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MODELLING RADIONUCLIDE BEHAVIOUR IN DEEP LAKES OF THE ITALIAN ALPINE REGION: SEASONALITY EFFECTS AND COMPARISON WITH DEEP VOLCANIC LAKES OF CENTRAL ITALY

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Summary

The present report describes the results of research carried out following the Chernobyl accident to analyse the behaviour of radionuclides in some Italian lakes. The following lacustrine systems were examined: volcanic lakes Bolsena, Bracciano and Vico (central Italy) and lake Como (north Italy) whose drainage area is located in the Alpine region.
The average residence times of ^{137}Cs in water of volcanic lakes are much higher than the radionuclide residence time in lake Como. As quantitative analyses can show, the differences between the mean water retention times of the examined lakes do not suffice to explain this occurrence. Some peculiar seasonal effects (thermal stratification of water and ice/snow melting in lake drainage area) and high sedimentation rates are responsible of ^{137}Cs efficient removal from water of lake Como.

Riassunto

I risultati di alcune ricerche effettuate dopo l'incidente di Chernobyl per analizzare il comportamento dei radionuclidi in alcuni laghi italiani vengono descritti nel presente rapporto tecnico. I sistemi lacustri esaminati sono situati nell'Italia centrale (laghi vulcanici di Bolsena, Bracciano e Vico) e nell'Italia settentronale (lago di Como caratterizzato da un bacino di drenaggio alpino). I tempi medi di residenza del ^{137}Cs nelle acque dei laghi vulcanici sono molto alti rispetto al tempo medio di residenza del radionuclide nel lago di Como. Come é possibile dimostrare mediante un'analisi quantitativa, la differenza dei tempi teorici di ricambio delle acque dei laghi oggetto dello studio non é sufficiente a spiegare questo comportamento.
Alcuni effetti stagionali (stratificazione termica delle acque e fusione dei ghiacci e delle nevi nel bacino di drenaggio) e alti ratei di sedimentazione sono responsabili di una più efficiente rimozione del ^{137}Cs dalle acque del lago di Como.

INTRODUCTION

Following the Chernobyl accident researches were carried out on the behaviour of ^{137}Cs in some Italian lacustrine systems. The goal of the present paper is the quantitative analysis, that has been carried out by model MARTE (Model for Analysing Radionuclide Transport in aquatic Environment, Monte et al. 1991, Monte, 1993), of the radionuclide in lake water to explain the peculiarities of the radionuclide time behaviour in volcanic lakes of central Italy and in lake Como whose drainage area is located in the Alpine region. The comparative analysis of radionuclide behaviour in these two different kinds of lakes may offer valuable information on the phenomena controlling the dynamic of contaminants in lake water. The deposition of ^{137}Cs of Chernobyl origin on the North Italy was significantly higher than on central Italy. For instance, around lake Bracciano (Central Italy), the deposition was estimated, approximately, 1000 Bq m^{-2}, whereas deposition around lake Como (north Italy) was higher than 20000 Bq m^{-2}. This difference in ^{137}Cs deposition reflected on the initial concentrations of the radionuclide in lake water (90 Bq m^{-3} in lake Bracciano, >2000 Bq m^{-3} in lake Como, May 1986). On the contrary, some years after the accident, the concentrations in lakes of North Italy ($\approx$1 Bq m^{-3} in water of lake Como) were very low compared with the concentrations in volcanic lakes (lake Vico $\approx$ 70 Bq m-3, lake Bracciano $\approx$ 20 Bq m^{-3}, lake Bolsena $\approx$25 Bq m^{-3}). This peculiar time behaviour can not be explained exclusively accounting the yearly mean water turn-over (average water retention time: 4.5 years for lake Como, 17 years for lake Vico, more than one century for lake Bracciano and lake Bolsena). In the present study the authors will show that some important seasonal phenomena (termal stratification of water and ice melting) and the sedimentation of suspended matter may give reason of the different time behaviour of ^{137}Cs in the examined lakes. This work was partially financed by the Commission of the European Community (contract N° FI3P-CT93-0073).

DESCRIPTION OF LACUSTRINE SYSTEMS

The main characteristics of the lakes are reported in table 1. Lake Como is of glacial origin and lies in the Alpine region. It is a deep lake with a very large drainage area prevailingly located in high mountain. During the Chernobyl accident the lake was heavily contaminated by ^{137}Cs and ^{134}Cs wet deposition. The lake shows a stratified structure from around the beginning of May to the end of December. During the spring the water inflow from the catchment shows a marked peak due to ice and snow melting in catchment. Vico, Bolsena and Bracciano are located in Central Italy. They are deep lakes of volcanic origin with very little drainage areas. Each has a small outlet. The above lakes show a stratified thermal structure from the second half of the Spring to the month of December (Monte et al. 1991A, Monte et al. 1993). A detailed description of the characteristic of the lakes are reported by Carollo et al. 1974.

MODEL DESCRIPTION

Model MARTE was developed to predict the behaviour of radionuclide concentration in water following the deposition of radioactive substances on a lake and its drainage area. The examined processes are the following:

a) direct deposition of radionuclide onto water surface;
b) effect of water thermal stratification on radionuclide diffusion in water;
c) adsorption of radionuclide by suspended matter;
d) radioactive decay;
e) removal of radionuclide, in dissolved form, by the emissary outflow;
f) removal by the emissary of radionuclide attached to suspended matter;
g) sedimentation;
h) diffusion of radionuclide in sediments;
i) migration of radionuclide from catchment basin to lake.

The quantitative formulation of the model (equations and parameter values) is reported by Monte et al., 1991 and Monte, 1993.
The model is solved using STELLA™ (Richmond et al. 1987) Software running on a Macintosh IIci computer (Apple™ Computer, Inc. 20525 Marian Ave. Cupertino, CA 95014).
Model structure is reported in figures 1 and 2.

RADIONUCLIDE BEHAVIOUR IN LAKE WATERS

The time behaviour of radionuclide concentration in surface water of deep lakes shows some peculiarities that are here summarised:

a)the water thermal stratification induced an high concentration of radionuclides of Chernobyl origin in lake surface water in Spring and Summer 1986;
b) surface water of lake Como showed, during such period, high ^{137}Cs concentrations due to the considerable radionuclide deposition on the lake;
c) initial concentrations (May-October 1986) of ^{137}Cs in water of volcanic lakes (Bracciano 90 Bqm^{-3}, Vico 500 Bqm^{-3}) were lower than in lake Como due to the low levels of radionuclide deposition on these lakes;
d) some years after the Chernobyl accident the concentrations of ^{137}Cs in water of volcanic lakes were higher than the concentration in lake Como (and, generally, in lakes of North Italy).
Figure 3 shows the time behaviour of ^{137}Cs concentration in water (epilimnion) of the examined lakes.
A non negligible amount of ^{137}Cs due to the nuclear tests in atmosphere of past decades is present in lake Bracciano. The concentration in water of ^{137}Cs of Chernobyl origin was estimated to be approximately the 50% of the total radionuclide concentration. This evaluation was carried out by the measurements of ^{134}Cs concentration in water and using a ratio $^{134}Cs/^{137}Cs$ of about 0.5 at 1-May-1986 (Monte et. al. 1990).

DISCUSSION AND CONCLUSIONS

The behaviour of dissolved substances in deep lakes is influenced by seasonal effects due to thermal stratification of water and to the dependence of the lake water residence time on the ice and snow melting and on rain rates in drainage area. During the stratification period (second half of Spring to first half of Autumn), the temperature of water of Italian deep lake shows a typical vertical profile comprising three main layers: the epilimnion, thermocline and hypolimnion. In such period the diffusion coefficient of dissolved substances from the epilimnion to the hypolimnion, through the thermocline, is lower than during the mixing period. As consequence, the vertical distribution of dissolved substances in water is not homogeneous. Contaminant substances, accidentally introduced into the epilimnion during the stratification period, accumulate in this upper layer of lake water up to the winter when phenomena of water mixing result in dilution of the radionuclide in the entire lake volume. The average residence times of water and of dissolved substances in lakes of Alpine region, strongly depend on the snow and the ice melting. Both the stratification and ice/snow melting occur in the Spring-Summer period and considerably contribute to the turn-over of water and, consequently, of contaminant substances in lakes of North Italy.

Indeed, the thermal stratification, in conjunction with increased levels of water inflow and outflow, may imply a mean water residence time in the epilimnion significantly lower than the yearly mean water residence time in the whole lake.

Volcanic lakes in Central Italy are affected by phenomena related to thermal water stratification. These lakes are characterised by very small drainage areas and, consequently, by negligible contribution of water from the catchment and by low levels of sedimentation. On the contrary, lakes of large drainage areas may show high sedimentation rate due to the transport, by inlets, of suspended matter from the catchment to the lake. The described time behaviours of ^{137}Cs concentrations in water can not be explained exclusively by the mean water retention time of the different lakes (lake Como 4.5 years, lake Vico 17 years, lake Bracciano 137 years, Bolsena = 121 years) and on the different lake mean depths (Vico 20 m, Bracciano 89 m Como 153 m, Bolsena = 81) that represent some of the most important factors involving the radionuclide dilution in water.

Indeed lake Como, 7-8 years after the contamination event, shows an approximate level of radionuclide concentration in water of 1 Bq m^{-3}, whereas waters of volcanic lakes show higher levels of contamination. ^{137}Cs concentration in water of lake Bracciano, for instance, is of the order of 20 Bq m^{-3} (10 Bq m^{-3} are of Chernobyl origin). The initial concentration in lake Como was approximately 2700 Bq m^{-3} (Capra et al. 1988). Supposing that the initial amount of radionuclide is concentrated in a layer of 10 m corresponding to the average thickness of the epilimnion, the concentration, after the dilution, would become approximately 2700*10/150 (a factor 15 lower than the initial value). 7 years after the accident, using a mean water residence time of 4.5 years, we get that the concentration in water is a factor 5 lower. As consequence, the concentration in lake should be, approximately, a factor 75 lower than the initial concentration in epilimnion, that is, $\approx$36 Bq m^{-3}, a value significantly higher than the experimental one. Similar calculations for lake Bracciano give an approximate concentration of 10 Bq m^{-3}, in agreement with the experimental concentration of ^{137}Cs Chernobyl origin. These approximate calculations give a concentration in lake Vico of $\approx$160 Bq m^{-3}, a value that is close to the experimental data. On the other hand the ratio between the radionuclide concentrations in epilimnion of lake Como and lake Bracciano is about 20 at May 86; the same ratio is, approximately, O.1 seven years after the Chernobyl accident. As demonstrated by the previous discussion, this significant variation of the ratio can not be explained by the radionuclide dilution in water during the mixing period and by a yearly water turnover of 4.5 years in lake Como. Figure 3 apparently shows that the decrease with time of the radionuclide concentration in lake Como is faster than in the volcanic lakes. In the case of lake Como, other phenomena play an important role in removing the radioactivity from the water column. The low value of radionuclide concentration in lake Como, 7 years after the Chernobyl accident, may be explained accounting the following occurrences:

a) Seasonal effects contribute to remove more efficiently the radionuclide from the lakes of Alpine region. During the stratification period the flux of water from the catchment to the lake (and the outflow of water from the lake) is very high due to the melting of ice and snow and to the Autumn rain. As consequence the residence time of water in the epilimnion is significantly lower than the mean water residence time averaged over the year. Indeed, whereas the mean water residence time for the entire water volume is of about 4.5 years, the mean water residence time in the epilimnion during the stratification period is considerably lower (months). During the Spring-Autumn 1986 the deposited radionuclide remained, prevailingly, in the upper layer of the lake water. As consequence, during that period, a large part of the total amount of ^{137}Cs deposited on lake Como was removed from the epilimnion by the water outflow.

b) Sediment and suspended matter of lake Como are characterised by k_d (partition coefficient sediment/water) values higher than the corresponding values in volcanic lakes (order of magnitude of k_d: lake Como $k_d \approx 10^2$ m^3 kg^{-1}, volcanic lakes 10 m^3 kg^{-1}). The high radionuclide interaction with suspended matter and bottom sediment implies a more efficient removal of radionuclide from the water column; moreover sedimentation plays an important role in lake Como, whereas, in volcanic lakes, this effect is less important due to the low values of k_d and to the low levels of sedimentation rates.

Figures 4, 5 and 6 show the experimental results of ^{137}Cs contamination of water with the predictions of model MARTE. The model results are in good agreement with the experimental data. The fast decrease of ^{137}Cs concentration in water of lake Como was simulated using values of k_d and sedimentation higher than the values used for volcanic lakes (lake Como: k_d=50 m^3 kg^{-1}, order of magnitude of sedimentation rate 10^{-8} kg m^{-2} day^{-1}; volcanic lakes: k_d =15 $m^3 kg^{-1}$, sedimentation rate ≈ negligible) and accounting the seasonal variation of the water inflow from catchment. Results of simulation carried out using value of k_d and sedimentation rate for lake Como similar to the values used for volcanic lake are, at least, one order of magnitude higher than the experimental values. Figure 7 shows the model results obtained for lake Como in three different circumstances:

a) seasonal effects (thermocline formation and snow and ice melting) and sedimentation are neglected (k_d=15 $m^3 kg^{-1}$, sedimentation rate ≈0);

b) seasonal effects are considered whereas sedimentation is neglected;

c) both seasonal effects and sedimentation are considered.

On the hypotheses a) and b), the predicted values are significantly higher than results obtained on hypothesis c) corresponding to the data reported in figure 4.

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TABLE 1. LAKE CHARACTERISTICS

	Como	Bolsena	Bracciano	Vico
Mean depth (m)	153	81	89	22
Surface of lake (km^2)	145	114	57	12
Surface of lake drainage area (km^2)	4570	273	147	41
Mean water retention time (years)	4.5	121	137	17
^{137}Cs deposition ($kBq\ m^{-2}$)	20-30	≈ 3	1	8

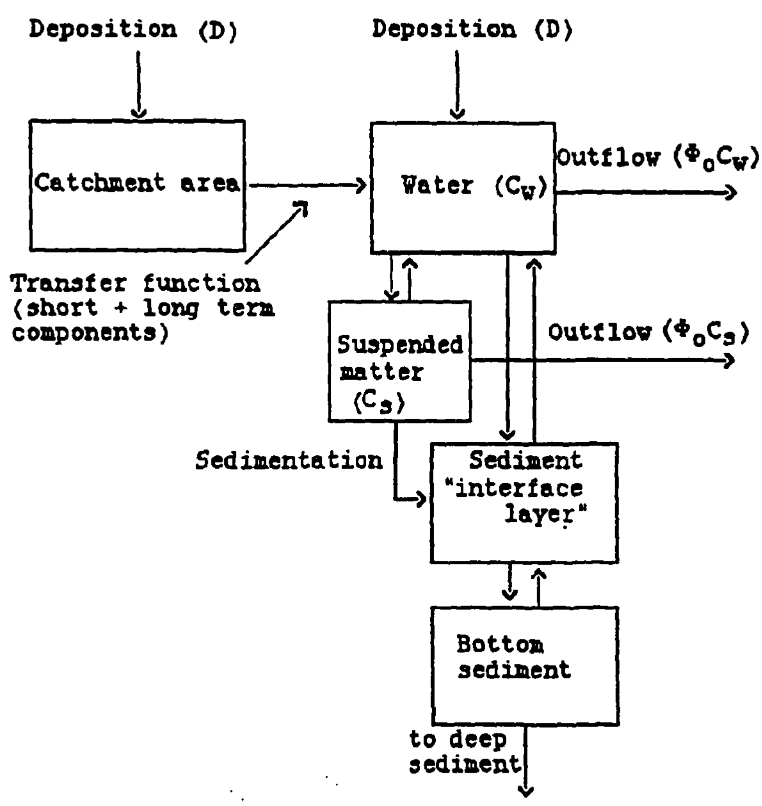

FIGURE 1

Structure of model MARTE

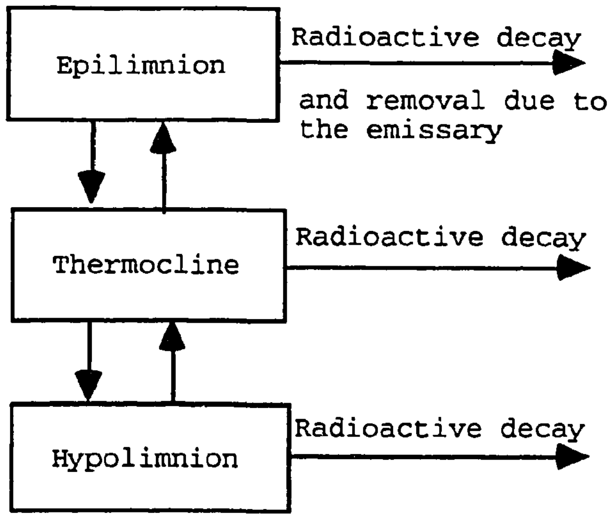

FIGURE 2

Structure of model MARTE for predicting vertical profile of radionuclide concentration in water.

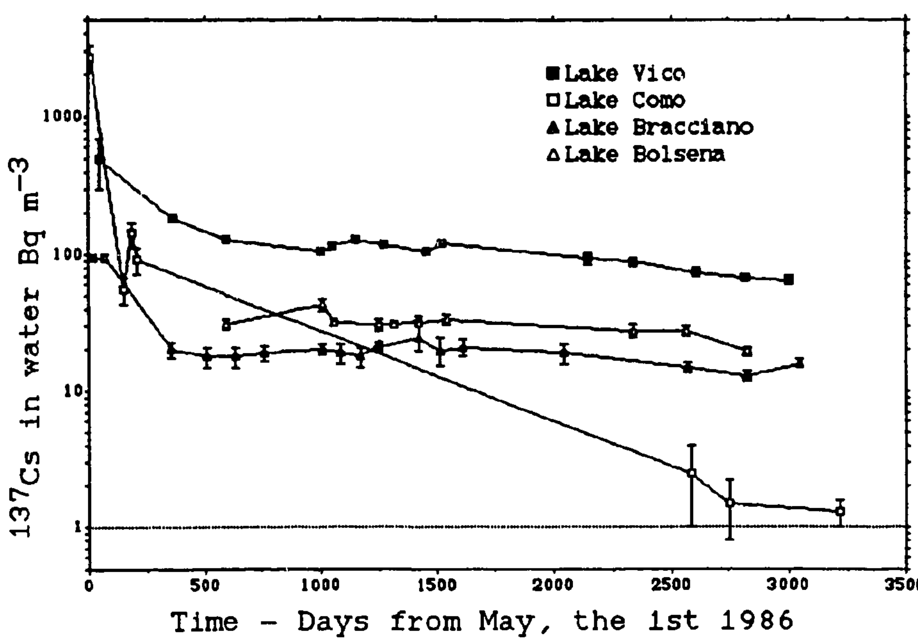

FIGURE 3

Experimental values of radionuclide concentrations in waters of lakes Como, Bolsena, Bracciano and Vico.

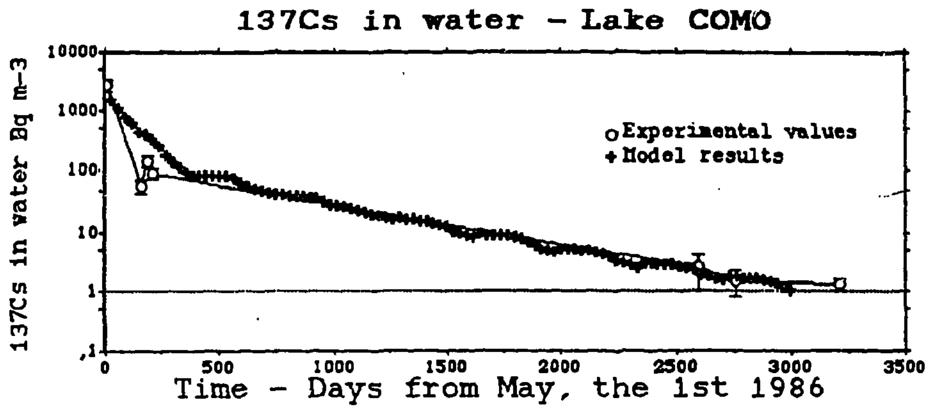

FIGURE 4

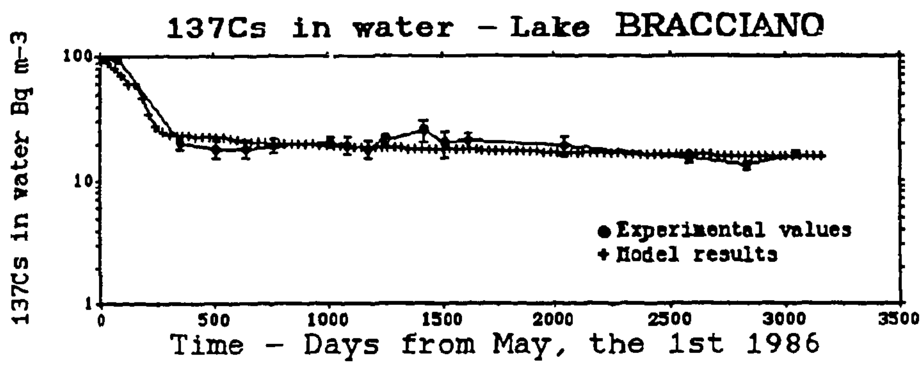

FIGURE 5

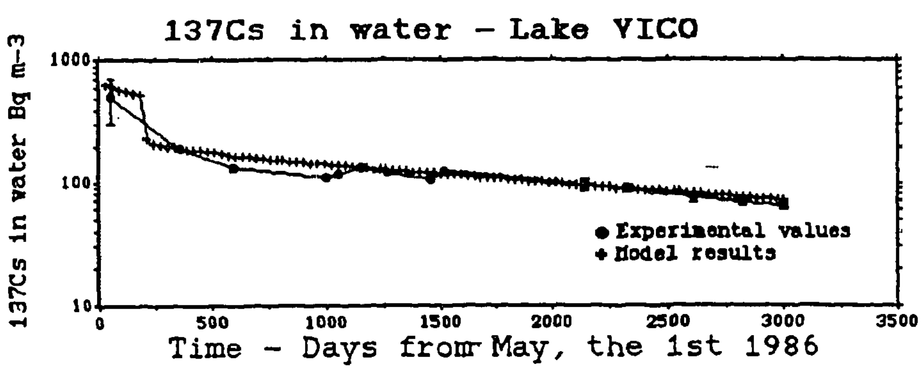

FIGURE 6

FIGURE 4 - 5 - 6

Comparison of model predictions and experimental values (lake Como, lake Bracciano, lake Vico).

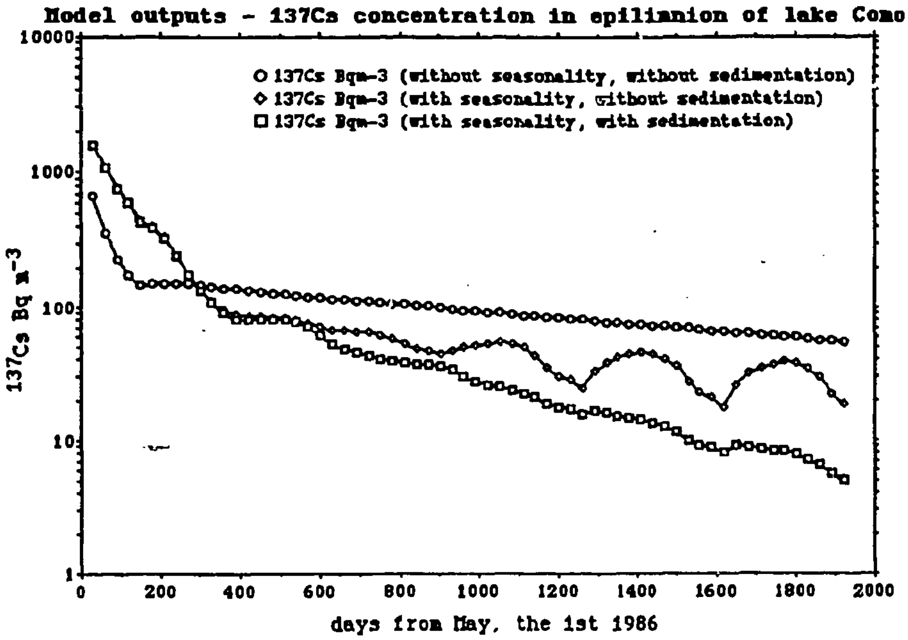

FIGURE 7

Model results obtained on three different hypotheses: a) neglecting seasonal effects and sedimentation; b) neglecting sedimentation and considering seasonal effects; c) considering both seasonal effects and sedimentation.

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