dunes were constructed. The topographic zones in Table 1 include the beach and the active dunes, and these are collectively called the active sand-movement zone. The active sand zone can easily be detected on aerial photographs, since the dense cover of the dune grasses usually marks a sharp transition between the stable and the active areas of the barrier islands.

The results in Table 1 show that in 1945 the beach represented 51.5 percent of the active sand-movement area and by 1969 it represented 54.5 percent. The reason for this increase is that when the dune system is stabilized, the active sand zone, which is critical to the long-term equilibrium of the barrier system, is no longer a dynamic element of the system. When the dunes are reduced to essentially an inactive state, the actual beach becomes the only dynamic element of the system. It can also be seen that during this period the beach width was reduced by 9.3 percent, the active sand zone was reduced by 20.1 percent, and the dune area was reduced by 10.7 percent. The latter figure is highly significant as it indicates that although extensive dune areas have been stabilized, new dune areas are not developing to replace those being eroded on the ocean side of the barrier.

Since it is impossible to move the stabilized system inland with each reduction in the beach profile, which does, in effect, occur in a natural system, the inevitable has taken place. The beaches are narrower, steeper, and coarser, and wave reflection is common. The sediment most vulnerable to these changes is the fine materials (0.20 to 0.40 mm) that are the natural supply for renourishment of the native dune system. This sediment is associated with the uppermost limit of the uprush on an altered beach (*4*).

With little prospect for a reversal of the trend of the sea level to rise, and little hope for a change in the sediment balance, it appears that although the densely vegetated barrier dunes reduce the amount of windblown sand and overwash material, this continued effort to stabilize the beaches and dunes may be detrimental to the long-term equilibrium of the barrier islands themselves. Major amounts of fine sand are being lost by winnowing to the offshore and by increased attrition within the swash zone. Equally important, the National Park Service has recently started using immovable materials to protect some beach areas (Fig. 1c). Sandbags and revetments cause a great deal more swash reflection than even the oversteepened beaches. The loss of sand is a costly price to pay for temporary stabilization.

With the rapid deterioration of the barrier dune systems along the Outer Banks of North Carolina in recent years and the large expenditures of resources necessary to reestablish or maintain them, or both, this research suggests that this is an appropriate time for the National Park Service and the Corps of Army Engineers to review the basic concept of dune construction in light of the geological and ecological implications. This is not to suggest that we should simply return the barrier island to nature and adjust to the whims of the elements, but rather that we should consider very carefully the long-term implications of our present decisions. This is particularly desirable now that the National Park Service has nine large seashore areas within its control (*6*), and several others may be added in the near future.

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Groundwater Contamination by Road Salt: Steady-State Concentrations in East Central Massachusetts

Abstract. *The average steady-state contamination of groundwater by road salt in the suburban area around Boston, on the assumption that current rates of application of salt will continue, is about 160 milligrams of sodium chloride per liter of water (100 milligrams of chloride per liter). This value is compared with values of 50 to 100 milligrams of chloride per liter found rather commonly now in town wells in eastern Massachusetts. These salt concentrations may be of concern to persons on low-sodium diets and to persons who obtain water from wells in the vicinity of major highways where salt concentrations could be several times higher than average.*

Salt, mainly NaCl, has been used in increasing amounts in recent years to remove ice and snow from roads in northern areas. The rate of application of salt to Massachusetts state highways is now about 20 metric tons of total salt ($\mathrm{NaCl} + \mathrm{CaCl_2}$) per lane mile per year (*1*). Relatively little salt was used prior to 1955 in Massachusetts, especially on town roads.

One consequence of the use of salt on roads is the inadvertent contamination of water supplies (*1–3*). The situation encountered in the town of Burlington, Massachusetts, over the past several years represents a good example of the contamination of groundwater by road salt (*4*). Chloride concentrations in water from town wells increased over several years prior to 1970 and reached values exceeding 100 mg per liter of water in 1970, with one well showing peak concentrations in excess of 200 mg/liter. The use of salt in Burlington on town roads was subsequently suspended. Recent surveys reveal that wells in at least 14 other communities in eastern Massachusetts produce water containing > 100 mg of chloride per liter (*5*). These findings may imply a more general future contamination of water supplies in the heavily populated areas of east central Massachusetts.

We attempt here to estimate the steady-state concentrations of salt that may be expected in groundwater in the suburban area around Boston if present rates of application of salt are continued. For our calculations we consider several contiguous towns lying north and west of Boston in an area which includes Burlington. The towns are representative of suburban communities around Boston with respect to population densities and salt use (*6*). Data concerning land use and rates of application of salt are given in Table 1, from which a yearly value of 107 metric $\mathrm{ton/km^2}$ ($10.7\ \mathrm{mg/cm^2}$) is obtained over the total area considered.

Salt is applied during a 3-month

Table 1. Rates of application of salt for deicing in a set of representative communities in suburban Boston. Salt is assumed to consist entirely of NaCl; in fact, $CaCl_2$ composes 5 percent or less by weight of the salt applied to roads.

Town or city	Distance from Boston (km)	Area* (km^2)	Area of streets and alleys* (km^2)	Salt used on town roads† (metric ton/year)	Salt used on town plus state roads‡ (metric ton/year)	Salt/unit area per year (metric ton/km^2 per year)
Cambridge	3	18.5	2.83	2500	2900	157
Arlington	11	14.5	2.36	2170	2580	178
Medford	11	22.6	3.42	3170	3770	167
Winchester	14.5	16.4	1.51	4070	4340	265
Stoneham	16	17.3	1.66	800	1090	63
Lexington	19.5	43.2	3.56	1070	1680	39
Bedford	27.5	35.9	1.48	1320	1580	44
Total		168.4	16.8	15,100	17,940	
Area average						107

* Areas from (*16*). † For 1969–70; from information supplied by town officials and (*4*). ‡ State highways serviced with salt represent about 5 percent of the road area of Massachusetts, and the yearly rate of application is about 3500 metric tons per square kilometer of highway. From (*1*) and information supplied by the Massachusetts Department of Public Works.

period from about mid-December to mid-March, and its infiltration into the ground will be related to the fraction of precipitation which infiltrates during and immediately after winter. The infiltration of water is retarded in winter because of ground frost and the accumulation of some precipitation as surface ice and snow. Over a drainage area, infiltration of water is equal to precipitation minus the contribution of direct surface runoff to river flow. The effects of evapotranspiration can be neglected in winter around Boston. For the period December through March we estimate that infiltration totals about 59 percent of the precipitation for the Charles River and other regional drainage areas (*7, 8*). Data for the Charles River basin are summarized in Table 2. A similar fraction of salt could accompany the water, but salt is not, of course, uniformly distributed. Roadside drainage ditches and storm sewers serve to divert some salt into direct runoff and to diminish its infiltration. On the other hand, the lower melting point of roadside brine tends to favor infiltration, especially since Boston experiences an average of one major thaw every 2 to 3 weeks throughout winter. We estimate that at least 35 percent of the salt applied in winter will infiltrate and become dissolved in groundwater; the remainder is removed in runoff. This gives a value of about 3.7 mg of NaCl per square centimeter of ground area infiltrated per year. Our estimate of 35 percent can be compared to an estimate of about 50 percent by Bubeck *et al.* (*9*) for the Irondequoit Bay basin of New York and to an estimate of about 25 percent from Kunkle's data (*10*) for the Sleepers River basin of Vermont. The former basin is in low country which experiences frequent winter thaws; the latter is a part of more hilly terrain in which winter thaws are infrequent.

The residence time of salt in groundwater in eastern Massachusetts is expected to be rather variable, owing to the complex topography and the nonuniform properties of glacial soils. However, the mean residence time clearly exceeds 1 year (*11*), so that the average concentration of salt is that achieved through the average yearly contribution of precipitation to groundwater. The average yearly precipitation in the Boston area is 104 cm, and yearly evapotranspiration amounts to about 60 percent of this or 62 cm (*7, 8*). During the 8½ months of the year when the ground is free of frost (mid-March to December), the fraction of precipitation that runs off directly is very small in the area because of the even yearly distribution of precipitation, the heavy cover of vegetation, the low slopes, the prevalence of sandy soils, and the generally unsaturated condition of the surface soil. Direct runoff occurs largely in late winter and amounts to about 15 to 20 percent of the yearly precipitation (*7*). The remaining 20 to 25 percent (about 23 cm) is the fraction of the precipitation that contributes to groundwater.

The dissolution of 3.7 mg of NaCl per square centimeter of ground area in 23 cm of water yields an average steady-state NaCl concentration of about 160 mg/liter (100 mg of chloride per liter). Local deviations from this regional average could be easily two to four times this figure, especially in the vicinity of major highways (*1, 3, 4*) or in areas of high population (Table 1). The regional estimate does not include contributions of salt from other sources. For example, many communities in suburban Boston are served by domestic septic systems which inject salt from sewage directly into the ground at rates exceeding 3600 g of NaCl per person per year (*1*).

The recommended limit for chloride in drinking water is 250 mg/liter (*12, 13*), and a desirable concentration is considered to be 25 mg/liter or less

Table 2. Climatological data for the Charles River drainage area during the winter months; averaged values for 1941–45 (*7, 8*).

Month	A Precipitation minus evapotranspiration* (cm)	B River flow (cm)	C Apparent infiltration (A − B) (cm)	D Average summer-autumn flow† (cm)	E Infiltration (C + D) (cm)
December	9.65	4.19	5.46	1.83	7.29
January	9.01	3.94	5.07	1.83	6.90
February	6.60	4.32	2.28	1.83	4.11
March	10.29	9.40	0.89	1.83	2.72
Total	35.55	21.85	13.70	7.32	21.02
			Percent precipitation		
			38.5		59.1

* Evapotranspiration is taken as 0 for December, January, and February and 0.8 cm for March.
† Average monthly flow for June through October. This is the period of lowest flow during which direct runoff is very small and flow is sustained largely by groundwater. It is assumed that the flow of groundwater remains essentially unchanged throughout the winter.

(*13*). Although NaCl at a concentration of 100 to 200 mg/liter may not be harmful to the general population, it is of concern to persons on salt-restricted diets. The American Heart Association recommends that water containing more than 22 mg of sodium per liter (59 mg of NaCl per liter) should not be used when patients are on diets with an intake of sodium restricted to < 1 g/day (*14*). The normal adult intake of sodium is about 4 g/day (*1*). In this regard the water supplies of some 62 communities in Massachusetts were considered to contain excessive amounts of sodium in 1970 (*15*). It is thought that the bulk of the sodium originates from the use of salt on roads.

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Carbon Monoxide Balance in Nature

Abstract. *Consideration of the steady-state equations for stable carbon monoxide and for radioactive carbon monoxide in the troposphere leads to the conclusion that carbon monoxide is produced at a rate of* 5×10^{15} *grams per year, a value some 25 times greater than the rate of carbon monoxide production from combustion. The concomitant residence time for carbon monoxide is 0.1 year, in agreement with a previous estimate of Weinstock. Hydroxyl radicals are shown to account for both the production of this large amount of carbon monoxide by methane oxidation and for its removal by carbon monoxide oxidation. The average concentration of hydroxyl radicals in the troposphere required to achieve this effect is* 2.3×10^6 *molecules per cubic centimeter, with a daytime concentration of twice that. Levy and McConnell, McElroy, and Wofsy have deduced concentrations of hydroxyl radicals in the troposphere of the same magnitude from purely photochemical considerations, in support of this model.*

In an earlier publication (*1*) Weinstock pointed out that the residence time of CO in the atmosphere could be derived from radiocarbon data because the "hot" ^{14}C nuclei produced by the ^{14}N(np) reaction of cosmic-ray neutrons are first fixed as CO (*2*) before being converted into CO_2. A residence time of 0.1 year for ^{14}CO was then derived from measurements of the concentration of ^{14}CO in the atmosphere (*3*) and an estimate of its rate of formation (*4*). This 0.1-year value was suggested as a lower limit because a significant fraction of the ^{14}CO is formed in the stratosphere and may be converted to $^{14}CO_2$ there, before mixing into the troposphere. The same residence time was presumed to apply for stable CO. On the other hand, a residence time for stable CO of 2.7 years had been derived from estimates of the global production rate of CO and the average concentration of CO in the atmosphere (*5, 6*). The discrepancy of an order of magnitude between these two independent estimates of the CO residence time would be resolved if the global production rate used in the 2.7-year calculation had been underestimated by an order of magnitude. Presumably this overlooked source would be from "living" carbon and would also be a significant source of ^{14}CO. In this report the residence time of CO derived from ^{14}CO data and that from data on stable CO are brought into agreement and the amount of CO produced by nature is concomitantly derived. A quantitative explanation is then offered for the major aspects of the formation and removal of CO in nature.

The balance of CO in the troposphere can be expressed in terms of two steady-state equations, the first for stable CO and the second for radioactive ^{14}CO:

$$\frac{d(\mathrm{CO})}{dt} = P_1 + P_2 - k(\mathrm{CO}) = 0 \qquad (1)$$

$$\frac{d(^{14}\mathrm{CO})}{dt} = NP_1 + P_3 - k(\mathrm{CO}) = 0 \qquad (2)$$

In these equations, $d(\mathrm{CO})/dt$ and $d(^{14}\mathrm{CO})/dt$ are the rate of change with time of the total number of moles of stable CO and of radioactive ^{14}CO in the troposphere, respectively. These are equal to zero in the steady state. The quantity P_1 is the unknown rate of production of CO (in moles per year) from "living" carbon that is introduced into the troposphere. This will contain ^{14}CO of mole fraction N equal to 1.17×10^{-12} (*7*). The rate of introduction of ^{14}CO into the troposphere from this source is then NP_1 moles per year. The quantity P_2 is the rate of production of CO from "dead" carbon (fossil fuels) estimated to be 7×10^{12} mole year^{-1} (*6*); P_3 is the rate of production of ^{14}CO in the troposphere by cosmic-ray neutrons, 290 mole year^{-1} (*8*). The same first-order rate constant, k (per year), is assumed to apply for the removal of both CO and ^{14}CO from the troposphere; (CO) is the total amount of stable CO in the troposphere, $1.7 \times$