Dispersion modelling in rivers for water sources protection, based on tracer experiments. Case studies.

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Abstract: - Judicious selection of mathematical models for application in a specific river basin management can mitigate prediction uncertainty. Therefore, intervention times will be established with better reliability and alarm systems could efficiently protect the aquatic ecosystems and the public health. The main purpose of this paper is to evaluate the performance of river water systems dispersion modelling, based on tracer experiments data for calibration and validation. The present work describes the methodology used in the monitoring programs, which were carried out using tracer injection (*rhodamine WT*) to determine the *in situ* river water dispersion behaviour and the mathematical models applied to simulate different water quality management scenarios on each reach of the three rivers studied: Mondego, Douro and Tagus rivers. The models were calibrated in order to produce operational tools to estimate the probabilistic arrival/peak/recession times, and reminiscent substance concentrations to define, for example, how long water intake need to be suspended after a pollutant spill. The good correlation between experimental data and simulation results allows us to conclude that the applied models showed enough accuracy to describe and predict conservative pollutant transport under different hydrodynamic scenarios, validating this methodology to support the environmental impact assessment of pollutant loads, in order to select the best water sources protection practices.

Key-Words: - water sources protection; dispersion modelling; *rhodamine WT* experiments; portuguese rivers.

1 Introduction

River hydrodynamics and pollutant discharge dispersion characteristics are determinant factors in river basin planning and management, where different waters uses and aquatic ecosystems protection must be considered. Ever increasing computational capacities provide the development of powerful and user-friendly mathematical models for the simulation and forecast of quality changes in receiving waters after land runoff, mining and wastewater discharges [1].

The main purposes of this research work were parameter estimation for *in situ* characterization of dispersive behaviour in river water and performance evaluation of numerical models, when applied to pollutant transport modelling in three different river systems. Several tracer dye experiments were carried out in order to improve knowledge about the water bodies' dispersion patterns and to provide field data for water quality model calibration and validating procedures. The results showed that this approach can constitute a power and useful operational tool to establish better warning systems and to improve management practices for efficiently protect river water sources and, consequently, public health.

2 Methods

2.1 Tracer experiments

The three monitoring programs, with several sampling campaigns, were carried out using *rhodamine WT* as tracer dye, recommended for its characteristics: it is non-toxic, non-reactive, has high diffusivity, is highly detectable, and has low sorption and low acidity. A *Turner Designs* fluorometre was used for tracer concentrations measurements. Blanks were taken in all sampling sites for river natural fluorescence determination.

For each case study, the location of the sampling sites was established according to the aims of its monitoring program, the sites accessibility (bridges), river physic characteristics, mixing conditions, weirs location and availability of human resources.

Experimental longitudinal dispersion coefficients were calculated from concentration time curves at consecutive sampling sites, using the methodology described by Chapra [2] for tracer studies.

The injected tracer dye mass was calculated considering the water volume estimated in the river reach or reservoir system and the fluorometre detection limit.

The tracer mass recovered at each site allowed the assessment of the importance of physical and biochemical river processes by quantifying precipitation, sorption, retention and assimilation losses.

The river flow selection for each water body and sampling program was considered under different hydrodynamic scenarios: hydropower plant discharge patterns; dry-weather conditions, flood and frequent flows obtained from flow gauge station records [3].

2.2 Mathematical modelling

The *Duflow package* [4] was designed to cover a large range of applications in different water systems and to assess water quality problems [5]. The model is based on the one-dimensional partial differential equations to describe non-stationary flow in open channels. These equations are the mathematical translation of the laws of conservation of mass and momentum. The water quality part of the *Duflow package* is based on the partial differential equation describing the concentration of a constituent in a one dimensional system as function of time and place, where a *production* term includes all physical, chemical and biological processes to which a specific constituent is subject to. The process descriptions can be supplied by the user, who can create different types of kinetics for a specific river model. The *Duflow* equations compute flow discharges and elevations at the same point.

The *ADZ* modelling technique (*ADZTOOL*) is a common approach to modelling dispersion processes, providing accurate predictions of the travel time and spread moving downstream in a natural stream [6]. This tool was applied only to the Mondego river case study, because the *Duflow* model has presented best performances on model calibration and validation procedures.

3 Case studies

In order to cover comprehensive hydrodynamic regimes and river system characteristics, three case studies are presented in the following subsections.

3.1 Mondego river

Run-off from Urgeiriça uranium mine discharged to Pantanha streamlet, a tributary of river Mondego, has determined the interest of an environmental impact assessment on receiving waters, considering the downstream presence of Carregal do Sal water supply impounding.

3.1.1 Study area

The study area occupies the medium part of the Mondego river basin, located in the central region of Portugal. The drainage area is 6670 km2 and the annual mean rainfall is between 1000 and 1200 mm. The river reach considered in this work begins downstream from the Caldas da Felgueira bridge and ends at the Tábua bridge (Fig.1), with a length of approximately 24 km. The river water is intensively used for hydroelectric generation, domestic and industrial water supply and agricultural irrigation.

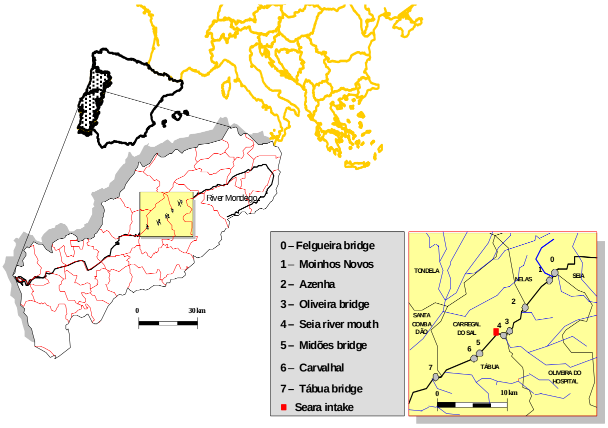

Fig.1 Mondego river basin and sampling stations

Seven sampling sites were considered, with site 0 (Caldas da Felgueira bridge) being the upstream tracer dye injection point, where a single gauge station is located in this reach (before Aguieira dam).

The location of sampling stations was established according to their accessibility (bridges), mixing conditions, weir location, logistics and human resources availability.

The flow regime of this river reach is strongly influenced by the Aguieira reservoir water level and by the fourteen weirs considered. Water levels at Aguieira reservoir were recorded during the monitoring program.

The flow discharge values considered for calculations were obtained from Nelas flow gauge station records.

3.1.2 Monitoring program

A monitoring program was carried out using tracer injection (*rhodamine WT*) to evaluate the *in situ* characterization of dispersive behaviour in river water under three different hydrodynamic regimes: flood (140 m^3s^{-1}), frequent (40 m^3s^{-1}) and dry-weather (0,74 m^3s^{-1}) flows.

Table 1 presents the information about all the tracer injections on the three sampling programs made in this study. Due to operational reasons, tracer dye was injected simultaneously in two distinct river sections.

Table 1. Synthesis of tracer injections (Mondego)

Injection	Date	Hour	Point	Flow (m³/s)	Rhodamine mass (g)
1	89-12-09	8:20	Site 0	140	100
2	89-12-09	15:40	Site 3	144	200
3	89-12-10	8:00	Site 0	100	200
4	89-12-10	8:30	Site 5	110	400
1	90-06-15	7:32	Site 0	0.74	400
2	90-06-15	8:30	Site 3	0.74	200
1	90-11-09	7:40	Site 0	40	400
2	89-11-10	8:00	Site 3	29	400

Figure 2 shows the *rhodamine* spread evolution for the first injection of the November monitoring program at Caldas da Felgueira bridge. The mixing conditions are increased by the weir effect.

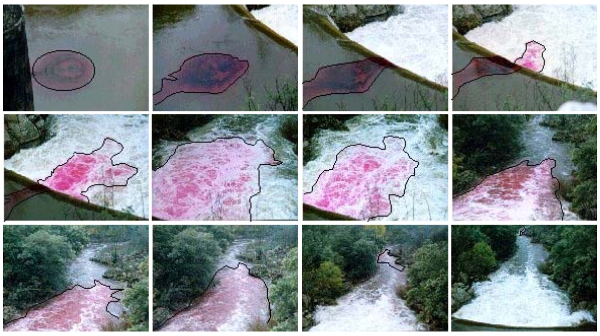

Fig.2 *Rhodamine* spreading after their injection

3.1.3 Results and discussion

Table 2 compares the average velocity, travel time and dispersion results obtained from Mondego river model simulations with experimental tracer data.

Table 2. River Mondego model calibration results

MONITORING PROGRAM	REACH	AVERAGE VELOCITY (ms^{-1})		TRAVEL TIME (h)		DISPERSION COEFFICIENT (m^{2}s^{-1})		RECOVERED MASS
		EXPER.	DUFLOW	EXPER.	DUFLOW	EXPER.	DUFLOW	(%)
3 rd. (Nov.-90)	S1 – S2	0.526	Var.	2:37	2:35	14	10	57
	S2 – S3	0.497	Var.	2:41	2:41	51	45	56
	S3 – S5	0.473	Var.	3:21	3:19	37	35	55
	S1 – S3	0.511	Var.	5:18	5:16	34	-	-
	S1 – S5	0.497	Var.	8:38	8:35	35	-	-
1 st. (Dec.-89)	S1 – S2	1.105	Var.	1:14	1:14	52	40	62
	S2 – S3	0.949	Var.	1:24	1:24	61	70	62
	S1 – S3	1.023	Var.	2:38	2:38	58	-	-

Experimental longitudinal dispersion coefficients were calculated from concentration-time curves at consecutive sampling sites using the analytical solution of first order decay kinetics [7].

The good agreement between model results and experimental data can be supported by the range of correlation coefficients values calculated: 95% for sites 1 and 2; 98.5% for sites 3 and 4, validating the longitudinal dispersion coefficients adopted for the Mondego river model calibration. Figure 3 shows the correlation between experimental concentration-time curves, the analytical solution values and the Mondego river models outputs (based on *Duflow* and *ADZ* packages), at sampling stations 2 and 3.

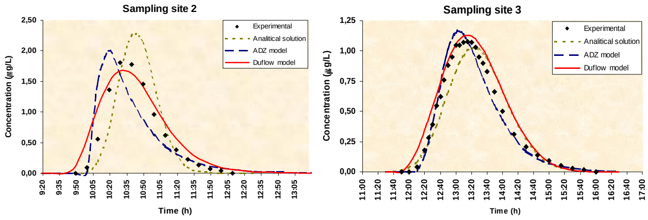

Fig.3 Mondego river models calibration with experimental data (S2 and S3 sampling sites)

A relatively better performance of the *DUFLOW* package can be inferred from these graphics. The Mondego river model was validated using experimental data from the December 89 monitoring program (first injection), under flood flow conditions. A good correlation with field data was also obtained, as supported by the correlation coefficient values depicted in Figure 4.

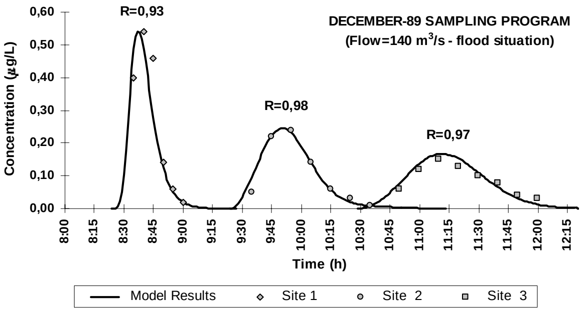

Fig.4 Mondego river model validation and its correlation coefficients

In practice, river water dispersion characteristics can be evaluated from the peak concentration decrease with dye spread travel time variation at a downstream site. After initial tracer and river water mixing, the ratio – peak concentration (Cp) / total injected tracer mass (M_{inj}) – decreases with a power function of its travel times (Fig. 5).

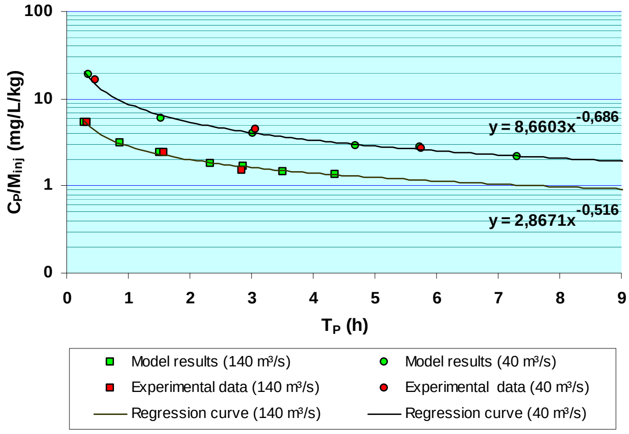

Fig. 5 Peak concentration variation with dye spread travel time (Mondego river)

3.2 Douro river (Miranda reservoir)

This case study had the purpose to assess the environmental impact of accidental pollutant discharges in an international reach of the Douro river, between the Castro dam (Spain) and The Miranda dam (Portugal).

3.2.1 Study area

The study area is located on a Douro river international reach at the north-eastern region of Portugal. This river reach begins downstream of the Castro reservoir and ends at the Miranda reservoir, with a length of approximately 13.5 km. Four sampling sites were considered, with the site 0 (downstream Castro dam) being the upstream tracer dye injection point (Fig. 6).

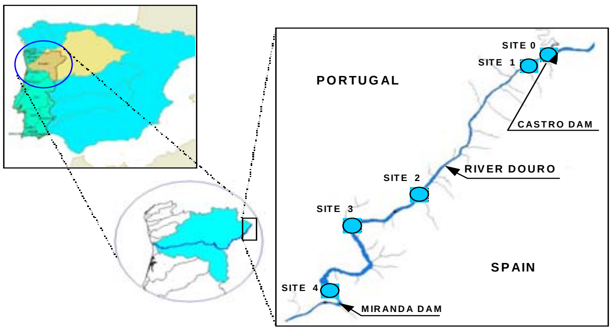

Fig.6 Douro river basin and sampling sites location

The flow regime of this river reach is strongly influenced by the discharged flow from the Castro dam, by the turbinated flow in the Miranda dam, and by the surface water levels in the Miranda reservoir (Fig. 7).

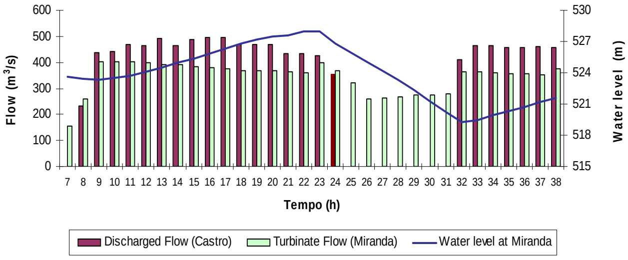

Fig.7 River Douro flow discharges and surface water level at the Miranda reservoir

3.2.2 Monitoring program

Seven sampling campaigns were carried out using tracer injection (*rhodamine WT*-20% solution) to evaluate the *in situ* characterization of dispersive behaviour in reservoir water under flow ranges from 170 to 457 $m^3 \cdot s^{-1}$. Blanks were taken at all sampling points for river natural fluorescence determination.

Table 3 presents the information about all tracer injections on the seven sampling campaigns made in this study.

Table 3. Synthesis of tracer injections (Douro river)

Year	Program	Date	Time	River flow (m^3/s)	Water level ** (m)	Rhodamine WT mass (kg)	Sampling L	Sampling V	Sampling T
1985	1º	85-05-07/09	9:00	400	-	11.5 *	1-4	-	-
	2º	85-09-24/26	8:00	170	-	5	1-4	-	-
1986	1º	86-10-01/03	7:30	254	524	5	1-4	-	-
	2º	86-10-29/31	8:00	265	526	5	1-4	2-4	3, 4
1987	1º	87-04-08/10	10:00	457	525 - 522	5	1-4	3	2, 3
	2º	87-07-22/24	6:35	100 (?)	527 - 526	5	1-4	2	1, 2
	3º	87-11-18/20	7:30	352	525 - 524	5	1-4	3	1-3

Nota : L = longitudinal ; V = vertical ; T = transversal .
* - Rhodamine B ; ** - Miranda reservoir

Average values of flow discharges at the Castro reservoir and mass of injected rhodamine were considered as the upstream boundary conditions. Surface water level at the Miranda reservoir was taken as the downstream boundary condition. Transversal variation of the tracer concentration verified in sampling site 2 is presented in Figure 8.

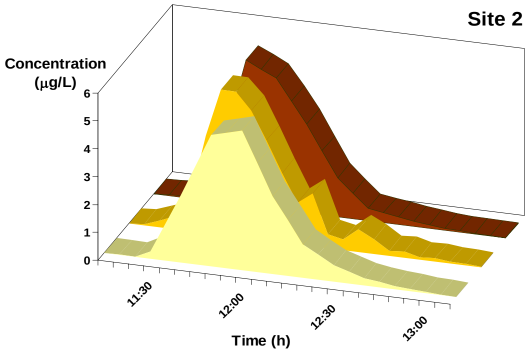

Fig.8 Transversal variation of tracer concentration (site 2)

Similar results were obtained at the other sites allowing the conclusion that mixing conditions were favourable to a rapid equalisation of concentrations in that direction.

3.2.3 Results and discussion

The model calibration procedure (Fig.9) included the adjustment of the friction bottom values and the longitudinal dispersion coefficients. The model was validated using other sampling data set (Nov. 87), obtained under a different flow regime (Fig. 10).

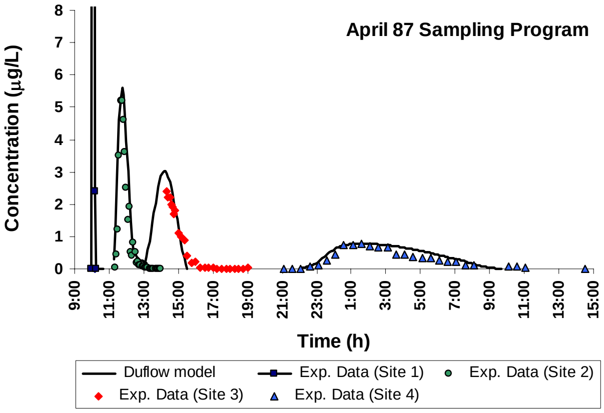

Fig.9 Douro river model calibration with field data

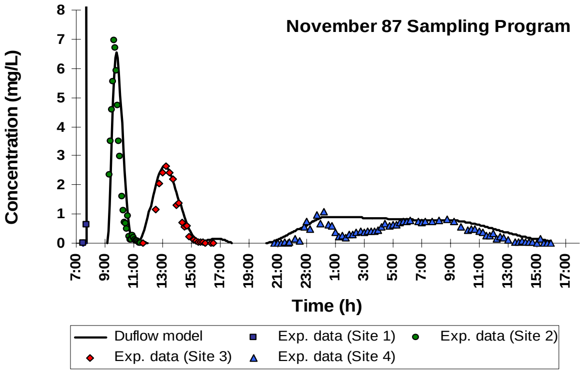

Fig.10 Douro river model validation with field data

Table 4 compares travel times and dispersion coefficients obtained from the Douro river model with experimental tracer data used for the calibration procedure.

Table 4. River Douro model calibration results

REACH	TRAVEL TIME (h)				DISPERSION COEFICIENT $(m^2.s^{-1})$	
	APRIL 87		NOVEMBER 87		DUFLOW	
	EXPERIMENTAL	DUFLOW	EXPERIMENTAL	DUFLOW	APRIL 87	NOVEMBER 87
Site 0 - Site 1	0:05	0:05	0.06	0:05	50	45
Site 1 - Site 2	1:45	1:45	2:10	2:20	30	20
Site 2 - Site 3	4:10	4:20	5:45	5:40	5	20
Site 3 - Site 4	15:35	15:45	16:45	17:30	2	2

The presented values show apparent slight differences between experimental longitudinal dispersion coefficient values and those adopted for model calibration. This can indicate that a 2D-V modelling approach must be performed in future works in order to improve the correlation between model results and experiments tracer data.

It was reported that the *ratio* tracer peak concentration (Cp) over total mass of injected *rhodamine* varies with a negative power of the travel time. This exponent is a constant value (0.84 and 0.86) depending on the dispersion river reach characteristics (Fig. 11).

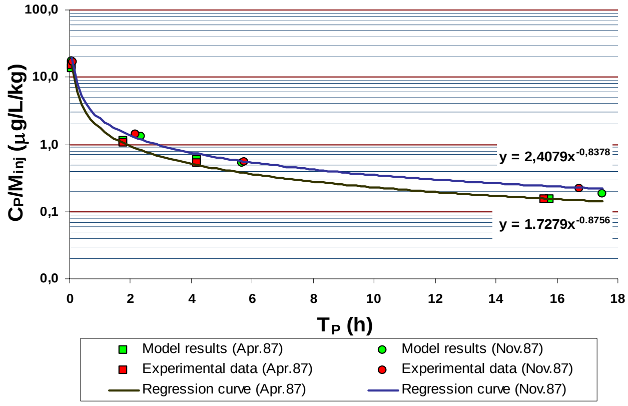

Fig.11 Peak concentration variation with dye spread travel time (Miranda reservoir)

3.3 Tagus river (Belver reservoir)

This case study had the purpose to assess the environmental impact of accidental radioactive refrigeration water discharges in an international reach of river Tagus, between the Cedillo dam (Spain) and the Belver dam (Portugal).

3.3.1 Study area

The study area presented in this work is located on a Tagus river national reach. This river reach begins downstream of the Fratel reservoir (Portugal) and ends at the Belver dam, with a length of approximately 9.2 km (Fig. 12). Four sampling stations were considered (S8, S9, S10 and S10a), with the site 8 (downstream from the Fratel dam) being the upstream tracer dye injection point.

Fig.12 Tagus river basin and the studied reach

The flow regime of this river reach is strongly influenced by the Fratel dam discharged flows and also by the turbinated flows and the surface water levels at the Belver dam.

3.3.2 Monitoring program

Four sampling campaigns were carried out using tracer injection (*rhodamine WT*-20% solution) to evaluate the *in situ* characterization of dispersive behaviour in reservoir water under flow ranges from 23 to 300 $m^3 \cdot s^{-1}$. Blanks were taken in all sampling points for river natural fluorescence determination.

Table 5 presents the information about all tracer injections made in this study.

Table 5. Synthesis of tracer injections (Tagus river)

Sampling monitoring	Date	Hour	Local	Sampling sites	Flow (m^3/s)	Reservoir water level (m)	Dye Mass
1ª	91-06-08	7:45 7:31	Cedillo Fratel	S2, S3, S4 S9, S10, S11	150	73 (Fratel) 48 (Belver)	10 5
2ª	91-11-23	9:15 9:15	Cedillo Fratel	S2, S3, S4 S9, S10, S11	300	72.7 (Fratel) 45.9 (Belver)	10 10
3ª	92-04-12	8:02	Cedillo	S1a, S2, S2a, S3, S4	148	72.75 (Fratel)	20,1
4ª	92-11-03	8:11	Fratel	S8, S9*, S10, S10a	23	47 (Belver)	5

Average values of flow discharges at the Fratel reservoir and mass of injected *rhodamine* were considered as the upstream boundary conditions. Surface water level at the Belver reservoir was taken as the downstream boundary condition.

3.3.3 Results and discussion

The model calibration procedure included the adjustment of the friction bottom value in each reach and longitudinal dispersion coefficients obtained in the sampling program of Nov.92. Table 6 compares travel times and dispersion coefficients obtained from the Tagus river model outputs with experimental tracer data.

Table 6. Tagus river model calibration results

Monitoring program	Reach	Average velocity (m/s)		Travel time (h)		Dispersion Coeficients (m^2/s)	
		Exper.	Duflow	Exper.	Duflow	Exper.	Duflow
4ª (Nov. 92)	**S8 – S8a**	0,156	0,1563	1:00	0:50	14,80	5,0
	S8a – S9*	0,126	0,1260	1:25	1:16	7,50	9,0
	S9* – S9a	0,129	0,1291	2:43	2:50	7,30	8,0
	S9a – S10	0,111	0,1110	2:45	3:14	11,40	8,0

The model has been validated using other sampling data (Nov. 91), obtained under a different flow regime. After initial tracer and river water mixing, the *ratio* – peak concentration (C_p) / total injected tracer mass (M_{inj}) – decreases with a power function of its travel times (Fig. 13). The exponent is a constant value in the range (0.77 to 1.23) depending on the dispersion river reach characteristics.

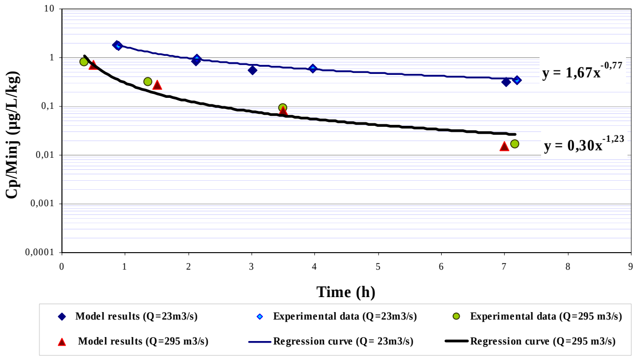

Fig.13 Peak concentration variation with dye spread travel time (Belver reservoir)

The exponent range values are very high, indicating that a 2D-H modelling must be applied for this river system in order to improve model results correlation with tracer experimental data sets.

4 Conclusions

This work presents the results of longitudinal dispersion coefficients estimation and proposes mathematical equations for peak concentration decrease with dye spread travel time based on tracer experiments made in several reaches of three different Portuguese river systems.

Mathematical modelling appears to be a powerful tool to solve pollutant transport problems in river systems with longitudinal dispersion behaviour similar to the case studies presented, even under different flow regimes.

For the Miranda and the Belver reservoirs further developments must be done to simulate vertical and transversal dispersion processes in order to improve model results correlation with experimental tracer data and to mitigate some prediction uncertainty.

The *DUFLOW* package is a useful tool to develop accurate river models and to simulate pollutants transport in water bodies with different dispersive characteristics. In general, models results showed a satisfactory agreement with experimental data, allowing a reasonable support for impact assessment of different pollutant load scenarios in the river water quality. This procedure is of paramount interest in river basin management strategy for defining alarm schemes, minimizing the effects from accidental pollutant spills, and to improve water sources protection practices.

Acknowledgments

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