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LONG-TERM STUDIES OF RADIONUCLIDE CONTAMINATION OF MIGRATORY WATERFOWL AT THE SAVANNAH RIVER SITE: IMPLICATIONS FOR HABITAT MANAGEMENT AND NUCLEAR WASTE SITE REMEDIATION

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Abstract. Past nuclear industrial activities at the U.S. Department of Energy's Savannah River Site (SRS) have resulted in low-level radionuclide contamination of a variety of the site's wetlands, including a series of abandoned reactor cooling reservoirs. As a result of their long-term stable water levels and protection from public hunting and disturbance, these reservoirs have come to serve as a regionally important inland wintering site for diving ducks (Anatidae: Aythyinae) and other waterfowl species. These birds have been studied to determine the rates and patterns by which radionuclide levels in their whole body and muscle tissue have changed over time. Studies have focused particularly on the American Coot (*Fulica americana*) as a sentinel species. Coots have proved to consistently have the highest levels of contamination with the long-lived gamma-emitting radioisotope radiocesium (^{137}Cs), the most ubiquitous of the radioactive contaminants accumulating in biota on the SRS. From 1971 through 1986, radiocesium body burdens of 311 coots decreased in a negative-exponential pattern, with an ecological half-life of about four years. Radiocesium levels were initially higher in two of the reservoir's three arms where contaminated effluent had entered the watershed in the late 1950s to mid-1960s. Differing rates of decline of coot radiocesium burdens among arms of the reservoir reflected histories of reactor effluent flow that caused differential movement of this contaminant within the system. For the past two decades, average radiocesium levels in wintering coots have been well below those generally considered to be of concern for human consumption. However, our findings suggest the importance of continuing these contaminant monitoring programs while also maintaining a thorough understanding of the ecology and natural history of these birds on the SRS. Future options under consideration by the Department of Energy for its former reactor cooling reservoirs, intended as either cost-saving or remediation activities, include the cessation of make-up water pumping (leading to widely fluctuating reservoir water levels) and permanent partial or complete reservoir drawdown. Our long-term information together with continued monitoring programs will be necessary to predict some of the possible radiological consequences of any such reservoir management activities.

Key Words: American Coot, contamination, *Fulica americana,* long-term study, radiocesium, radionuclide, risk assessment, Savannah River Site, U.S. Department of Energy, waterfowl.

Nuclear production facilities of the U.S. Department of Energy (DOE) such as the Savannah River Site (SRS) are charged with assuring that habitats previously contaminated by site radionuclide releases will not threaten the health and well-being of wildlife populations, site workers, or the general public. Since the SRS is closed to public access, there is little or no opportunity for persons to come directly into contact with contaminated habitats, and offsite airborne and groundwater contaminant releases are monitored routinely to assure that all associated health risks are minimized (e.g., Ashley and Zeigler 1978, Zeigler et al. 1987). However, a frequently overlooked vector of onsite contaminants to the food chain of the public offsite is the hunting and consumption of mobile fish and wildlife species, particularly gamebirds including waterfowl. Birds that reside in contaminated habitats within the secured boundaries of the SRS can leave the site quickly and move to nearby public hunting lands where they could be harvested and consumed by hunters and their families. This possibility is of particular concern at the SRS where the site's abundant wetlands are protected from public disturbance and have come to represent an important inland wintering refuge for diving ducks in the state of South Carolina (Mayer et al. 1986). As a result of these concerns, a waterfowl research and monitoring program on the SRS was initiated by the Savannah River Ecology Laboratory in the early 1970s. From its inception, this program has focused on ^{137}Cs (radiocesium), a long-lived gamma-emitting radioisotope that is one of the most ubiquitous of the fission-product contaminants of biota on the SRS (Brisbin 1991a, 1993). The purpose of the present investigation was to examine long-term changes in the bioavailability and accumulation of radiocesium in waterfowl on the SRS and to discuss the results within the context of risk to human consumers and the need for site managers to be able to predict the radiological consequences of future habitat remediation and management activities in these or similar reservoirs.

Early studies of radiocesium levels in the migratory waterfowl community wintering on the SRS have shown that the American Coot (here-after coot), one of the most abundant members of that community (Brisbin 1974, Mayer et al. 1986), was also the "worst possible case" for radiocesium contamination in that it consistently showed higher body burdens of this radionuclide than other wintering species investigated (Brisbin et al. 1973). The latter study also showed that radiocesium levels increased in SRS coots from October through February, with peak body burdens from December through February. Body burdens then declined from March through May, as the SRS's winter-resident population was "diluted" by northward-moving spring migrants that had not wintered in SRS contaminated wetlands. On the basis of this annual pattern, Brisbin and Vargo (1982) recommended the more-or-less stable period of peak body burdens between early December and late February of each year as the most appropriate time to sample coots to assess changes in radiocesium levels across years. Using this plan, these authors then showed that radiocesium levels in coots wintering on the SRS's Par Pond reservoir declined during the period of 1971–1972 through 1975–1976 as the isotope continued to undergo radioactive decay (physical half-life = 30 yr) and/or was sequestered in the reservoir's bottom sediments, thus reducing its availability to the birds (Brisbin 1991a).

The Par Pond reservoir (Fig. 1) includes three major extensions—the North Arm (NA), Hot Arm (HA), and West Arm (WA). The history of previous reactor discharges to these three arms of the reservoir has created a spatial mosaic in contamination levels, with radiocesium levels in sediments and biota from the North Arm exceeding those of the Hot and West Arms (Brisbin et al. 1973). Brisbin and Vargo (1982) stated that this spatial contamination mosaic was maintained as radiocesium levels declined from the winter of 1971–1972 through 1975–1976, with coots from the North Arm continuing to show the highest body burdens. Their analysis showed no significant effects upon radiocesium levels in the birds that could be attributed to any two-way or the three-way interaction of location (arm of the reservoir), month, and year, thus indicating that during that four-year period, the levels of greatest contamination in coots had not shown any tendency to move "downstream" out of the North Arm and into the other regions of the reservoir (Fig. 1).

In the intervening years since the study by Brisbin and Vargo (1982), a number of additional studies have been conducted of the uptake and dynamics of radiocesium in Par Pond coots (Clay et al. 1980, Harris 1981, Potter 1987, Potter et al. 1989). These and other unpublished studies provided data on coot radiocesium body

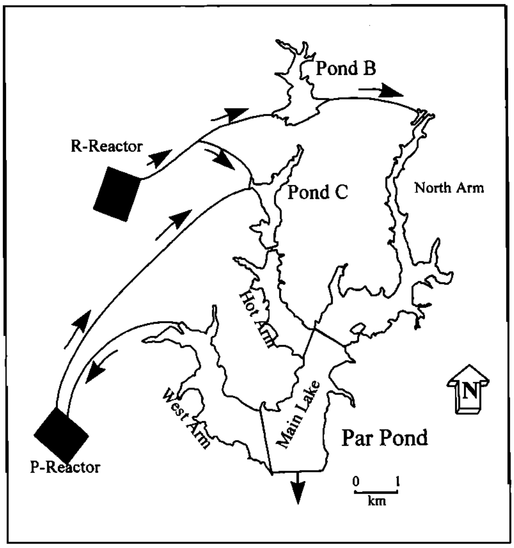

FIGURE 1. Map of the U.S. Department of Energy's Par Pond reactor cooling reservoir system, showing the P and R nuclear production reactors, effluent canals (heavy lines), Ponds B and C, and Par Pond. Regions of Par Pond, including the North Arm, Hot Arm, West Arm and Main Lake are also shown. Arrows indicate the flow of former reactor cooling effluents, some of which contained elevated levels of ^{137}Cs (see text).

burdens in one or more arms of Par Pond, through the winter of 1986–1987, using essentially the same sampling protocol as Brisbin and Vargo (1982), i.e., sampling birds during the period of maximum expected body burdens, from December through February. Although complete samples of 10 birds each were not always obtained from all three reservoir arms for all three months during these other studies, when combined with the data analyzed by Brisbin and Vargo (1982) these additional data provide a unique opportunity to determine the rates and patterns of change in the radiocesium body burdens of Par Pond coots over a 15-year period. Throughout these years, stable water levels were maintained in Par Pond. The data presented here thus represent long-term "baseline" patterns of contamination decline that can be expected in such reservoir habitats if no water-level manipulations are undertaken for management purposes. This information therefore can be used to predict and assess the results of continuing to maintain stable water levels or implementing other habitat management options (e.g., remediations necessitating partial or complete drawdowns) in radioactively contaminated reservoirs.

The widespread occurrence of migratory waterfowl in contaminated wetlands at other former DOE nuclear weapons production sites in the

TABLE 1. SUMMARY STATISTICS FOR RADIOCESIUM WHOLE-BODY BURDENS (BQ/G WET MASS) OF AMERICAN COOTS COLLECTED FROM DECEMBER TO FEBRUARY WHILE WINTERING ON THE PAR POND RESERVOIR OF THE DOE SAVANNAH RIVER SITE

	Hot arm		North arm		West arm	
Year	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
1971–72	0.44 (0.11)	0.21–0.66	0.51 (0.11)	0.28–0.71	0.40 (0.12)	0.25–0.87
1975–76	0.33 (0.14)	0.03–0.55	0.41 (0.16)	0.20–0.74	0.24 (0.14)	0.01–0.54
1977–78	0.20 (0.05)	0.10–0.33	0.36 (0.50)	0.12–2.97	0.17 (0.06)	0.10–0.31
1984–85	0.04 (0.02)	0.02–0.07	0.06 (0.02)	0.04–0.08	0.05 (0.01)	0.03–0.06
1986–87			0.08 (0.01)	0.07–0.10		

Notes; Locations of the three reservoir arms are shown in Fig. 1. Arithmetic means are presented. Sample sizes for each collection are given in text.

United States (e.g., Fitzner and Rickard 1975, Halford et al. 1981) and in regions contaminated by nuclear accidents such as the Chernobyl site in the Ukraine (Brisbin 1991b) makes this information particularly important since migratory waterfowl can accumulate contaminant body burdens and then rapidly move long distances away from such sites before being harvested by hunters (see calculations in Brisbin 1991a). Information of this kind can and therefore should be considered when making decisions concerning options for long-term use, public access, and/or the need to maintain surveillance/monitoring programs at such sites until elevated levels of radioisotopes have declined due to physical decay processes.

METHODS

Using gamma-spectroscopy techniques described by Brisbin et al. (1973) and Brisbin and Vargo (1982), whole-body burdens of radiocesium (expressed as Becquerels [Bq] ^{137}Cs/g wet mass) were determined for 311 coots that were collected from the three arms of Par Pond. Including coots from the earlier studies, all birds were collected (shot) as follows: December 1971–February 1972, 10 birds per month from NA, HA, and WA (90 birds); December 1975–February 1976, 10 birds per month from NA, HA, and WA (90 birds); December 1977–February 1978, 10 birds per month from NA, HA, and WA (90 birds); February 1985, 10 birds each from NA and WA, and 11 birds from HA (31 birds); and December 1986, 10 birds from NA. These data thus represented radiocesium values for 131 additional coots collected between December 1977 and December 1986, beyond those 180 birds used in the original studies of Brisbin et al. (1973) and Brisbin and Vargo (1982). The coot whole-body radiocesium data used in this study are summarized in Table 1.

Negative-exponential regressions were fit to the data for all birds, fitting each reservoir arm separately. Since radiocesium body-burden data from Par Pond coots tend to be log-normally distributed (Pinder and Smith 1975), all data were natural-log transformed before applying a homogeneity of slopes model (PROC GLM; SAS Institute 1988). We used this analysis to test for differences of slope (i.e., rate of decline in annual peak radiocesium levels attained by the wintering coot populations) and intercept (i.e., predicted 1965 geometric mean coot radiocesium levels) between individual reservoir arms. We calculated intercepts as occurring in 1965 on the assumption that this would have been the first year that the wintering coot population on Par Pond would have been exposed to the maximum extent of contaminated reactor effluent input (Ashley and Zeigler 1980). In conducting this analysis, we treated winter season (i.e., different years) as a continuous rather than as a class variable as was done in the analysis reported by Brisbin and Vargo (1982). This change in analytical approach was necessitated in part due to the absence of samples from some arms of the reservoir during some winters (1984–1985 and 1986–1987). In addition, since we analyzed data from more than two winter seasons, the interpretation of an interaction term between year and location (reservoir arm), with both effects treated as class variables as in the analysis by Brisbin and Vargo (1982), could be misleading and might not be clearly indicative of the overall similarity or dissimilarity of the rates of radiocesium decline across time among the different reservoir arms. We considered results significant at the $P \leq 0.05$ level.

RESULTS

Negative-exponential regressions describing the long-term decrease in radiocesium whole-body burdens of coots in the three arms of Par Pond are presented in Fig. 2. Parameter estimates (intercepts and slopes) are presented in Table 2 for simple linear regressions of the relationship: $ln[y] = A + Bx$, where y is the predicted whole-body radiocesium level (Bq/g wet mass) in year x. Inspection of Type I (sequential) sums-of-squares from the homogeneity of slopes model comparing these three regressions indicated significant differences among average coot radiocesium levels in the three reservoir arms and across years (Table 3). A marginally significant interaction between reservoir location and years ($P = 0.054$, Table 3) suggested that the rates (slopes) at which coot radiocesium body burdens were declining may differ between the three reservoir arms. Contrast analysis sums-of-squares indicated that the more rapid decline of radiocesium levels in coots from the Hot Arm

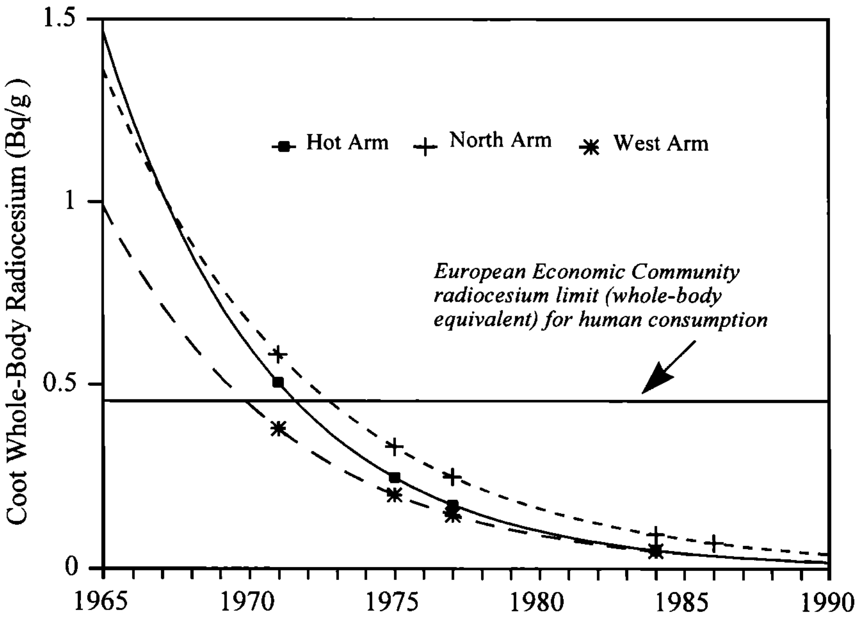

FIGURE 2. Negative-exponential regressions describing the long-term declines in American Coot whole-body ^{137}Cs from the three arms of the contaminated former reactor cooling reservoir, Par Pond. Data points represent geometric means from a total of 311 coots collected over a 15-year period. Sample sizes for given reservoir arms for given years are presented in text. The horizontal line represents the whole-body burden equivalent (0.47 Becquerels [Bq]/g wet mass) of the European Economic Community's radiocesium limit in fresh meat for human consumption (0.60 Bq/g; EEC 1986).

(Table 2) tended to differ from that of the other two arms combined (P = 0.053, Table 3), while there was no indication of a difference between slopes for the North vs. West Arms (P = 0.25, Table 3).

Type III (partial) sums-of-squares for the effect of reservoir location on intercept (coot radiocesium levels in 1965) approached significance (P = 0.09, Table 3). Contrast analysis of these intercepts indicated that the geometric mean radiocesium level in coots from the West Arm in 1965 was lower than that in coots from the combined North and Hot Arms (P = 0.029, Table 3), while those for coots from the North and Hot Arms did not differ from one-another (P = 0.65, Table 3) at that time.

Finally, we compared Par Pond coot radiocesium whole-body burdens to levels generally considered to be safe for human consumption (0.60 Bq/g fresh mass of meat; EEC 1986). Based on the relationship of whole-body to skeletal muscle levels of radiocesium in coots (Potter et al. 1989), this limit would correspond to a fresh-mass whole-body burden of 0.47 Bq ^{137}Cs/g. All geometric means of coot radiocesium body burdens on Par Pond fell below this level after 1975 (Fig. 2). However, the geometric mean body burdens for Hot and North Arm coots were both above this level in the winter of 1971–1972, and in the mid-late 1960s all such means would have been expected to exceed this level on the basis of regressions calculated in

TABLE 2. PARAMETER ESTIMATES AND 95% CONFIDENCE INTERVALS (CI) FROM SIMPLE LINEAR REGRESSIONS ($\ln[Y] = A + BX$) OF AMERICAN COOT WHOLE-BODY RADIOCESIUM (BQ/G WET MASS, Y) ON YEAR OF COLLECTION (X)

Reservoir location	Intercept (e^A)		Slope (B)		
	Estimate	95% CI	Estimate	95% CI	R^2
Hot Arm	1.47	1.16–1.87	−0.179	−0.201–−0.157	0.72
North Arm	1.36	1.11–1.67	−0.141	−0.159–−0.123	0.71
West Arm	0.99	0.72–1.35	−0.159	−0.188–−0.130	0.54

Notes; Estimates of intercepts (e^A, where e is the base of the natural logarithm) in Bq ^{137}Cs/g and slopes (B), are presented for the Hot, North, and West Arms of the Savannah River Site's reactor-cooling reservoir, Par Pond. Intercept parameter estimates correspond to radiocesium levels that would have been expected to be found in coots in the year 1965 (see text).

TABLE 3. RESULTS OF HOMOGENEITY OF SLOPES MODEL (PROC GLM; SAS INSTITUTE 1988) TESTING SPATIAL AND TEMPORAL EFFECTS OF WHOLE-BODY RADIOCESIUM (LN BQ/G WET MASS) IN AMERICAN COOTS WINTERING ON THE PAR POND REACTOR-COOLING RESERVOIR

Source of variation	df	SS[a] (Type)	*F*	*P*
		(Model SS)		
Overall model	5, 305	138.53	125.90	0.0001
		(Type I SS)		
Reservoir location (Loc)	2	7.10	16.14	0.0001
Year	1	130.13	591.33	0.0001
Year*Loc	2	1.30	2.95	0.054
		(Type III SS)		
Reservoir location (Loc)	2	1.07	2.43	0.09
Year	1	127.58	579.74	0.0001
Year*Loc	2	1.30	2.95	0.054
		(Contrast SS)		
Slope contrasts:				
Hot vs. Other Arms	1	0.83	3.76	0.053
North vs. West	1	0.30	1.34	0.25
Intercept contrasts:				
West vs. Other Arms	1	1.05	4.79	0.029
North vs. Hot	1	0.05	0.21	0.65

Notes: Model intercepts are compared by examination of Type III sums-of-squares for the effect of reservoir location. Tested model intercepts were set to the year 1965 (see text).
[a]Sums-of-squares.

this study. After 1975, the radiocesium body burden of only one coot examined in this study exceeded the EEC limit. This bird contained a level of 2.97 Bq/g wet mass, and was collected in the North Arm of Par Pond in January of 1978.

DISCUSSION

RADIOCESIUM LEVELS IN COOTS

Coots wintering on Par Pond migrate from the contaminated area each spring and, while on their more northerly breeding grounds, they eliminate radiocesium accumulated from Par Pond. The summer elimination of radiocesium from coots is the result of physiological/ metabolic processes taking place in each individual bird's body (i.e., biological elimination). The rate at which this elimination occurs (biological half-life; Potter 1987, Brisbin 1991a) should be sufficiently rapid to ensure that those birds returning to the reservoir each fall are essentially at background levels. Resightings of marked coots on Par Pond in successive winters confirm some level of fidelity to the reservoir as a whole and even to specific arms of the reservoir (Potter 1987). Returning birds then re-acquire equilibrium levels of radiocesium each winter (Brisbin et al. 1973), but with successively acquired equilibrium levels being lower each year as described in the present study (Fig. 2; Table 3). However, there is also a separate and distinct process of elimination of radioisotopes from environments like Par Pond as contaminants are either sequestered in the reservoir's bottom sediments or are otherwise removed by being flushed downstream (i.e., ecological elimination). Rates of turnover of radionuclide contaminants in various abiotic or biotic components of ecological systems may be quantified and compared in terms of ecological half-lives, which represent the amount of time required for a given radioisotope level in a population or other ecosystem component to decrease by 50% under free-living natural conditions (Brisbin 1991a).

Calculated on the basis of an average regression slope for the three arms of Par Pond as determined in this study, the ecological half-life of radiocesium in the wintering coot population on this reservoir was 4.3 years. Usually five such half-lives (i.e., the time required to reduce an initial contamination by 97%) is considered to represent the time required to essentially reach "background" levels of contamination (Brisbin 1991a). According to the ecological half-life calculated here, levels near background should have been reached by Par Pond coots about 22 years after the winter of 1965–1966, or by the winter of 1987–1988. Our data (Fig. 2; Table 3) show in fact that by the winter of 1986–1987, radiocesium body burdens of Par Pond coots had begun to reach these levels, having been reduced by 94% from the winter of 1965–1966 estimates.

IMPLICATIONS FOR ECOSYSTEMS

Brisbin (1991a) presented data for ecological half-lives of radiocesium in Wood Ducks (*Aix sponsa*) and rat snakes (*Elaphe obsoleta*) inhabiting bottomland river swamp habitat on the SRS. Although the biological half-lives of radiocesium differed greatly in these two species (6 vs. 902 days, respectively), their ecological half-lives were relatively similar (1.9 vs. 3.8 years, respectively). Both of these values were less than Brisbin (1991a) reported for coots on Par Pond (>20 years). On inspection of the original data upon which this latter value was based, however, we found this estimation of the ecological half-life to have been incorrectly reported. The ecological half-life estimated for coots in this study (4.3 years) however, still reinforces the conclusion that radiocesium ecological turnover rates and/or declines in waterfowl inhabiting the lentic Par Pond reservoir system are slower than in waterfowl inhabiting lotic swamp forest habitats. Radiocesium tends to persist longer in biogeochemically stable lentic environments than in lotic habitats where radiocesium is lost from the system through downstream movement and bioavailability of remaining radiocesium is reduced because of redeposited stream sediments (Brisbin et al. 1989, Brisbin 1991a).

Some of our results contrast with conclusions reached by Brisbin and Vargo (1982) with regard to differences in rates of decline of coot radiocesium levels among the three arms of Par Pond. These authors found no significant difference in coot radiocesium levels due to the interaction of location (arm of the reservoir) and year, for birds collected in 1971–1972 and 1975–1976, and on that basis they concluded that there was a tendency for coots in all three reservoir arms to "decrease proportionally in radiocesium contents between years, . . ."(Brisbin and Vargo 1982:268). However, these authors' analysis was based on untransformed data, and Par Pond coot radiocesium burdens tend to be log-normally distributed (Pinder and Smith 1975). We therefore repeated the analysis of Brisbin and Vargo (1982) using only the 1971–1972 and 1975–1976 data as in their study, but using natural-log transformed data, and found a significant interaction between location and year ($P < 0.03$). This finding confirms our results reported here for the longer period 1971 through 1986, indicating the more rapid decline of coot radiocesium body burdens in the Hot Arm than in the remainder of the reservoir (Table 3). This pattern may relate to the past history of reactor effluent and/or radiocesium introduction into Par Pond and its effect on movements of this contaminant within the reservoir sediments and water column.

The North Arm of Par Pond received cooling-water effluent from the R-reactor (Fig. 1) from the time of reservoir completion in 1958 until all reactor input to this arm ceased in 1964 (Neill and Babcock 1971, Alberts et al. 1979). In contrast, the Hot Arm received cooling water effluent from the P-reactor (and to some extent the R-reactor; see Fig. 1) from 1958 until 1988 when that reactor finally was placed on indefinite standby (Whicker et al. 1993). The introduction of contaminated effluents from R-reactor occurred primarily in 1963 and 1964 (total release of about 130 curies [Ci] ^{137}Cs), and has been deemed responsible for the contamination of the entire reservoir since the time of its construction (Ashley and Zeigler 1980). In addition, in 1957, prior to the filling of Par Pond, contaminated R-reactor effluent, carrying about 47 Ci of radiocesium, deposited contaminants along the streambed of Joyce Branch which later became Pond C (Fig. 1) and the Hot Arm of Par Pond (Ashley and Zeigler 1980).

In the summer of 1976, Alberts et al. (1979) found Par Pond water concentrations of radiocesium to be higher in the vicinity of the lower dam retaining the Main Lake portion of the reservoir (Fig. 1) than near the upper reaches of the Hot Arm where much of this contamination originally had been introduced. They suggested that this may have resulted from the downstream flushing of contaminated water out of the Hot Arm. Later, Evans et al. (1983) found that radiocesium was remobilized annually from the sediments of Par Pond into the water column during periods of intense summer anoxia of the hypolimnion. Furthermore, Stephens et al. (1997), using Par Pond sediment slurries in laboratory experiments, determined that the release of radiocesium from sediments to overlying water is augmented by elevated levels of conductivity. The introduction of Savannah River water (median specific conductance: 85 microsiemens[μS]/cm at 25 C; Newman et al. 1986) into Par Pond as make-up water for circulation to reactors apparently increased the specific conductance in Par Pond (median value in the Hot Arm: 65 μS/cm at 25 C; Newman et al. 1986) from a level that probably was similar to that found in a nearby reservoir, Pond B, no longer receiving river water inputs (20–30 μS/cm at 25 C; Alberts et al. 1988). The increase in radiocesium in the water column as a result of this process together with the continuing effluent pumping activity described earlier, effectively moved radiocesium from the Hot Arm to the

Main Lake through the introduction of relatively less contaminated effluents from P-reactor into the Hot Arm via Pond C. We suggest that this flow process over the thirty years that effluents were introduced into the Hot Arm resulted in substantial movements of dissolved/suspended radiocesium out of the Hot Arm and into the Main Lake and West Arm of the reservoir, thereby accounting for a more rapid decline in availability of radiocesium to coots and other biota in the Hot Arm than in other portions of the reservoir, such as the North Arm.

Our findings that coot radiocesium levels and rates of decline differed spatially within Par Pond suggest that on the average, most coots must confine their activities to relatively small areas of the reservoir. A study of coot movements on Par Pond (Potter 1987) confirmed such a suggested level of site fidelity when only 2% of 272 sightings of 85 marked birds occurred outside of the region where they had been initially captured. In fact, 75% of the multiple resightings of 14 individuals were estimated to be less than 10 m from the previous sighting (Potter 1987).

MANAGEMENT IMPLICATIONS

Our study describes radiocesium movements and patterns of spatial/temporal distribution under conditions of full-pool water level in Par Pond from the time of its formation in 1958 through 1988. However, if future management needs should require alterations of water levels or flow patterns in this reservoir system, the rates and patterns of radiocesium decline indicated in this study might be altered significantly. It might even be possible for radiocesium levels to increase in these birds as the result of management practices that either would remobilize or increase the bioavailability of radiocesium currently sequestered in the reservoir's sediments. Since the physical half-life of ^{137}Cs is 30 yr and the ecological half-life of ^{137}Cs in the coot population is currently 4.3 yr, proportionally more radiocesium must still be present in abiotic portions of the Par Pond ecosystem than currently remains in coots. There is also the possibility that future departures from the reservoir's status quo might alter the rate at which radiocesium body burdens are now declining in coots and other waterfowl. If a decision should be made, for example, to return the Par Pond reservoir ecosystem to it's former lotic nature, we would predict that the ecological half-life would decrease from the current 4.3 yr, and approach Fendley's (1978) estimate of 1.9 yr for Wood Ducks inhabiting lotic swamp forest habitat. We would also predict that if the management options of either naturally fluctuating reservoir water levels or partial reservoir drawdown are selected, an ecological half-life in waterfowl near the current 4.3-yr estimate or perhaps even higher would result from ecosystem destabilization and the resultant remobilization and increased bioavailability of radiocesium.

In 1991, it was necessary to lower the water level in the Par Pond reservoir by 6 m for over three years to make repairs to the retention dam. This temporary partial drawdown exposed nearly half of the lake's bottom sediments, and provided an opportunity to evaluate any related changes in waterfowl radiocesium body burdens during this period. A preliminary assessment of samples collected during this period suggests that whole-body radiocesium levels in at least some coots increased to levels not seen since the study began more than 20 years earlier (I. L. Brisbin and R. A. Kennamer, unpubl. data). Further studies are therefore needed to document any changes that this drawdown may have produced in the ecological half-life of these birds. A study of radiocesium levels in Mourning Doves (*Zenaida macroura*) utilizing the exposed areas of the lakebed found that levels in these birds declined quickly (Kennamer et al. 1998), with an ecological half-life of about one year.

The information reported above improves the accuracy of risk assessments designed to predict the probability that a bird might become contaminated with radiocesium in a habitat such as the Par Pond reservoir and then migrate from the restricted area to be harvested and consumed by a member of the hunting public. While our data suggest that some birds in the past may have exceeded levels currently considered safe for human consumption (0.60 Bq/g fresh meat; EEC 1986), there is no evidence that any threat would exist from the consumption of coots using Par Pond under the long-term stable conditions described in this study. Since 1975, only one coot in this study exceeded the EEC limit of radiocesium for human consumption. This bird contained 2.97 Bq/g whole-body wet mass and was collected in January, 1978, in the North Arm of Par Pond, to where it had likely recently moved from Pond B (Fig. 2). Although radiocesium concentrations in Pond B coot tissues averaged 26 times higher than in Par Pond North Arm birds (Potter et al. 1989), Pond B coot densities (<2 birds per km shoreline) were about two orders of magnitude lower than at Par Pond, and Potter (1987) concluded that movement of coots between the two reservoirs probably occurred but was limited in extent.

Assessments of risks to hunters from the consumption of radiocesium-contaminated waterfowl from Par Pond must consider that annual maximum levels of contamination, as are reported here, are not attained until mid-late winter when most waterfowl hunting seasons have been closed. Earlier in the fall, when birds are more likely to be harvested, contamination levels generally are lower since many birds have not yet had sufficient time to accumulate asymptotic body burdens (Brisbin et al. 1973). Moreover, those waterfowl species most eagerly sought by sportsmen in North America tend to have lower radiocesium body burdens than coots (Brisbin et al. 1973). In contrast to numerous environmental contaminants (e.g., mercury) that bio-magnify in species feeding at higher trophic levels, in SRS reservoir systems, radiocesium accumulates in lower concentrations in carnivorous, omnivorous, and piscivorous waterbirds than in the largely herbivorous coot (Brisbin et al. 1973, Brisbin 1993). There are many parts of the world where coots are consumed regularly as a staple of the diet (Ripley 1976). Studies of flyways in eastern Europe (Brisbin 1991b) have confirmed, moreover, that migratory waterfowl passing through those areas most contaminated by the Chernobyl nuclear accident are likely to winter in regions where coots are frequently consumed by humans. The results of our study are therefore particularly relevant to the prediction of long-term future risks to human health from radiation exposure resulting from such global contaminating events.

Taken together, our results suggest the importance of long-term studies of not only radionuclide contaminant cycling, but also the basic ecology of migratory waterfowl and other gamebirds inhabiting contaminated habitats. Long-term studies can help to predict the future likelihood of contaminant uptake and human exposure, and can serve as a baseline against which the consequences of future changes in habitat management practices can be evaluated. Finally, they also can be used (with caution) to project backward in time to learn more about past contaminant uptake and exposure that might not have been as readily apparent at the time without the benefit of both long-term contaminant databases plus an enhanced understanding of the basic ecology of the birds themselves.

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