Modelling the spatio-temporal evolution of ^{3}H in the waters of the River Tagus

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Abstract

Measurements of tritium specific activity levels and of temperatures in waters of the Torrejón−Tagus reservoir (Spain) showed that their radioactive characteristics were basically influenced by the radioactive liquid effluent from the Almaraz Nuclear Power Plant. This enters the Torrejón−Tagus reservoir via the Arrocampo cooling reservoir, which exchanges water with the first. We studied the temporal and spatial (in two dimensions) evolution of the mentioned parameters for years 1997 and 1998. The tritium levels were found to be significantly correlated with temperature. Two numerical models were constructed for a quantitative study of the tritium levels along Torrejón reservoir: a 1D model was used for the dispersion of tritium along the whole length of the reservoir, and a 2D depth-averaged model was used for a detailed study of the area where tritium is released into the reservoir. Both models solve the hydrodynamic equations, to obtain the currents induced by the exchanges of water between the reservoirs in the River Tagus and Arrocampo, and the advection/diffusion equation to calculate the dispersion of tritium. In general, the model results were in agreement with the experimental observations.
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Keywords: Reservoir water; Tritium; Temperature; Numerical modelling; Dispersion

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1. Introduction

The quality of the planet waters notably influence their use, with the presence of radionuclides being one of the limiting factors. In this sense, the study of the tritium content of different waters has a threefold interest. Firstly, its universality, since tritium levels due to natural origins (Kaufman and Libby, 1954) may be raised by several orders of magnitude by an anthropogenic component (UNSCEAR, 1988; IAEA, 1990; Okada and Momoshima, 1993). Secondly, its radiotoxicity, which, while relatively low in comparison with that of other radionuclides, is 25 000 times greater when the ^{3}H is in the form of HTO instead of HT (ICRP, 1978). Thirdly, the practically indistinguishability for hydraulic systems of tritiated water from untritiated water (Thibodeaux, 1979), so that this radionuclide may be a good parameter for studying the dynamics of water masses (Fontes, 1983a,b; Baeza et al., 2002), and in particular for studying the spatial and temporal distribution of other substances contained in them, whether conservative or not.

One of the Iberian Peninsula hydrological systems that is most affected by the presence of tritium is the River Tagus. The principal reason is that three nuclear power plants use its water for cooling (CSN, 1998). Its course is highly regulated by an almost completely coupled series of reservoirs, which are especially important in the river passage through the regions of Extremadura (Spain) and the Alentejo (Portugal), with five reservoirs in 200 km. The authors studied previously, for the years 1994–1996, the basic aspects of the tritium's spatial and temporal evolution (Baeza et al., 1997), including various simple models that allowed us to understand certain facets of its dynamics, such as its mean transit speed (Baeza et al., 2001, 2004).

One fact deduced was the importance of Torrejón reservoir in understanding the spatial and temporal evolution of tritium in this part of the River Tagus, since the water is used not only for hydroelectric power production and irrigation, but also to cool the Almaraz Nuclear Power Plant (henceforth, ANPP) through water exchanges with Arrocampo reservoir. In the present work, we study in detail the influence of this water exchange on the distribution of tritium in Torrejón reservoir, using data for years 1997 and 1998. To this end, we collected monthly water samples, in which we determined their temperatures simultaneously with the collection. In this way we were able to analyze both the spatial distribution of tritium levels in two dimensions in Torrejón reservoir, transversally and longitudinally, and their temporal evolution.

The currents caused by the exchange of water between the different reservoirs in this part of the River Tagus make it difficult to give a detailed quantitative interpretation of the measured tritium levels, in a form allowing predictions of their future evolution. A prerequisite is to construct appropriate models for Torrejón reservoir. We made a first approximation by using simple box models to simulate the temporal evolution of tritium levels in the Arrocampo (Baeza et al., 1997) and Torrejón (Baeza et al., 2001) reservoirs, in particular studying the area where the exchange of water with the Arrocampo reservoir takes place. The present work describes the development of two new numerical models for the Torrejón reservoir. The first is a one-dimensional model constructed to reproduce the large scale dispersion of tritium, covering the total length of the cited reservoir. This model cannot, however, describe the dispersion of tritium at a small scale, in particular in the area of the discharges from Arrocampo reservoir. A higher resolution two-dimensional depth-averaged model was therefore constructed for this area. The advance represented by these models is that they are physical models in which the instantaneous currents are obtained for each point of the Torrejón reservoir and for each instant of time. These currents are then used to calculate the tritium dispersion. Hence, the tritium concentrations may be calculated for any position and time in this reservoir.

2. Experimental

2.1. Study area

The River Tagus has its source in the Sierra de Albarracín (Spain), and its mouth in Lisbon (Portugal). Its total length is 1107 km (Fig. 1). The area of the Tagus basin is about 8.1×10^4 km^2, of which 69% is in Spain. The ANPP, with two 930 MWe PWR-type units is located on the river right bank, in the region of Extremadura and 180 km west—southwest of Madrid. The River Tagus receives discharges from the ANPP (Baeza et al., 1991) and from other two nuclear power plants located below 300 km upstream — José Cabrera and Trillo — as well as several smaller contributions from a significant number of laboratories and hospitals (CSN, 1998).

The flow regime of the River Tagus is controlled through a chain of reservoirs. One of them, in the region of Extremadura (Fig. 1), is, in cubic hectometres (1 hm^3 = 10^6 m^3), the 166 hm^3 capacity Torrejón reservoir, which is the object of the detailed study of the present work. It is 42 km long, with a mean width of 130 m and a mean depth of 20 m. Immediately upstream, the 500 hm^3 capacity Valdecañas reservoir is located. The Alcántara reservoir, with a normal volume of 1600 hm^3, is situated downstream from Torrejón. The water of Torrejón reservoir is periodically partially exchanged with that of Arrocampo, since the latter is used as the ANPP's
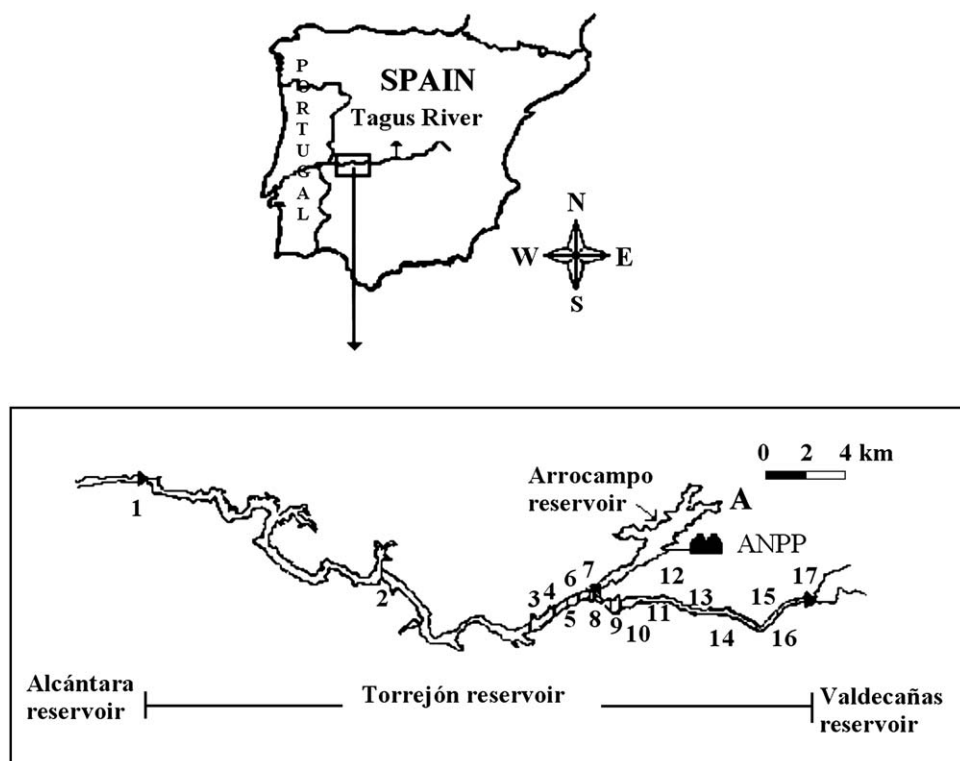

Fig. 1. Map of the River Tagus with the locations of the sampling points. The location of the dam of each reservoir is indicated by ►.

secondary cooling circuit. The purpose of the exchange is to maintain Arrocampo's volume practically constant at 35 hm^3 (ANPP, 1998) and its water temperature sufficiently low to fulfil its cooling function.

The lower part of Fig. 2 shows the temporal evolution of the flows between the Arrocampo and Torrejón reservoirs. The strong 12-month period seasonality of these exchanges, as has been described in previous studies (Baeza et al., 2001), is observed. The upper part of the Fig. 2 shows the monthly discharges of water between the Tagus reservoirs present in Fig. 1, i.e., from Valdecañas to Torrejón, and from the latter to Alcántara. It can be seen that the management of the discharges between these three reservoirs is perfectly coupled, which, as was indicated above, is a common characteristic to all the River Tagus reservoirs. On the other hand, this management is radically different from that between Torrejón and Arrocampo, since the observed seasonality in this case is conditioned by the availability of water in the Tagus River, which in turn is related to the intensity and frequency of rainfalls in the area.

2.2. Sampling

Two sampling programs — one monthly and the other intensive — were carried out in 1997 and 1998 in the above described study area. The intensive program of sampling was designed to determine the spatial distribution of tritium levels in two dimensions in Torrejón reservoir: longitudinally, for 17 sampling points distributed along the length of the reservoir, and transversally, in the centre and on the two banks of the reservoir for each of those 17 points. The monthly program was to allow us to analyze the temporal evolution on the basis of monthly
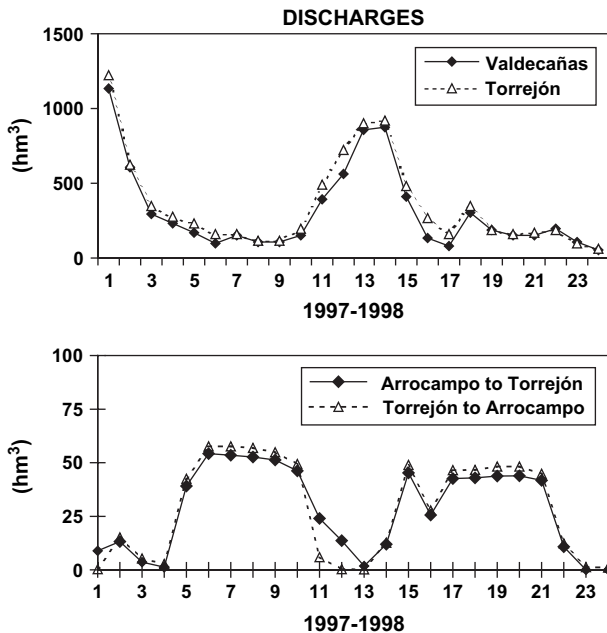

Fig. 2. Upper part: monthly discharges of water from Valdecañas to Torrejón, continuous line, and from Torrejón to Alcántara, dotted line. Lower part: monthly exchange of water from Arrocampo reservoir to Torrejón reservoir, continuous line, and from Torrejón to Arrocampo reservoir, dotted line.

records at three of the aforementioned sampling points in Torrejón reservoir and at another point in Arrocampo reservoir. Water temperature was simultaneously recorded with each sample collection.

2.2.1. Monthly sampling

Every month, surface water samples were collected at the three sampling points of the Torrejón reservoir identified as 1, 7, and 8 in Fig. 1, and at one sampling point of the Arrocampo reservoir identified as A in the figure. As was noted above, Arrocampo is the cooling reservoir for the ANPP. There is a constant forced circulation of water at a rate of 88 m^3/s around the separation dyke constructed in the centre of the reservoir. As a result, its water has perfectly homogeneous physicochemical properties (Baeza et al., 1991), so that point A is entirely representative of the characteristics of water in the reservoir. The locations of points 1, 7, and 8 in Torrejón reservoir are the following. Point 1 is some 10 m from the Torrejón dam, on the left bank of the Tagus. Point 7 is downstream the Arrocampo dam and close to the outlet from that reservoir into Torrejón, on the right bank of the Tagus. Finally, point 8 is some 400 m upstream of point 7, on the left bank of the river and clearly in the opposite direction to the natural flow of the water. These last two points are logically those that will be most intensely affected by the mixing of waters between the Torrejón and Arrocampo reservoirs, which, as we shall see below, have very different radiological and thermal characteristics.

2.2.2. Intensive sampling

Intensive sampling was carried out on two specific dates: 1997-08-01 and 1998-02-12. As can be seen in the lower part of Fig. 2, the former date corresponds to the time of year when the exchange of water between Torrejón and Arrocampo reservoirs is maximum, while the latter is representative of the time of year when the volumes of exchanged water are relatively low. On both dates, surface water samples were collected in a number of longitudinal and transversal transects of the Torrejón reservoir. Fig. 1 shows the location of the points in the three longitudinal transects, covering the 42 km length of the reservoir. The separation of these points was kept as homogeneous as possible, except for a zone of the reservoir that is especially protected because of its wildlife. The number of sampling points on the 1998-02-12 date was increased in light of the results of the analysis of the 1997-08-01 samples.

2.3. Analytical methods

At each sampling point, 1.5 L of water was collected in polyethylene bottles, and temperature was measured with a precision of 0.1 °C. After transport to the laboratory, the samples were filtered through 0.45 μm pore filters prior to their preparation for ^{3}H assay.

For the tritium assay, a 50 mL aliquot was taken and subjected to a process of simple distillation to eliminate colouration, organic matter, and salts that might interfere with the analysis. The distilled sample was then mixed with a scintillation solution of Optiphase Hisafe 3 from LKB-Wallac at a sample/scintillator ratio of 8/12 (Schönhoffer and Henrich, 1987) in 20 mL teflon-coated polyethylene vials. Tritium content was determined using a Quantulus-1220, LKB-Wallac, liquid-scintillation alpha–beta spectrometer. The quenching calibration was performed with tritium standards quenched to increasing degrees with CCl$_4$. The background in the region of the tritium β-emission was of the order of 1.5 cpm. The systematically used counting time was 1000 min (200 min × 5 measurement cycles). The resulting Lower Detection

Limit at a 95% confidence for tritium was 0.5 Bq/L and the figure of merit, $(efficiency)^2$/background, was 320 (Baeza et al., 1999).

3. Results and discussion

3.1. Temporal evolution (1997−1998)

Fig. 3 shows the temporal evolution of ^{3}H levels and the temperature at the surface water for the sampling points identified in Fig. 1 as 1, 7, and 8, belonging to Torrejón reservoir, and point A in Arrocampo reservoir. Table 1 lists the mean values and ranges recorded at these sampling points for the cited variables − tritium and temperature. The following results stand out.

The highest activity levels were recorded at point A, as was to be expected since this is the cooling reservoir for the ANPP. Activity levels and their temporal evolution are consistent with the findings of previous studies (Baeza et al., 2001). The observed temporal evolution is a consequence of the management of these waters, whose regime of exchange with those of the Torrejón reservoir (see lower part of Fig. 2) is conditioned by the maximum temperature that the water can reach to be used to cool the ANPP. Thus, point A not only had the highest temperatures of all the study area, but it also had the narrowest range of temperatures as well. This is because in the cold months of the year, when it is unnecessary to exchange water in order to satisfy the thermal requirements, its temperature falls to less than that of the Torrejón reservoir waters. The reiterated use of the Arrocampo water as coolant during winter is also the reason why ^{3}H levels at point A were higher in these months. In particular, there was a significant negative correlation between tritium levels and temperature at point A (see the last row of Table 1).

For the three points sampled monthly in the Torrejón reservoir − points 1, 7, and 8 − both tritium levels and temperature decreased from point 7 to 8, and from the last to point 1. This is readily understandable given the spatial location of these three points (see Fig. 1) relative to the
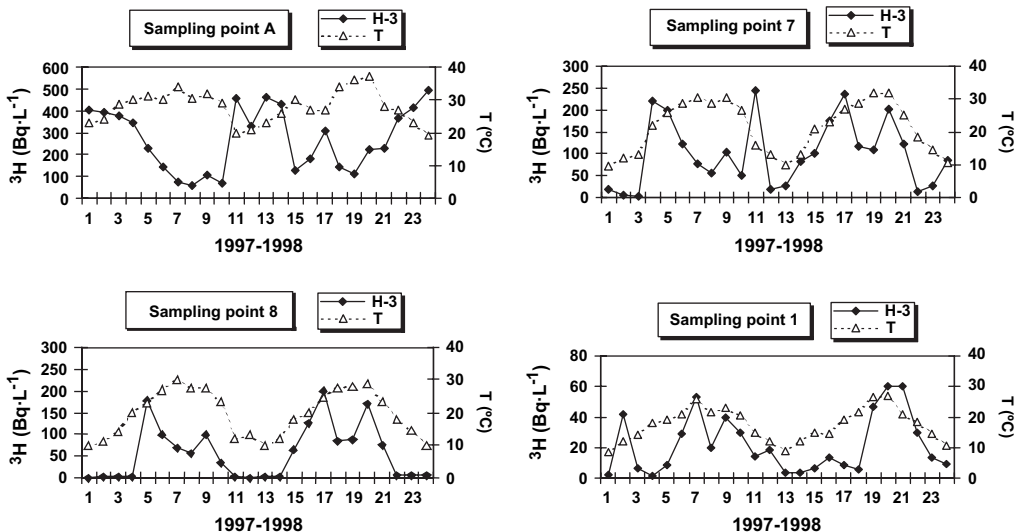

Fig. 3. Specific activity of tritium and temperature measured during 1997−1998 at sampling points A, 1, 7, and 8 of the study area.

Table 1

Mean values and ranges of tritium and temperature recorded during years 1997 and 1998 in waters of Arrocampo reservoir (point A), and Torrejón reservoir (points 1, 7, and 8)

Sampling point	A	1	7	8
^{3}H ± SD (Bq/L)	270 ± 144	22 ± 19	101 ± 77	57 ± 63
Range ^{3}H (Bq/L)	59–496	1.4–6.0	2.4–243	1.2–199
T ± SD (°C)	28 ± 5	18 ± 5	21 ± 8	20 ± 7
Range T (°C)	19–36.2	9–26.5	10–30.5	10–28.5
Correlation ^{3}H−T (significance level)	−0.774 (<0.0001)	0.676 (0.0003)	0.484 (0.0165)	0.711 (<0.0001)

Details of the correlation between these two parameters, at the four sampling points that were selected for the study of the temporal evolution, are also given.

local source of tritium and heat into Torrejón reservoir, i.e., the discharge from the Arrocampo reservoir. Local temporary increases in activity were directly correlated with increases in the exchange of water between the Arrocampo and Torrejón reservoirs (see lower part of Fig. 2), and therefore had a statistically significant positive correlation with rises in Torrejón reservoir water temperature (see the last row of Table 1). These temperature increases of course have a natural component during the hot months, reinforced by the cited exchanges with the hotter water in Arrocampo reservoir. The coupled regulated transit of water in this zone of the River Tagus (see upper part of Fig. 2) is ultimately responsible for the transport of tritium discharged into the Torrejón reservoir to waters below Torrejón dam. This transit occurs preferentially during winter, so that tritium is spread out along the mentioned reservoir during the summer months.

3.2. Spatial evolution

To check the veracity of the foregoing statement, we performed an intensive study on the spatial distribution of tritium and temperature on two dates that were clearly identifiable with the previously typified characteristics for the months of winter and of summer. Results are presented in Table 2. The table lists, firstly, the distance of the 17 points selected along the length of the Torrejón reservoir (see Fig. 1) from the outlet of the discharges from the Arrocampo reservoir (point 7). Secondly, for each of the two sampling dates and each sampling point, it lists the ^{3}H level and, in parentheses, water temperature in the centre and near the banks.

It can be observed that the results were radically different in the conditions identified as summer (sampling date 1997-08-01) and winter (sampling date 1998-02-19). The summer samples showed a good transversal mixing in both tritium levels and temperatures at each sampling point. Indeed, the maximum relative transversal variation was 13.8% for ^{3}H and 5.2% for temperature, both corresponding to point 17. Likewise, the overall spatial homogeneity was also very significant. In particular, omitting the activities and temperatures measured at point 17 which is 12.4 km away in the opposite direction to normal water flow in the reservoir, we can consider that the rest of the reservoir has a well defined tritium level and temperature in the conditions that were identified as summer. In particular, for that sampling date, the values were 56.6 ± 3.2 (SD) Bq/L and 29.2 ± 1.5 (SD) °C, respectively. The two parameters were closely correlated, with a correlation coefficient of 0.880 at a significance level quantified by the value of the parameter $p = 5 \times 10^{-4}$.

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Table 2
Details of the two intensive sampling campaigns, identifying the distance (m) of each sampling point from the outlet of water discharged from Arrocampo reservoir into Torrejón reservoir

Notation	Distance (m)	Sampling 1997-08-01			Sampling 1998-02-19		
		Left side	Centrum	Right side	Left side	Centrum	Right side
1	+28 600	53 ± 3 (26.0)	54 ± 3 (26.5)	56 ± 3 (26.0)	1.5 ± 1.5 (11.5)	1.5 ± 1.5 (11.5)	1.5 ± 1.5 (11.5)
2	+13 100	58 ± 3 (27.0)	58 ± 3 (27.0)	61 ± 4 (27.0)	17.5 ± 2.0 (10.5)	17.7 ± 2.0 (10.5)	17.8 ± 2.0 (10.5)
3	+2600	56 ± 3 (28.7)	55 ± 3 (29.0)	56 ± 3 (29.0)	34 ± 3 (11.0)	16.6 ± 1.9 (10.0)	10.7 ± 1.7 (11.0)
4	+1600	57 ± 3 (29.0)	58 ± 3 (29.5)	57 ± 3 (29.0)	44 ± 3 (11.5)	48 ± 3 (12.0)	7.6 ± 1.7 (11.0)
5	+600	57 ± 3 (29.5)	58 ± 3 (29.5)	60 ± 4 (30.0)	32 ± 3 (12.0)	87 ± 5 (13.0)	58 ± 4 (12.0)
6	+300	53 ± 3 (30.2)	57 ± 3 (30.5)	56 ± 3 (30.0)	88 ± 5 (13.5)	111 ± 6 (14.0)	81 ± 5 (13.0)
7	0	59 ± 4 (31.0)	58 ± 3 (31.5)	55 ± 3 (32.0)	3.7 ± 1.6 (10.0)	229 ± 11 (18.5)	371 ± 18 (24.0)
8	−400	58 ± 3 (30.5)	54 ± 3 (30.5)	55 ± 3 (30.5)	1.6 ± 1.5 (10.0)	2.5 ± 1.5 (10.0)	1.5 ± 1.5 (9.5)
9	−2400	54 ± 3 (29.5)	56 ± 3 (29.5)	53 ± 3 (29.5)	3.9 ± 1.6 (10.5)	5.0 ± 1.7 (9.5)	4.4 ± 1.6 (10.0)
10	−2900	52 ± 3 (28.0)	51 ± 3 (29.0)	53 ± 3 (29.0)	3.7 ± 1.5 (11.0)	3.8 ± 1.5 (10.0)	1.5 ± 1.5 (9.5)
11	−3900	No data	No data	No data	3.3 ± 1.6 (10.0)	3.0 ± 1.5 (10.0)	2.0 ± 1.5 (10.0)
12	−4900	60 ± 4 (30.3)	67 ± 4 (30.2)	61 ± 4 (29.0)	2.2 ± 1.5 (9.5)	2.5 ± 1.5 (9.5)	2.4 ± 1.5 (9.5)
13	−6400	No data	No data	No data	2.9 ± 1.5 (9.5)	3.8 ± 1.5 (9.5)	2.8 ± 1.6 (9.5)
14	−7900	No data	No data	No data	2.2 ± 1.5 (9.5)	2.2 ± 1.5 (9.5)	2.2 ± 1.5 (9.5)
15	−8900	No data	No data	No data	2.2 ± 2.0 (10.5)	1.5 ± 1.5 (9.5)	2.5 ± 1.5 (9.5)
16	−11 400	No data	No data	No data	1.5 ± 1.5 (9.5)	1.5 ± 1.5 (9.5)	2.6 ± 1.6 (9.5)
17	−12 400	2.2 ± 1.3 (19.0)	2.0 ± 1.3 (19.0)	2.3 ± 1.3 (20.0)	1.5 ± 1.5 (9.5)	1.5 ± 1.5 (9.5)	2.8 ± 1.6 (9.5)

The sign + or − indicates whether it is in the same direction or the opposed one, respectively, as the normal advance of the water in the Torrejón reservoir. The table lists, for each of the two sampling dates, the ^{3}H levels (Bq/L) and, in parentheses, the temperature (°C) for the surface water close to the two banks and in the centre of the reservoir.

With respect to the spatial distribution in the Torrejón reservoir determined on the sampling date typical of winter conditions, i.e., when there was a small flow of relatively warm water from the Arrocampo reservoir containing relatively high levels of tritium, as well as a large water flow in the direction of the natural current in this tract of the River Tagus, the following facts may be observed. Firstly, the radioactive and thermal contributions from the Arrocampo discharges were only notable in a limited portion of the Torrejón reservoir. This zone was in the direction of the natural advance of the water, also favoured by the direction of the Arrocampo discharge canal on the right bank of the River Tagus at point 7. One observes in Table 2 that it was precisely at that point where the highest temperature and ^{3}H activity were detected. Both the transverse and the longitudinal homogeneities of these parameters in the Torrejón reservoir water have disappeared under the operating conditions that were identified as being typical of winter. Indeed, during these winter months, the impact of the Arrocampo discharges was only partially detectable downstream from the outlet point into the Torrejón reservoir. It could not even be detected at the head of the reservoir, as indeed was the case on the summer date of our intensive sampling. Nonetheless, the two parameters − ^{3}H activity and temperature − were again perfectly correlated, reflecting their common origin in the discharges from Arrocampo into the Torrejón reservoir. The correlation coefficient was 0.974, with a significance level quantified by the value of the parameter $p = 10^{-4}$.

4. The modelling study

4.1. 1D model

The use of a longitudinal model to study the dispersion of tritium in the whole Torrejón reservoir is justified by its narrowness and shallowness relative to its length (see the Section 2.1). Also, discharges from Arrocampo are designed to achieve a rapid mixing of the pollutants both in depth and transversally. Thus, we are dealing, essentially, with a one-dimensional dispersion problem. Indeed, 1D models have been found to be adequate tools for studying the dispersion of pollutants in channeled regions and rivers (Abril and Abdel-Aal, 2000; Abril et al., 2000; Prandle, 1974). The hydrodynamic equations are solved to obtain the currents along the reservoir for the time period of interest. In the present case, the advection/diffusion dispersion equation for tritium is solved simultaneously. The 1D hydrodynamic equations are (Prandle, 1974)

$$\mathrm{d}S\frac{\partial z}{\partial t} + \frac{\partial(Au)}{\partial x}\,\mathrm{d}x - Q = 0$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial z}{\partial x} + C_\mathrm{d}\frac{u|u|}{h+z} = 0$$

where S is the horizontal surface area, z the height of the water surface above the mean level, u the water velocity along the x direction, A the cross-section area of the reservoir, g the acceleration due to gravity, Q the external flow of water entering/leaving the reservoir at each point, and h a depth parameter defined as $h = A/b$ where b is the width of the reservoir. The bed friction coefficient is defined as

$$C_\mathrm{d} = \frac{g}{C_h^2}$$

where C_h is the Chezy friction coefficient, measured in $m^{1/2}/s$:

$$C_h = \frac{1}{n} h^{1/6}$$

with n being the Manning roughness coefficient, which is equal to 0.035 for natural channels (Streeter and Wylie, 1988).

The solution of these equations, using explicit finite difference schemes, gives z and u values for each of the grid cells into which the reservoir is divided and for each time step. Currents are produced by flows Q exchanged between Torrejón, Alcántara, Valdecañas and Arrocampo reservoirs, whose monthly values are shown in Fig. 2.

The advection/diffusion dispersion equation is:

$$\frac{\partial(AC)}{\partial t} + \frac{\partial}{\partial x}(AuC) = \frac{\partial}{\partial x}\left(AK\frac{\partial C}{\partial x}\right) - \lambda AC$$

where C is tritium concentration, K the diffusion coefficient, and λ the tritium radioactive decay constant. The sources and sinks of tritium must be added to this equation at the corresponding points. Exchanges with the atmosphere are not included since can be neglected in comparison with the input from the nuclear power plant (Baeza et al., 1997).

For the purposes of calculation, the Torrejón reservoir was divided into 84 compartments of size $\Delta x = 500$ m, and fixed the time step at $\Delta t = 20$ s. The dispersion equation was solved using a second-order accuracy explicit finite difference scheme for both the advective and diffusive terms. All the stability conditions were satisfied with the resolutions of the model given above.

The diffusion coefficient was chosen, as it is usual, according to the model spatial resolution. Following Breton and Salomon (1995), $K = 3.2$ m^2/s, this formulation has been used in several modelling studies (Schonfeld, 1995; Periáñez, 2000, 2002). Some more discussion about the diffusion coefficients is included below.

The model was integrated for the years 1997 and 1998. The input parameters were the mean monthly values of the water flows exchanged between the Arrocampo, Torrejón, Alcántara, and Valdecañas reservoirs, obtained from the values presented in Fig. 2. As was noted in the previous section, the main source of tritium in the Torrejón reservoir is the discharge of water from the Arrocampo reservoir. Since the tritium distribution is uniform in the Arrocampo reservoir (Baeza et al., 1997), we took the specific activity in the water released into Torrejón to be equal to that measured at sampling point A. There is also a source term at the tail of the reservoir due to the input of River Tagus water from the Valdecañas reservoir. We assumed the specific activity of tritium in this water to be practically constant, using for the calculation the value of 3.3 ± 1.1 (SD) $\times 10^3$ Bq/m^3 measured at a sampling point in the Valdecañas reservoir (García, 2000).

Results given by the model were the temporal evolution of tritium levels at sampling points 1 and 7, and the tritium profiles along the length of the reservoir on the dates of the two intensive sampling campaigns, 1997-08-01 and 1998-02-19. There are no measurements of water velocities in the reservoir to compare with the calculated currents. However, these must be realistic as the model gives tritium activity levels in agreement with measurements, since tritium is a perfectly conservative radionuclide.

The temporal evolution of the specific activity of tritium in two of the grid cells where measurements were available is presented in Fig. 4, together with the calculated activities. It must be noted that the model spatial resolution is insufficient to separate points 7 and 8. Thus, the
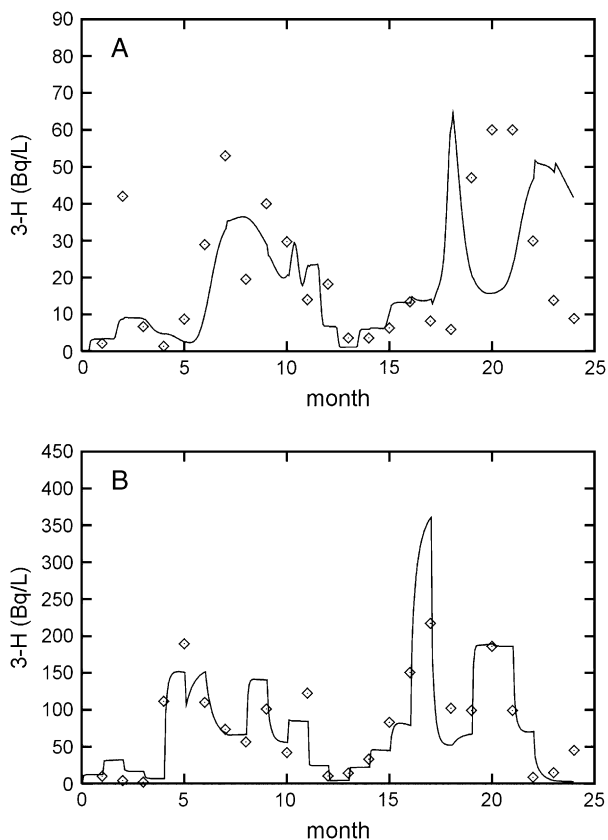
Fig. 4. Temporal evolution during 1997–1998 of the measured (dots) and calculated (lines) tritium specific activities at points 1 (A) and 7–8 (B) starting at January 1, 1997.

measurements presented for point 7 actually are the average of the measurements at points 7 and 8. As can be seen, the model, in general, gives a realistic representation of the measured activity levels and of their temporal variation.

The tritium profiles measured along the length of the Torrejón reservoir in August 1997 and February 1998 are shown in Fig. 5, together with the calculated profiles. It can be clearly seen that for the last date there was no significant migration of tritium upstream from the release point.

Tritium was well mixed in the transverse direction along the whole Torrejón reservoir during the August sampling campaign. The same was the case in February except for the area of the discharge from Arrocampo. The measurements presented in Fig. 5 for August correspond to the mean specific activities of the left and right banks and the centre of the reservoir, since they were essentially the same (see Table 2). This was also the case in February, except that in grid cells 58–61, which correspond geographically to the area of the Arrocampo discharges, there was no mixing in the transverse direction. Thus, the experimental results presented in Fig. 5 for cells 58–61 correspond only to the left bank of the Torrejón reservoir, because the discrepancies between the model and the measurements would be quite large if mean values were used as in the August case. This is related to the fact that a 1D model is inapplicable when there is no mixing in the transverse direction. Indeed, there was an evident two-dimensional structure in the
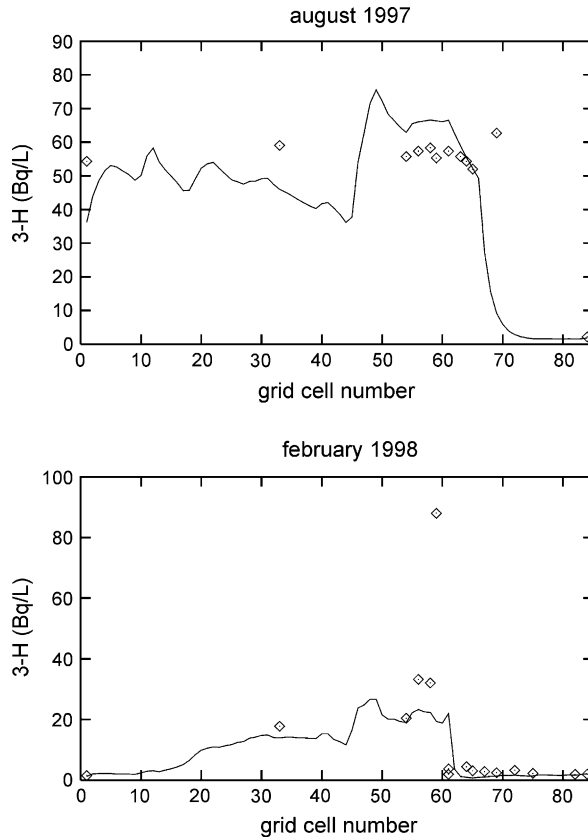
Fig. 5. Calculated (lines) and measured (points) tritium profiles (Bq/L) along the length of the Torrejón reservoir for the two sampling campaigns. The point $x = 0$ corresponds to the Torrejón dam, and $x = 84$ to the tail of the reservoir. Each unit on the x-axis represents 500 m.

data, so that a 2D model was developed for the discharge zone around point 7 in the Torrejón reservoir. This model will allow us to explain why there is mixing in August but not in February.

Another interesting point was that the diffusion coefficient had to be increased by an order of magnitude, to 32 m^2/s, during the summer months to improve the model results. While an increase in temperature will enhance diffusion, it does not explain an increase by a factor of 10. Abril et al. (2000) described a 1D model to simulate the dispersion of rhodamine B patches injected into the Suez Canal. They found that if the patch was initially homogenous in the transverse direction, the experimental results could be reproduced with a diffusion coefficient of 100 m^2/s. However, in the case of a point discharge, with no homogeneity in the transverse direction, a diffusion coefficient of 8 m^2/s was required. The difference in the required diffusion coefficients could only be explained by the different initial conditions. The situation that we observed in Torrejón reservoir was similar: in August, when there was mixing in the transverse direction, the diffusion coefficient required by the 1D model was larger than that of February. A 2D model of the release area is presented in the following subsection. It will be shown that a single formulation of the diffusion coefficient implemented in a 2D domain with transverse velocity gradients can reproduce the observational data in both August and February.

4.2. 2D model

The hydrodynamic and dispersion equations in a 2D depth-averaged approach are (see for instance Periáñez, 2002).

$$\frac{\partial z}{\partial t} + \frac{\partial}{\partial x}[(D+z)u] + \frac{\partial}{\partial y}[(D+z)v] = 0$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial z}{\partial x} - \Omega v + f\frac{u\sqrt{u^2+v^2}}{D+z} = 0$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial z}{\partial y} + \Omega u + f\frac{v\sqrt{u^2+v^2}}{D+z} = 0$$

$$\frac{\partial(HC)}{\partial t} + \frac{\partial(uHC)}{\partial x} + \frac{\partial(vHC)}{\partial y} = \frac{\partial}{\partial x}\left(HK\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(HK\frac{\partial C}{\partial y}\right) - \lambda HC$$

where u and v are the components of the water velocity along the x-and y-axes, D is water depth below the undisturbed surface, Ω the Coriolis parameter, f a bed friction coefficient, and $H = D + z$ is the total water depth.

The model covers 1 km of the Torrejón reservoir, in the area where water exchanges with Arrocampo take place. The grid consists of 50×23 cells with size $\Delta x = \Delta y = 20$ m. The currents given by the 1D model are used as boundary conditions along the open right border of the 2D model. These currents represent, however, values averaged over the transverse direction. Parabolic functions are constructed with mean values equal to the currents given by the 1D model and in such a way that transport is conserved. The flow is thus given a 2D structure, with maximum current in the centre of the reservoir and minimum values along the two banks, with the total flow being respected. The hydrodynamic equations were solved using these boundary conditions for August 1997 and February 1998, until a steady circulation was obtained over the model domain in both months. The water circulation was stored in files to be read by the program that solves the dispersion equation. All the equations were solved using explicit finite difference schemes, again using second-order accuracy to solve the dispersion equation. The time step used to solve the hydrodynamic equations was 0.5 s, and was increased to 60 s when solving the dispersion equations, since the stability conditions are less restrictive than those imposed by hydrodynamics. The bed friction coefficient was fixed as 0.050, except for the grid cells located along land boundaries where it was increased to 0.090 to take friction with the shoreline into account. As in the 1D model, the diffusion coefficient was selected according to the horizontal resolution of the model. The value used was $K = 0.068$ m^2/s.

It may result surprising at this point that three different values for the diffusion coefficients are required to simulate dispersion of a dissolved tracer in the studied environment. Thus, some discussion on the nature of diffusion coefficients will be included here. The diffusive part of the dispersion equation accounts for the reduction of maximum concentration and size increase of a contamination patch due to molecular diffusion. However, in real dispersion problems molecular diffusion can be neglected in comparison with diffusion induced by water turbulence. This turbulent mixing is characterized by an effective diffusion coefficient that is many orders of magnitude larger than the pure molecular diffusion coefficient ($\sim 10^{-6}$ m^2/s). Now the question is how the value of the effective diffusion coefficient can be selected for a given model. Actually, the diffusion term is representing sub-grid scale turbulent mixing: eddies that are smaller

than the grid size and that, as a consequence, cannot be solved. In other words, diffusion is representing advection that cannot be solved by the numerical scheme because of the finite grid size. Thus, the effective diffusion coefficient depends on the grid size: coarse grids require larger diffusion coefficients because larger eddies cannot be solved and their effects have to be described as turbulent mixing. This is the reason why the 2D model uses a diffusion coefficient that is several orders of magnitude smaller than that of the 1D model, whose grid size is larger. After the classical experiments of Okubo (1971), the parameterization used in this paper was proposed (and used in many models). Moreover, the values of the effective diffusion coefficients have to be different in a 1D and a 2D model of the same environment because of the so-called shear dispersion. This is produced because currents in a channel are larger in the central part than those close to the shores due to friction. If a contamination patch is released, its length increases in the central part of the channel due to the larger advection. Then there is diffusion from this central area towards the cleaner shores and the overall result is an enhanced dispersion relative to if the currents were constant across the channel. Shear dispersion is automatically included in a 2D model, since it solves the current profile across the channel, but not in a 1D model. In this case the diffusion coefficient should be larger to account for the effects of shear dispersion. Some more discussion on these points may be found in Periáñez (2005). Finally, the diffusion coefficients depend on the size of the released patch (Okubo, 1971): as this size decreases, smaller eddies move the patch as a whole and their result is a pure advective transport of the patch. Thus, the effective diffusion coefficient decreases as the size of the patch decreases and vice versa. This explains why (in the 1D model) the diffusion coefficients are larger in August, when the initial size of the patch is larger too, since there is mixing in the transverse direction. In conclusion, the diffusion coefficient does not have a definite value for a given environment. It also depends on the model structure (1D or 2D), model resolution (grid size) and initial conditions of the dispersion problem to be solved. Consequently, the selection of the diffusion coefficient is not easy and very often modellers apply empirical relations such as those used in this work.

The calculated water circulation for February 1998 is presented in Fig. 6A as an example. There is a net flow directed from Valdecañas to Alcántara reservoir, with water velocities of the order of 1 cm/s.

The calculated tritium distributions over the model domain are shown in Fig. 6B and C for August 1997 and February 1998, respectively. It can be seen that in August the model yields a tritium distribution that is homogenous in the transverse direction, as was observed in the measurements. The calculated specific activities, however, are higher than the measured values. Given that the model uses monthly averaged tritium discharges, and that the real discharge rate is not constant with time, there may appear discrepancies between calculations and observations depending on the particular release rate at the time of sampling. In February there is a clear tritium gradient across the reservoir, in agreement with observations. The calculated specific activities are in agreement with the measured values.

The differing behaviour of tritium is due to the different currents in the reservoir on the two dates. In February, the currents are relatively large. As a consequence, there is a rapid migration of tritium downstream from the release point. This gives rise to the banded structure seen in Fig. 6C. The main longitudinal currents in August are weaker, but there is a marked current in the release area, of the order of 5 cm/s, directed transversally across the reservoir due to the high discharge rate from Arrocampo. These effects – weak longitudinal currents plus strong transverse current – produce a rapid mixing of tritium in the transverse direction.
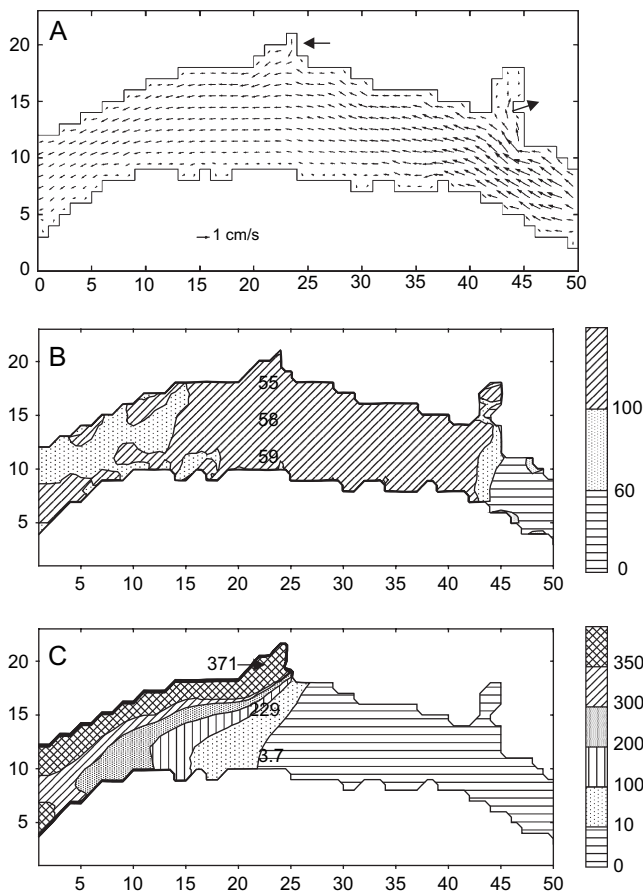
Fig. 6. (A) Calculated currents for February 1998. Arrows indicate the points where the inflow and outflow of water take place. (B) Calculated distribution of tritium, in Bq/L, for August 1997. (C) Calculated distribution of tritium, in Bq/L, for February 1998. Numbers inside the maps indicate the measured specific activities. Units in the *x*- and *y*-axes give the grid cell number (thus each unit corresponds to 20 m).

Thus, it has been shown that a single diffusion formulation implemented over a 2D domain can explain the different behaviour of tritium on dates when the conditions of the management of the Torrejón reservoir water are typical of the months of winter and of summer.

5. Conclusions

The present work has described and analyzed the spatial and temporal evolution for the period 1997–1998 of the tritium levels and temperature in the waters of the Torrejón reservoir, on the River Tagus. This reservoir is coupled hydrologically with the Valdecañas reservoir upstream, with the Alcántara reservoir downstream, and on its right bank exchanges water with the ANPP cooling reservoir. The results showed that the routine operation of the ANPP significantly increases the tritium levels and the temperature of its cooling reservoir. This reservoir therefore behaves as a source of heat and tritium for the Torrejón reservoir. The temporal

evolution of the levels of tritium in the reservoirs of Arrocampo and Torrejón hence depends strongly on the management of their waters. The temporal evolution of the water temperature is also conditioned by the natural evolution of the environmental temperature. The two magnitudes consequently presented seasonal variations with an annual period, which were six months out of phase in the Arrocampo reservoir, and perfectly synchronized at the three sampling points that were systematically analyzed in the Torrejón reservoir.

For the study of the spatial evolution of tritium in the Torrejón reservoir, we carried out intensive sampling at numerous points of the reservoir on two dates clearly typical of winter and of summer. In winter, due to the minimal exchange of water with the Arrocampo reservoir and to the large water flow in the natural direction of the River Tagus waters, the Torrejón reservoir was found to behave in a form similar to a river with a quasi-natural flow regime. Consequently, the relatively insignificant inputs of tritium and heat from the Arrocampo reservoir fundamentally affected the area close to and downstream from the discharge point (point 7 in our study), with major transverse and longitudinal gradients in both temperature and tritium activity. On the contrary, in summer, the Torrejón reservoir was found to behave in a form similar to a lake, since there were minimal flows of water from Valdecañas upstream, and into Alcántara downstream. The exchange of water with the Arrocampo reservoir, where the tritium levels and the temperature are higher, was maximal at that time, however. In these conditions, both the ^{3}H and the heat diffused practically over the whole Torrejón reservoir, with the consequent longitudinal and transversal homogenization of these two magnitudes.

A 1D model of the Torrejón reservoir was developed to study the behaviour of tritium. In general, the model yielded a temporal evolution of tritium specific activities along the reservoir, and tritium profiles along the length of the reservoir for the two intensive sampling campaigns, that were in agreement with the measurements. It was necessary, however, to use a larger value for the diffusion coefficient during the summer months. A 2D model of the release area was developed to study the behaviour of tritium near the ANPP discharge point. It was found that the different dispersion patterns measured in February and August (transverse gradients and mixing of tritium, respectively) were reproduced with a single formulation of the diffusion coefficient implemented over a 2D domain. The different behaviour in winter and summer arises from differing regimes of water circulation in those two seasons.

Acknowledgements

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