.* (1993).

The model grid actually covers an area larger than the Waquoit Bay drainage area. The eastern edge of the model grid extends to include the Mashpee River system. The western edge of the grid extends to the ground water divide between the Eel Pond sub-basin and the Coonamessit River (i.e., based on water table contours and personal communication with professional staff members of the US Geological Survey Water Resource Division). The northern edge of the grid extends to the regional ground water mound and divides in Sandwich, Massachusetts, just north of Snake Pond. The southern edge of the grid consists of coastal water of Waquoit Bay and model cells were assigned constant head values of zero metre, indicating sea level.

Based on numerous test runs, it was determined that the model is sensitive to boundary conditions (e.g., flow boundary) and surface and ground water interaction (e.g., seepage through streambed). The model was calibrated to field conditions measured by a team led by staff members of the Cape Cod Commission during 17–21 December 1991 (Cambareri *et al.* 1993). Additional calibration was conducted using mean flow for both the Quashnet and Childs Rivers.

Final results of the ground water model exercise were compared with a water table elevation map derived using surface and well level measurements during 17–21 December 1991 (Cambareri *et al.* 1993). The modelled water table elevations were generally lower than the observed water table elevations. The difference between modelled and observed values ranged from $+0{\cdot}01$ to $-2{\cdot}87$ m. The mean difference over the study area was $-0{\cdot}63$ m and the root mean square was 0·87. The variation between modelled and observed values averaged less than 3 per cent of the observed values over the entire drainage basin.

Using the particle-tracking model, specific cells occurring in streams and along the shorelines of estuarine inlets, the bay, and ponds were 'marked' for particle tracing along ground-water flow paths. Using the backward tracking routine in MODPATH, movement of particles from water edges (e.g., rivers and shorelines) were marked along each flow line at annual increments. A digital graphics file containing these locations was generated by MODPATH and exported in digital exchange format (DXF). The DXF file was transferred to a UNIX-workstation and imported into ARC/INFO (developed by the Environmental Systems Research Institute, Inc.). Once geographically referenced, the flow lines and their annual flow markers were incorporated into a base map of the drainage area.

From this new flow line base map, annual ground-water travel time bands were derived and manually digitized. The time bands were delineated from this base map in conjunction with the December 1991 water table map developed by the Cape Cod Commission (Cambareri *et al.* 1993). Figure 2 (*a*) represents the Childs River sub-basin with its annual ground-water travel time bands. The time band number indicates the length of time in years that it will take ground-water recharge to reach the bay from that particular time band.

2.2. *Quantifying residential loading rates*

To estimate the flux of nitrogen through the aquifer and to receiving waters, the rate of nitrogen input from each home must be specified. The value derived from this study was 29 mg/l for each household, which was determined from a literature search of nitrogen concentration of septic effluent reaching the water table (Valiela *et al.* 1994).

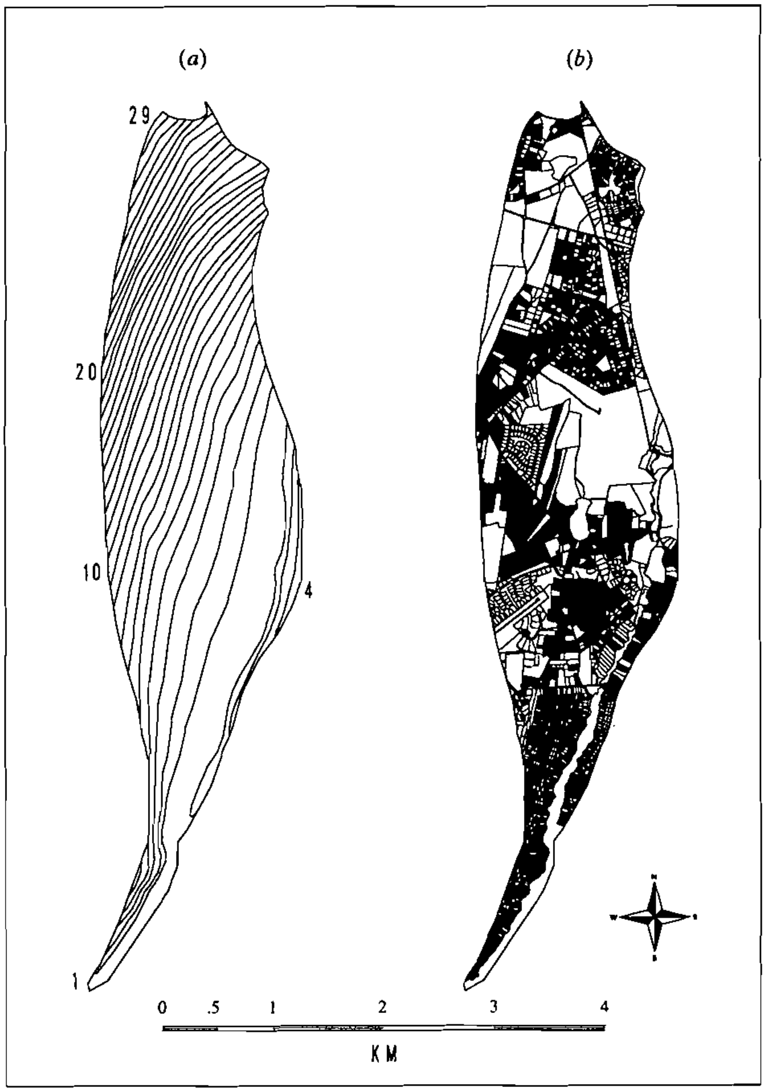

Figure 2. (*a*) depicts the Childs River sub-basin with annual ground-water travel bands and (*b*) shows land parcel coverage. The shaded polygons represents parcels of land that were developed into residential housing units as of 1989. Unshaded parcels were not developed and were classified as vacant land, agricultural land, or institutional.

Site-specific data on nitrogen removal during transport through the aquifer is not yet available for the Waquoit Bay area. Nitrogen transport through this type of aquifer is believed to the very conservative (Frimpter *et al.* 1990). Although it is possible that some attenuation of nitrogen is occurring, 100% conservative transport of nitrogen through the saturated zone of the aquifer is assumed until more conclusive data are available. If it is determined that the removal of nitrogen occurs during transport (i.e., over time) through the aquifer, it would require very little effort to incorporate removal rates of nitrogen on the basis of time bands of ground water flow.

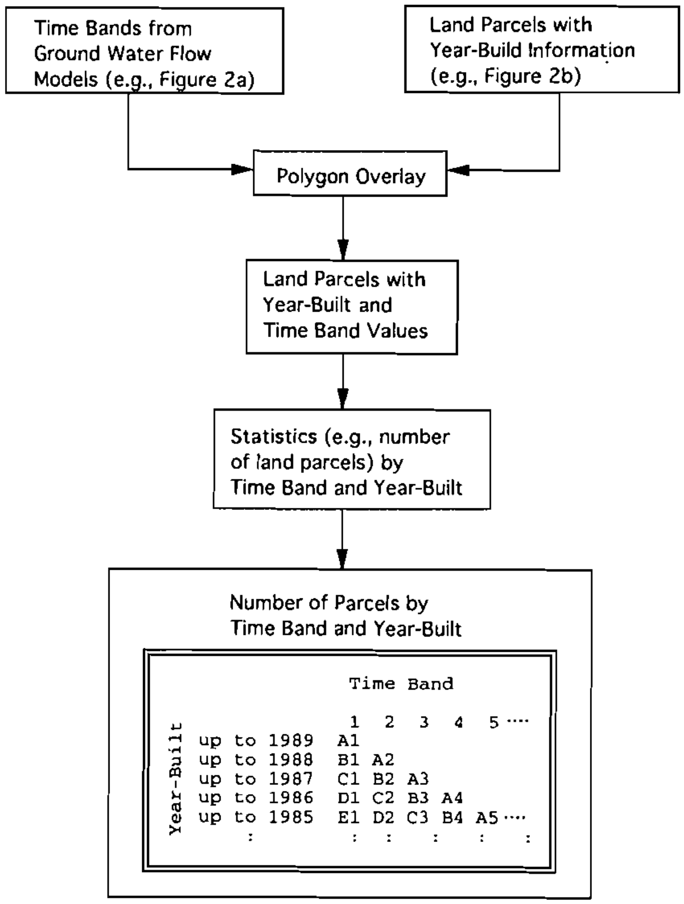

Figure 3. Procedure in using GIS to derive number of land parcels by time band and year-built.

2.3. *GIS analysis of time bands and land parcel data*

Digital 1989 land parcel data for the entire drainage area was acquired from the towns or Falmouth, Mashpee, and Sandwich and imported into the GIS. Figure 2 (*b*) shows land parcel polygons for the Childs River sub-basin. The shaded polygons represent parcels of land that were developed into residential housing units as of 1989. Unshaded parcels were not developed and were classified as vacant land, agricultural land, or institutional use. Attributes associated with the land parcel layer include: land use by property type (e.g., agricultural, developed and developable residential, and public utility), land parcel area and residential year-built data. Year-built data is more reliable for calculating nitrogen loading over time in this drainage area because large-scale, detailed land use data are limited and aerial photos that depict land use changes are only available on an infrequent basis.

Using the land parcel database and statistical functions in the GIS, an historical account of housing development was produced. The procedure used to derive the number of land parcels by time band and year-build is shown in figure 3. A limitation of the year-built data is that it may be skewed toward the present, due to the way parcel information is maintained at the local level. At least one town in the study area, Mashpee, updates year-built data for a parcel when any structural modifications are made on that parcel. For this reason, the land parcel database will tend to underestimate the number of houses built in earlier decades and overestimate the number of houses built in later decades. In terms of septic nitrogen loading to receiving waters, this could result in an underestimation of past input levels, but this skewing will lessen as future nitrogen loading is modelled. The practice of using the structural-modification data as the year-built data is believed to be limited; therefore, the error is probably small. In addition, if such a bias is causing some error, the error is temporal and not one of overall magnitude.

In total, residential parcels across the entire drainage area increased approximately 15-fold between 1940 and 1989. To determine the temporal effect of residential development on nitrogen loading to ground water, the land parcel data layer was overlaid with the annual ground-water travel time bands. Through this overlay procedure, it was possible to determine when a specific parcel started to contribute nitrogen to the ground water, and how long it would take for this specific contribution to enter the bay. Nitrogen associated with development in some portions of the drainage area may take several decades to reach the bay, with the longest possible path taking approximately 100 years.

To automate the repetitive process of 'backcasting' (i.e., selecting only those residential parcels that existed in a particular year and generating statistics for them), a set of macro programs was used to determine the number of developed residential parcels in each time band over the past 300 years. The number of developable residential parcels in each time band (as of 1989) was also extracted for projections of future growth scenarios. These statistics were extracted from the GIS as ASCII files and transferred from the UNIX-workstation to a personal computer. With the time- and site-specific statistics, it was possible to estimate nitrogen loading from residential septic systems to the water table and subsequently to the receiving bay.

2.4. *Total loading calculation model*

The total loading calculation model was written in the C programming language and run on an IBM-compatible personal computer. To compute loading for the whole drainage area, the model started at the northern end of the drainage area and worked southwards towards the bay. This operation is necessary because nitrogen loading must be calculated according to the flow direction of water in the Waquoit Bay drainage area (i.e., generally from north to south). Also, loading to the ponds must be calculated first, as pond water recharges areas down-gradient of the ponds. Specifically, loading to Snake Pond must be calculated first because water from Snake Pond recharges the Ashumet Pond, Johns Pond, and Quashnet River sub-basins. Owing to the large amount of data being manipulated for each sub-basin and recharge area (e.g., over 100 000 array elements), loading for each contributing area was computed separately and then totalled. Loading for a sub-basin in a particular year was calculated as total input into the sub-basin's first annual time band during the prior year, plus the total input into the second annual time band 2 years prior, and so on. This procedure is analogous to that of repeatedly totalling down the diagonals of a spreadsheet with time bands as columns and year-built data as rows.

For pre-1989 years, the statistics files indicated the number of residential parcels associated with each time band in the drainage basin. For post-1989 years, the model calculated residential growth in each time band according to various hypothetical growth rates (i.e., at 0%, 1%, 2%, and 5%). Because the statistics files also indicated the number of developable parcels in each time band in 1989, growth was allowed to continue up to the maximum number of developable parcels to simulate full residential build-out. The output of the total loading calculation model was a series of ASCII text files that listed the total nitrogen loading reaching Waquoit Bay over time. These output files were imported into a spreadsheet for the production of graphs and further analysis.

3. Results and discussion

Between 1940 and 1989, residential parcels across the entire drainage area increased approximately 15 fold to approximately 4230 parcels. While the bulk of nitrogen entering Waquoit Bay lags behind residential nitrogen input by about a decade, nitrogen from some portions of the drainage area may take several decades to reach the bay, up to a maximum of about 100 years. Because such a discrepancy exists between the level of nitrogen input to the aquifer and nitrogen output to the bay for a given year, it is clear that this methodology provides a reliable assessment of nitrogen loading over time.

In addition to holding the number of residential parcels constant at the 1989 level (0% growth), the post-1989 scenarios included annual uniform residential growth of 1%, 2%, and 5%. For the 0% growth scenario, the number of residential parcels and the nitrogen loading reaching the bay over time, are shown in figure 4. Nitrogen

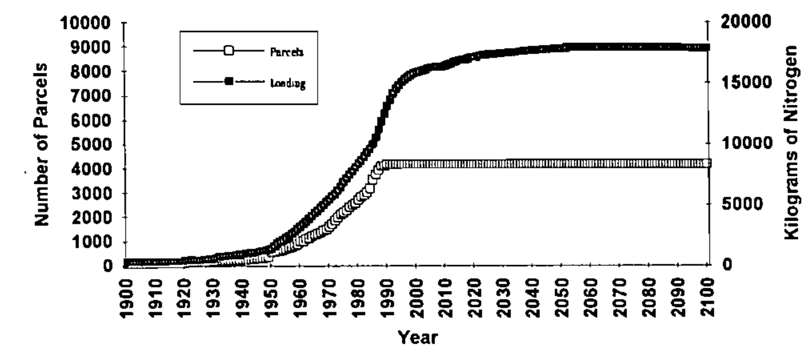

Figure 4. Residential parcels and septic nitrogen loadings over time. This scenario assumes no growth in residential development after 1989. Note that loading lags development and continues to increase long after development is held at a constant level.

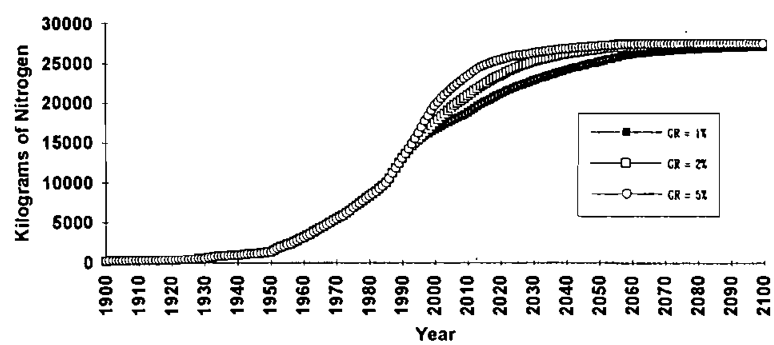

Figure 5. Growth scenarios for septic nitrogen loading over time. The graph shows the loadings associated with residential growth rates (GR) of 1, 2, and 5 per cent. Regardless of the growth rate chosen, loading will eventually reach the same level at full residential build-out.

continues to increase sharply over the next decade, finally leveling off more than 100 years from now at approximately 18 000 kg/year, which is about 36% higher than the current level of 13 200 kg/year. It is interesting to note the sharp increase in the rate of nitrogen loading to receiving waters beginning around 1950, which corresponds to the decrease in eelgrass beds over the same period, as noted by Costa (1988) and Valiela *et al.* (1990).

Figure 5 shows the growth scenarios for nitrogen loading reaching the bay. Regardless of the annual growth rate, it is apparent that nitrogen loading from septic sources continues to increase for many decades. The difference between the 1989 residential development level and full residential build-out in the Waquoit Bay drainage area is approximately 2280 parcels. At full residential build-out, total nitrogen loading from septic sources increases to approximately 28 100 kg/year, more than twice the current level.

The significance of these findings is highlighted when one considers that the ecological changes in Waguoit Bay are largely attributed to the increasing nitrogen inputs. There is concern that the frequency of anoxic and hypoxic events is increasing, and higher nitrogen inputs can only raise the likelihood of these events. Based on our analysis, it is apparent that septic nitrogen loading is increasing and will continue to increase and affect Waquoit Bay for many decades to come.

These findings also have implications in the planning of wastewater treatment standards and options in the Waquoit Bay drainage area. Over the past decade, a number of local organizations (e.g., the Association for the Preservation of Cape Cod, the Cape Cod Commission, and the Waquoit Bay National Estuarine Research Reserve) have been working toward restoring and protecting Waquoit Bay. Because the decline in eelgrass beds started around 1950, the 1950 residential development level has often been used as a benchmark for the assessment of nitrogen loading to Waquoit Bay. In fact, in order to estimate nitrogen loading to Waquoit Bay in the 1950s, the residential development level at an earlier date should be used for the calculations.

4. Conclusions

Quantifying septic nitrogen loading to Waquoit Bay, where septic systems are significant sources of nitrogen in the drainage area, is crucial to the understanding of ecological changes over time. Given our assumptions, this analysis indicates that septic nitrogen inputs to the bay have increased sharply as the ecological health of the bay has declined. The rate of increase rose sharply, beginning in the 1950s and the amount of nitrogen input will continue to increase.

This analysis demonstrated that it is necessary to incorporate the spatial and temporal characteristics of ground-water flow and land use data to accurately quantify nutrient loading in a drainage area such as Waquoit Bay. A dynamic analysis of nutrient inputs and outputs can produce more reliable loading estimates over time, unless ground-water flow is insignificant or the drainage area is largely sewered. Such a dynamic analysis of nutrient loadings requires repetitive manipulation of a large volume of spatial and temporal data, and can only be effectively and efficiently accomplished by coupling a GIS (e.g., the use of polygon overlay functions) and environmental model techniques. Although it is possible to manually extract year-built and ground water flow rate information from available information sources, it would take a substantial amount of time and energy to manipulate the data. In addition, without a GIS, it would be extremely difficult to carry out build-out scenarios and forecast time-dependent loading. The use of GIS technologies proves to be invaluable in this study.

Incorporation of these results with other research being conducted in the Waquoit Bay LMER project will result in a detailed model of the inputs, outputs, and biogeochemical processes that are occurring in the Waquoit Bay esturine system. Currently, there are projects being conducted to evaluate atmospheric deposition and vegetative uptake of nutrients, the nutrient transformation occurring in different types of ecosystems, and several other related topics.

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