Comparative Analysis of 1D and 2D Tools for the Modelling of the Dispersion of Liquid Discharges in Rivers

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1. KEY WORDS

Discharge dispersion, hydraulic modelling, comparative analysis, TELEMAC 2D, CASTEAUR 2D, SYMBIOSE, Loire River, tracer dispersion.

2. ABSTRACT

The modelling of the dispersion of liquid discharges in rivers relies heavily on the selection of appropriate models (hydrography, hydraulics and dispersion) in regard of the situation (normal operating conditions, crisis, case of expertise…) and operational criteria such as available data, calculation time and required precision. To ensure the best choice for a given case, this research aims to compare and characterize the optimal application areas of three modelling tools available at IRSN by considering their suitability for routine assessment (monitoring, site expertise, etc.) and accidental scenarios (situation assessment, decision support…), as well as their performance and operational constraints, including data requirements and response times. The tools compared are a 1D dynamic model (SYMBIOSE, developed at IRSN and co-owned by IRSN and EDF), a 2D analytical approach in steady-state conditions (CASTEAUR2D, developed at IRSN) and a numerical 2D model (TELEMAC 2D, originally applied by IRSN for flood risk assessment). The study focuses on the downstream of the Dampierre-en-Burly nuclear power plant (NPP) located on the Loire River, 50 km upstream from Orléans, which is already used as an application area for the TELEMAC 2D model at IRSN. To identify the privileged application domains of these tools, they are applied and compared on the base of in situ tritium activity concentrations measured in the Loire River by EDF during routine discharges of the NPP for low and medium flow rate conditions of the river and completed by an hypothetical case for high flow rate conditions. It can be concluded that SYMBIOSE excels in quick response but has limitations as it only provides mean activity concentration and maximum activity concentration values. CASTEAUR 2D offers accessible setup but simplifies river geometry. TELEMAC 2D provides authentic 2D data but demands more computational resources and expertise.

3. INTRODUCTION

Studying the dispersion of substances released in rivers is important due to its significance in multiple aspects. It enables to assess the potential environmental impact of discharges, offering insights to evaluate transfers of released substances. This knowledge is important to manage the industrial liquid discharges in such a way as to safeguard the quality of the river in terms of biodiversity and water uses. Moreover, it participates to the demonstration and possibly to the achieving of the compliance with regulatory limits governing the release of substances into water bodies [1]. Additionally, understanding substances mixing informs emergency response plans in case of an accident, contributing to effective mitigation efforts [2]. It helps to provide essential insights into the long-term environmental effects, such as the accumulation in sediments or aquatic life, thus facilitating informed decision-making for sustainable and responsible operations [3].

The release of radioactive gases and liquids is part of the normal and authorized operations of Nuclear Power Plants (NPP). These discharges are strictly regulated, limits of discharges are fixed, and each plant is equipped with devices and facilities for collecting, treating, and controlling effluents before discharge and monitor their dispersion and impact in the environment during and after the discharge [4]. In this context, IRSN, the French expert for radioprotection and nuclear safety, can employ an array of modelling tools for the analysis of the propagation of radioactive liquid discharges in river systems, each with different levels of precision and suitability across spatial and temporal scales. They are a 1D dynamic model incorporated in the SYMBIOSE platform [5], a 2D analytical approach with the CASTEAUR2D code which operates within a steady-state framework [6] and the TELEMAC 2D software [7] which is conventionally applied to flood modelling at the institute and not in the context of radioactive discharge propagation. Consequently, deeper understanding was required regarding the technical differentials and practical utility of these three tools for the modelling of the dispersion process in rivers.

In this context, this study aims to perform a comparative evaluation of these codes to provide a concrete guideline for their optimal application across a variety of different scenarios of dispersion in rivers (routine, crisis, expertise…) and for different flow rate conditions (mean flow, high flow, low flow…). To achieve this, an assessment is conducted on a site-specific case study allowing to unravel their performance attributes, operational constraints, and situational prioritization criteria, applicable to both routine scenarios and crisis management situations likely to be assessed by IRSN.

4. MATERIALS AND METHODS

For their comparison, the three codes are analysed in terms of required data, software characteristics, computer capacities and calculation times and their simulation results are compared to each other in the frame of three case studies with, for two of them, an additional confrontation to empirical data of two tritium tracing campaigns performed and provided by EDF to characterize the dispersion of the liquid discharges downstream the Dampierre-En-Burly NPP and between them for a hypothetical high flow rate scenario.

4.1. Study area

The study area is the Loire River over its first ten kilometers downstream the discharge manifold of the Dampierre-En-Burly NPP (Figure 1).

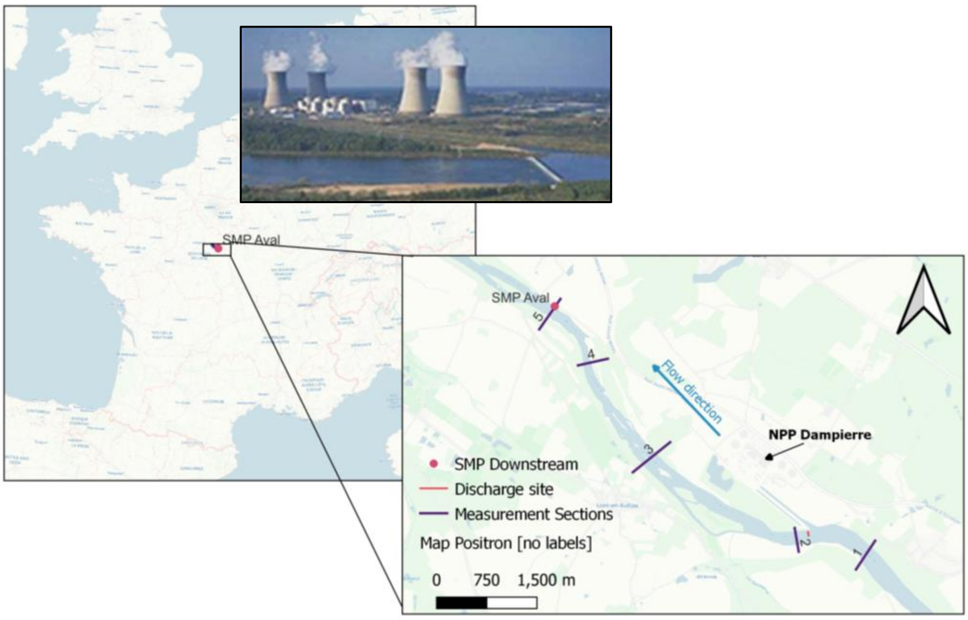

Figure 1: Study area, Loire River between the discharge manifold site and the SMP[1] downstream the Dampierre-en-Burly NPP

The NPP is located on the right bank of the Loire River on the territory of the city of Dampierre-en-Burly in the department of Loiret in France. The radioactive effluents are mixed with the cooling water before being discharged[2] in the Loire River through two pipes inserted in a concrete weir crossing the river over a distance of 140 m, each pipe disposing of 10 submerged perforations. It is located between three other infrastructures, two fish passes at the right and left bank and a boat pass at the left bank (Figure 2).

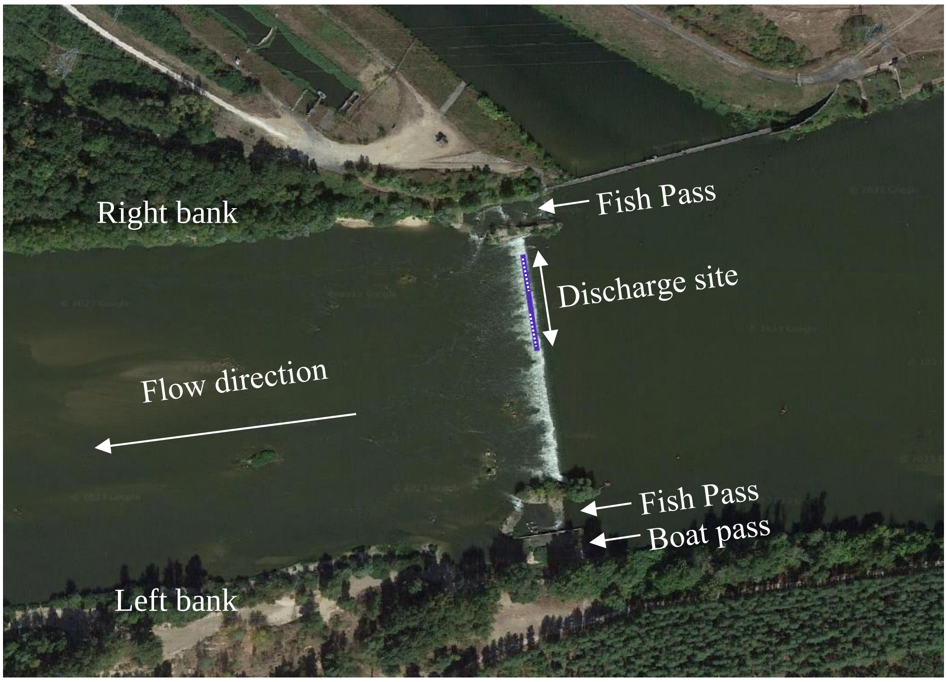

Figure 2: Discharge device of the Dampierre-en-Burly NPP

(Map data ©2015 Google)

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[1] Multi-parameter station

[2] Minimum dilution coefficient of 500 is legally required.

The ten first kilometers of the Loire River downstream the discharge site are characterized by a mean slope of approximatively 7.4 x 10^{-4} $m.m^{-1}$ and a braided bed dotted with several islands and sandbanks more or less submerged according to the water flow rate and relatively mobile with the flood events. The low flow rate conditions correspond to a water discharge of around 60 $m^3.s^{-1}$, the mean flow rate conditions to flow rates of around 300 $m^3.s^{-1}$ and the high flow rate conditions to flow rates greater than 800 $m^3.s^{-1}$.

4.2. Case studies

Three case studies are considered:

1. A mean flow rate scenario for which a dataset of tritium activity concentrations measured across several sections is available. This data comes from one of the measurement campaigns performed by EDF to follow and characterize the dispersion of the liquid discharges downstream the Dampierre-en-Burly NPP. The measurement campaign at mean flow rate was carried out on the 11th of December 2013.
2. A low flow rate scenario for which the dataset comes from the measurement campaign carried out by EDF on the 21st of August 2012 during a period of low flow rate.
3. A hypothetical high flow rate scenario was added to compare and analyze the behavior of the modelling tools for such conditions. The water flow rate is set at 1500 $m^3.s^{-1}$, which is the maximum flow rate at the river where liquid releases are allowed to occur [6]. For this case the same discharge rate and upstream activity concentrations than the scenario at mean flow rate were applied.

The main characteristics of the two tracings are detailed below.

4.2.1. Tracing campaign at mean flow rate

The campaign at mean flow rate was realized on the 11th of December 2013. Water samples were taken at 12 sections orthogonal to the Loire River. The first section was located upstream the release site to provide the upstream boundary condition of the tritium activity concentration. These conditions were stable during the tracing period with a value of 19 $Bq.L^{-1}$ induced by the releases of the Belleville Sur Loire NPP, located 30 km upstream the Dampierre-en-Burly NPP.

The section 5 corresponds to the location of the multi-parameter station (SMP) dedicated to the regulatory monitoring of the river downstream the NPP. The water flow rate of the Loire River (298 m^3/s) and the tritium discharge rate (9.2 x 10^6 $Bq.s^{-1}$) were almost stable during the campaign. For this study, the results of the modelling tools were confronted to the tritium activity concentrations measured at the sections 2, 3, 4 and 5 (Table 1) and at the downstream SMP.

4.2.2. Tracing campaign at low flow rate

Table 1: Loire sections for the tracing at mean flow rate condition

Sections	Distance to the discharge site (km)
2. Downstream of discharge site	0.2
3. Lion en Sullas	2.7
4. La Benne	4.5
5. Port Ouzouer	5.4

The campaign at low flow rate condition was done the 20 of August 2012. The water of the Loire River was sampled at the same sections than for the mean conditions (Table 1 and Figure 1). The upstream activity concentration measured at the section 1 remained stable during the period of the tracing with a value of 3 $Bq.L^{-1}$, close of the background value. The water flow rate of the Loire River

(67 m³/s) and the tritium discharge rate (2.1 x 10^6 Bq.s^{-1}) were almost stable during the campaign. As previously, the results of the codes were compared to the tritium activity concentrations measured at the sections 2, 3, 4 and 5 including the measures done by the downstream SMP.

4.3. Modelling tools

4.3.1. SYMBIOSE

SYMBIOSE is a modelling and simulation platform for environmental radiological risk assessments. It is developed within a R&D project co-funded by the IRSN and EDF dedicated to improving their capabilities to predict the fate, transport and impact of radionuclides released into the environment from nuclear sites and disperse through various means like atmospheric and aquatic pathways (river or sea) under normal operation, accidental, and decommissioning conditions. The primary purpose of SYMBIOSE is to model how these radionuclides behave over time and space and their impact within different biotic and abiotic components of the environment (atmosphere, river, sea, agricultural systems, forests, human and non-human biota populations).

Inside SYMBIOSE, the simulation of dispersion and movement of radionuclides within abiotic compartments of rivers relies on the utilization of IRSN's CASTEAUR code, which is integrated within the platform. Originally developed for emergency situations, this code assumes rapid and complete lateral spreading of discharges. It comprises various sub-modules designed to offer a relatively simplified and practical representation of the river and its temporal and spatial variations in terms of hydraulics, sediment behavior, and ultimately, activity concentrations of radionuclides in water, suspended solids, sediments, and the elements of a basic food chain (phytoplankton, zooplankton and planktivorous and omnivorous fish) [8].

The general approach is dynamic and one-dimensional [9]. The calculation domain is a linear of river described by a series of trapezoidal sections defined by their width, their bank angle and their Strickler coefficient. The model of the river can be built from scratch, however, SYMBIOSE's released versions have already pre-built river spatial models for the rivers harboring NPPs in France. For calculations, these spatial models are interpolated to mesh the domain according to the requested spatial step. The hydraulic data are chronicles of water flow rates at the different entrances of the domain (upstream condition and tributaries) and the code applies a pseudo-dynamic hydraulic model combining a dynamic mass balance equation and the Manning-Strickler relation to assess the propagation of water and the hydraulic parameters such as the average velocities. From these calculations, the model can assess the spread of effluent discharged at different sections of the domain and provide a chronical of the mean transverse activity concentrations at any section of the modelled river.

In addition, a maximum transverse activity concentration C_d^{Max} (Bq.m^{-3}) is calculated at any section of the modelled river downstream the releases. Beyond a so-called complete mixing distance downstream the release section (following the curved line modelling the river) denoted *D*, distance for which it is assumed that the mixing of the releases is complete vertically and laterally, the maximal activity concentration equals the mean transverse activity concentration C_d^{Mean} (Bq.m^{-3}). This complete mixing distance D is site-dependent and varies significantly with the river flow rate. In the version V3.0.3 of SYMBIOSE used for this study, for any distance *d* to the release section (following the curved line modelling the river) ranging between 0 m (release section) to *D* (complete mixing distance), the maximal transverse activity concentration in the case of discharges from pipes with multiple nozzles across the river is given by:

$$C_d^{Max} = \frac{3D}{2d+D} \cdot C_d^{Mean} \qquad \text{Equation 1}$$

Assuming a homogeneous distribution of river water flow rates laterally and a width of the river 3 times greater than the length of the release manifold, this empirical model proposes a maximum transverse value ranging between 1 (at the complete mixing distance) and 3 (in the vicinity of the outlet) times the mean transverse activity concentration. In the vicinity of the discharge manifold, it underestimates the maximal transverse activity concentration as it considers the release continuous along the pipe whereas the discharges truly transit through a discontinuous set of nozzles along the discharge manifold.
It should be noted that in the latest version V3.1.0 of SYMBIOSE (released during the summer 2023, after this study was performed) a new methodology enables to tune the coefficients 3 and 2, primarily to account for field observations on different sites and time variations with the river flow rate.

4.3.2. CASTEAUR2D

The code CASTEAUR2D is based on the analytical solution of the dispersion mass balance equation when assuming a punctual release, vertical homogenization, uniform, and stationary conditions [10]:

$$C_{x,y} = \frac{q_r}{h\cdot\sqrt{4\cdot\pi\cdot Ky\cdot u\cdot(x-x_r)}}\cdot e^{-\frac{u\cdot(y-y_r)^2}{4\cdot Ky\cdot(x-x_r)}} \qquad \text{Equation 2}$$

where x_r, y_r are the coordinates of the release point (m), x, y are the coordinates of calculation points (m), q_r is the discharge flow rate (Bq.s^{-1}), $C_{x,y}$ is the activity concentration at the point (x, y) (Bq.L^{-1}), u is the mean water velocity (m.s^{-1}), h is the water depth (m), and Ky is the transverse diffusion coefficient (m^2.s^{-1}). The calculation domain is described by reaches organized in series and/or parallel to represent the different parts of the river which can be considered as uniform. Each reach is parameterized by its length (L, m), slope (i, m.m^{-1}), width (l, m) and rugosity, by using Strickler coefficient (str, m$^{1/3}$.s-^{1}).

The mass balance associated to the connections relationships between the reaches give the water flow rates in each reach. Then, the hydraulic parameters, u and h, are determined with the Manning-Strickler relation [11] associated to the assumption of rectangular sections and the transverse diffusion coefficient, Ky, is given by the Fisher relation [12].

The activity concentrations at any points of a reach are finally obtained by summing the contributions (Equation 2) of all its specific sources and all the linking source points determined at its entrance. These last ones are located by discretizing the entering and exiting interfaces between the reaches according to a lateral space step Δy and by projecting the fluxes at the exiting points through the corresponding entering points of the downstream reaches and by adding an eventual specific background activity concentration. In this process, note that each of these source points is completed by several mirror sources used to supplement the mass losses when the plumes given by Equation 2 cross the banks of the river.

4.3.3. TELEMAC 2D

TELEMAC 2D is a numerical modelling tool specifically designed for simulating hydrodynamics and sediment transport in rivers, estuaries, coastal areas, and other free-surface water bodies. It has been developed by EDF R&D (Electricity of France R&D) with a development consortium for over 35 years [13]. TELEMAC-2D focuses on two-dimensional (2D) hydrodynamic simulations, which means it models the behavior of water and its interactions with the surrounding environment using a two-dimensional grid [7]. It considers factors such as water flow rate, water levels, velocities, and sediment transport. As a 2D tool, the equations used are depth-averaged [14], and for that reason TELEMAC 2D is better applied in cases where the horizontal scale is greater than the vertical scale [15]. It employs numerical techniques to solve the governing equations of fluid dynamics, such as the Saint-Venant equations (also known as Shallow Water Equations), which describe the motion of fluids. These equations are discretized and solved on an unstructured grid to simulate the behavior of water over time. TELEMAC-2D has a wide range of applications in the field of water resources, hydrodynamics, and environmental engineering. Some of the key areas where TELEMAC-2D is used include river and flood modelling, coastal and estuarine dynamics, sediment transport and, in the context of this study, water quality [16].

4.4. Comparison criteria

In this study, the assessment of the performance of the three codes was conducted based on a set of criteria that included both input and output aspects, as well as various requirements and additional capabilities. To evaluate the models' input requirements, factors such as calibration needs, flow type, and the basic data needed for hydraulics and tracer simulations were examined. In terms of outputs, the study considered the quality of results generated by the models and assessed the extent and complexity of the domain they could handle. In relation to other requirements, the study examined the computational time, the complexity of model usage, computational resource demands, and the operational capabilities needed for modifying existing models or creating new ones. Additionally, the study considered other capabilities that the models might possess, which could further enhance their utility in specific applications.

5. RESULTS

5.1. Setup for the three study cases of liquid discharges into the Loire River

5.1.1. SYMBIOSE

The configuration of the SYMBIOSE runs is presented in Table 2:

Table 2: Data for SYMBIOSE for each of the case studies

	Flow rate condition		
Description	Mean flow	High flow	Low flow
River flow rate	298 m³/s	1500 m³/s	69 m³/s
Upstream tritium activity concentration	19Bq/L	19Bq/L	3 Bq/L
Tritium discharge rate	9.2 x 10^6 Bq/s	9.2 x 10^6 Bq/s	2.29 x 10^6 Bq/s
Complete mixing distance (for max. value)	60 km	60 km	30 km

The 20 releases points of the discharge manifold are assumed as a single discharge point due to the 1D nature of the model. The values obtained from SYMBIOSE are time series at the specified sections. A 1D model being used, only the following values are obtained per section: a transverse mean value and a maximum transverse value.
Concerning the complete mixing distance, the value of 30 km for the low flow rate condition has been chosen as EDF's measurement campaign pointed to a distance comprised between 25 and 30 km.
For the medium flow rate case, EDF's measurement campaign concluded the complete mixing was not observed yet at the last measurement section, 35 km downstream. Experience gained by IRSN following previous [6] and on-going studies on the Loire River shows that the complete mixing distance can be significantly greater for medium flow rates than for low flow rates. The choice of 60 km, for this medium flow rate and for the high flow rate was arbitrary and made prior to calculations. Alternate distances of 40 km and 90 km were tested for the medium and high flow rates but led to small changes in the near range considered in this study: the maximum relative difference to the prediction using the 60 km complete mixing distance, which increases with the distance downstream, was +- 6%.

5.1.2. CASTEAUR 2D

For each study case, the parameterization of CASTEAUR2D involves the representation of the river by a network of reaches, the flow rate conditions of the Loire River, the tritium discharges and the tritium activity concentration at the entrance of the calculation domain (Figure 3).
The network of reaches is built from a Google Earth image dating from the 19 July 2010 and corresponding to a low flow rate condition at around 69 m^3/s [17]. It is made up of 24 reaches linked by a connectivity matrix and parameterized by their length, width, slope and Strickler coefficient.

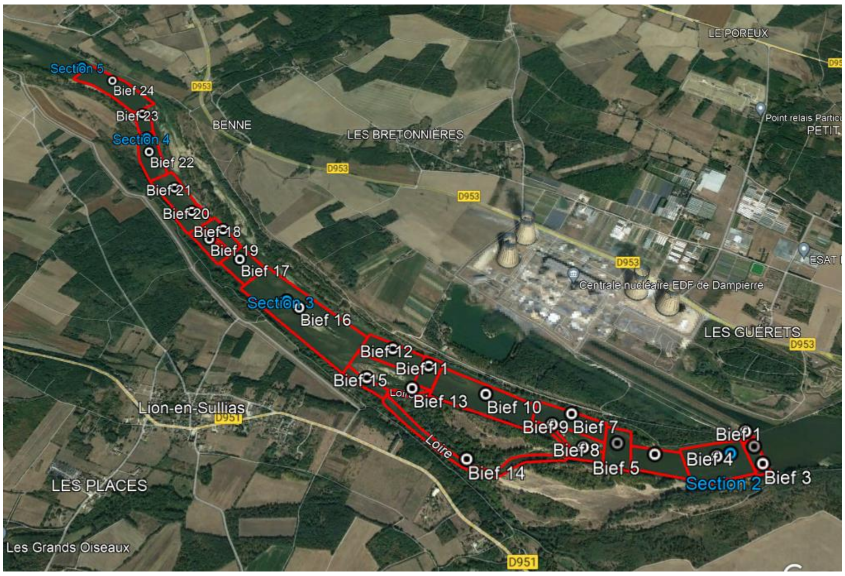

Figure 3: River reaches configuration for the simulation in CASTEAUR2D.

The mean values of the Strickler coefficients (30 $m^{1/3}.s^{-1}$), slopes (7.4 10^{-4} $m.m^{-1}$) and diffusion parameters (0.6) of the reaches were calibrated for the low flow rate condition and applied to the medium and high flow rate conditions with the exception of the widths which were multiplied by a widening factor of 1.2 for the medium flow rate condition and 1.6 for the high flow rate condition as presented in Table 3. The river flow rates and the upstream tritium activity concentrations for each case are also presented in Table 3. For the tritium discharges of the NPP, each of the 20 release points of the discharge manifold is simulated based on its position in the river and assuming that the tritium release flux is uniform and at each point equal to the total release flux (2.29, 9.2 and 9.2 x 10^6 Bq/s for low, mean and high flow rate conditions) divided by 20.

Table 3: Data for CASTEAUR 2D at each of the case studies

	Flow rate condition		
Description	Mean flow	High flow	Low flow
River flow rate	290 m^3/s	1500 m^3/s	69 m^3/s
Upstream tritium activity concentration	19 Bq/L	19 Bq/L	3 Bq/L
Release points	20	20	20
Total tritium discharge rate	9.2 x 10^6 Bq/s	9.2 x 10^6 Bq/s	2.29 x 10^6 Bq/s
Tritium discharge rate at the release points	4.60 x 10^5 Bq/s	4.60 x 10^5 Bq/s	1.11 x 10^5 Bq/s
Widening factor	1.2	1.6	1.0

5.1.3. TELEMAC 2D

The modelled area is a section of the Loire River bounded upstream by the town of Gien and downstream by the town of Jargeau. The model covers a span of around 50 km of the river (Figure 4), however for this study only the first 10 km are analyzed as shown in Figure 1. The Dampierre-en-Burly NPP is located on the right-side bank of the river Loire [18].

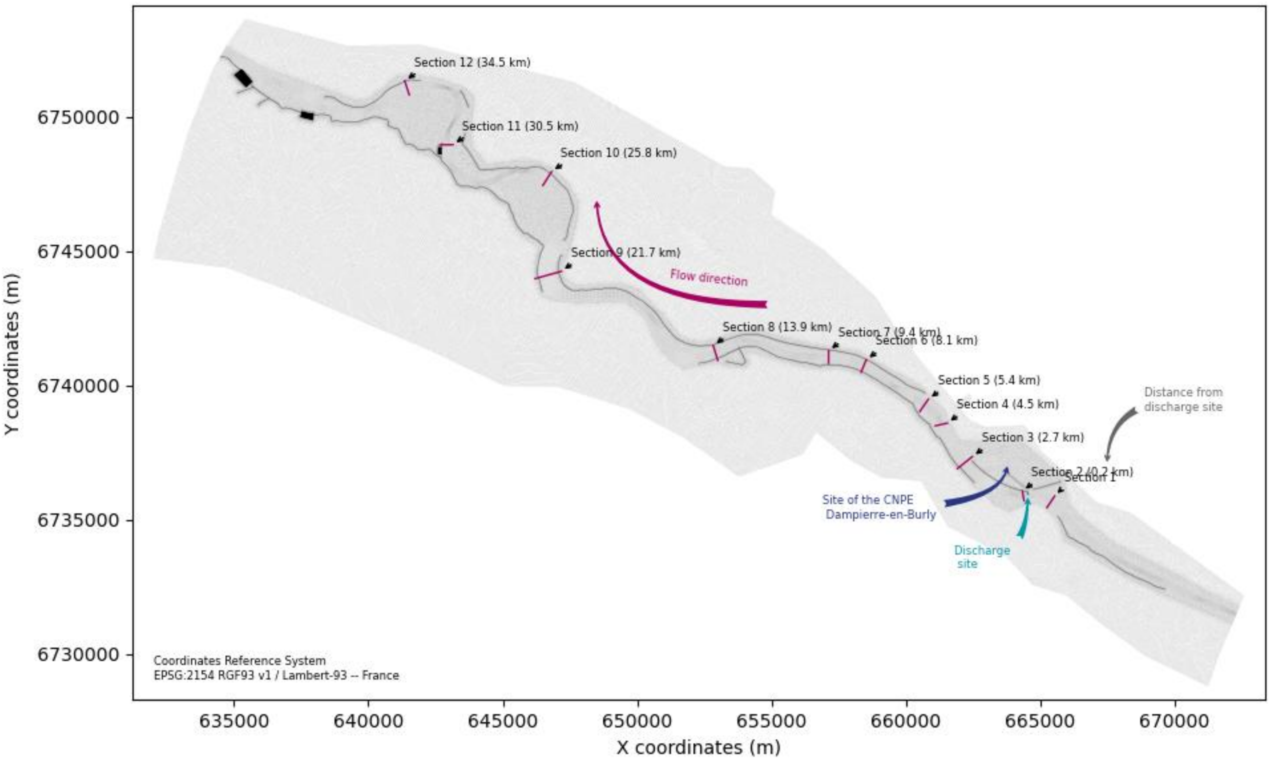

Figure 4: Diagram of the TELEMAC 2D model adapted for the study of tracer dispersion.

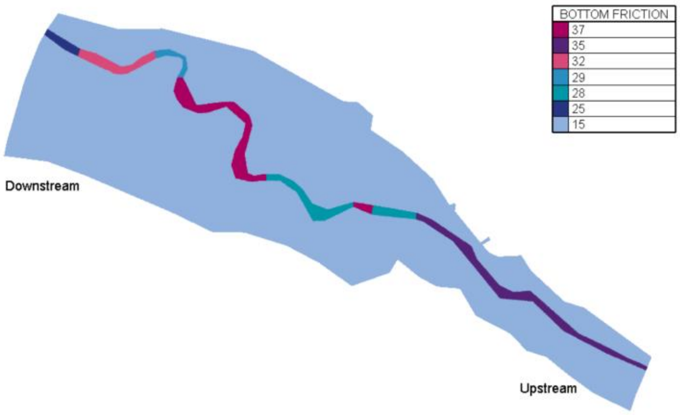

Figure 5: Strickler's friction coefficients values applied on the TELEMAC 2D domain

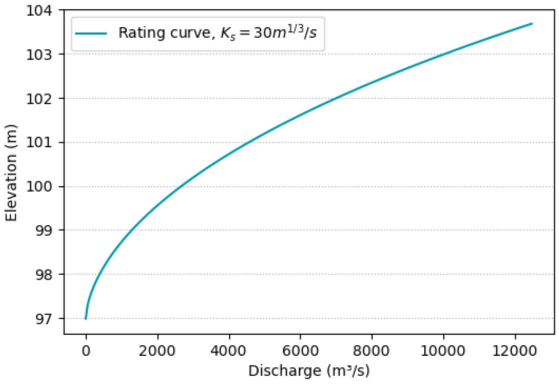

Figure 6: Stage-discharge curve

The TELEMAC 2D model used as a basis for this work is the model used by IRSN for flood modelling on the Loire River [18]. The existent calibration of the Strickler coefficients (Figure 5) and the existent stage-discharge curve (Figure 6) are used for the model in this work.

Further steps included a sensitivity analysis of TELEMAC 2D parameters employed for modelling tracers, culminating in the adaptation of the original model to incorporate tritium activity. This adaptation involved establishing the Dampierre-en-Burly NPP's infrastructure as the source point(s) within the model mesh. A mesh refinement process was implemented, accompanied by a thorough analysis of its effects on model results. The final mesh has a refinement of 40 cells across the main riverbed, with lengths of 15 m. The cells of the floodplain inside the levees have a size of 30 m and the rest of the domain has 60 m cells. Parameters were meticulously selected to optimize model performance, the scheme used for the TELEMAC 2D model is the N scheme with tidal flats treatment, in the predictor-corrector form (LIPS scheme) [19] to ensure a better fitting with the data obtained from the Loire River during both measurement campaigns.

The approximate locations of the sections were selected using the information of the approximate distance of the measurements and a map of the sections shown in the report due to the lack of exact locations in the bibliography. The lines to define the sections are wider than the profile of the river shown in some maps with the objective of making them more flexible for the study of several flow rate conditions in TELEMAC 2D. All the sections are shown in Figure 4 along with their approximate distance from the discharge site, and the location of the Dampierre-en-Burly NPP.

Once the TELEMAC 2D adaptation was completed, the study cases were prepared. In Table 4 is presented a summary of the most important parameters configured for the simulation of each case. At the TELEMAC 2D model the sources are set at the nodes and due to the size of the mesh the original 20 discharge points are simplified into 5 points.

Table 4: Data for TELEMAC 2D for each of the case studies

Parameters	Flow rate condition		
	Mean flow	High flow	Low flow
General parameters			
Mesh	VF Mesh. 41 points across the main channel.		
Upstream Boundary	298 m³/s	1500 m³/s	69 m³/s
Discharge and activity concentration	19 Bq/L	19 Bq/L	3 Bq/L
Downstream boundary	Rating curve		
Discharge at the release pipe	4.3 m³/s	4.3 m³/s	5.1 m³/s
Tritium activity concentration at the release pipe	2139.5 Bq/L	2139.5 Bq/L	449.3 Bq/L
Start time for the simulation	2013-12-10 18:00	2013-12-10 18:00	2012-08-20 18:00
Duration of simulation	1 day (86400 s)	1 day (86400 s)	2 days (172800 s)
Number of source points (Mesh nodes)	5	5	5
Main Physical and Numerical Parameters			
Turbulence model	1: constant viscosity		
Law of bottom friction	3: Strickler's formula		
Friction	Main channel: Between 25 and 37 $m^{1/3}/s$, Rest of the domain: 15 $m^{1/3}/s$		
Tidal flats	Yes. Option for the treatment of tidal flats #1 (corrected free surface gradient)		
Scheme for advection of velocities	13: Edge-based N-scheme		
Scheme for advection of tracers	4: N distributive scheme, option #4 locally semi-implicit predictor-corrector (for tidal flats): LIPS		

5.2. Results for the mean flow rate case study

For the mean flow rate condition, the activity concentration profiles obtained by each of the modelling tools are presented at the first four sections of the measurement campaign of December 2013 which are the sections between the discharge site and the SMP downstream of the Dampierre-en-Burly NPP (Figure 1). As shown in Figure 7, with the configuration used for the TELEMAC 2D model, most of the measurement points are matched with the model results in Section 2, while the measured point closest to the right bank is not reached. The profile presents only one peak that reaches a higher value than the peak given by the measurement points. In this case, it is possible that the shape of the peak could be different if the release points configuration were different and closer to reality. Different source points configurations were studied in the adaptation process, and it was found that it has an important effect for the sections closer to the discharge site. With different sources points, maybe the third measurement point can be reached while the maximum value could change.

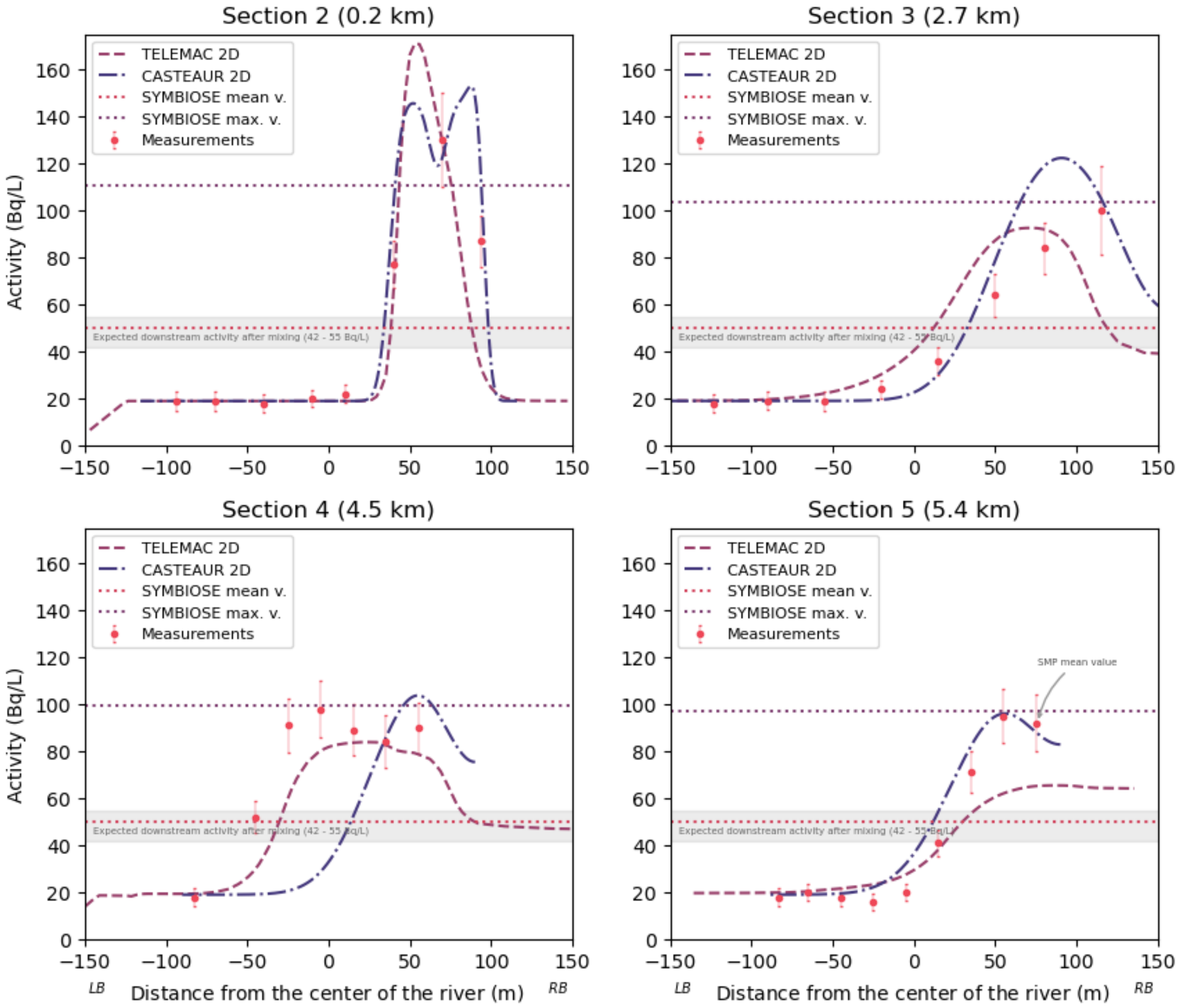

Figure 7: Comparison at the first sections for mean river flow rate (Q=298 m³/s)

At Sections 3 and 4 some lateral shift seems to occur between the TELEMAC 2D results and the measurements, but the shape of the profile is very similar, specially at Section 4. However, in Sections 4 and 5, TELEMAC 2D seems to model activity concentrations lower than expected, while the general shape of the profile seems to match even in Section 5. The lower activity concentration could be related to the numerical diffusion that was the most important problem during the adaptation of the TELEMAC 2D model. It is clear that the effect of the numerical diffusion is more evident in the profiles as their distance from the discharge site increases. It is possible that more refinement is needed in the model mesh to reduce the numerical diffusion that occurs along the river.

The results for CASTEAUR 2D matches all the measurement points in Section 2 with two clear peaks, which come from the separation between the two discharge pipes in the source discharge configuration. For the rest of the Sections, the results of CASTEAUR 2D reproduces the pattern of the measurements, with some variations. Results in Section 3 present a higher peak than what the measurements present, while in Section 4 they seem to present a lateral shift to the right. Finally, the profile obtained at Section 5 corresponds to most of the measurement values.

For SYMBIOSE, only two values are modelled for each section, the mean value and the maximum value. As a profile is not obtained, the results are represented as two lines. The maximum value obtained for Section 2 could be considered lower than the maximum value measured, and lower than the peak value obtained both with CASTEAUR 2D and TELEMAC 2D. However, for all sections, the maximum value obtained using SYMBIOSE is within the uncertainty range of the maximum measurement point. At Sections 3-5, the maximum values closely match the maximum values measured. In all cases, the mean value is within the range of the expected tritium activity downstream.

5.3. Results for the low flow rate case study

This case study is done only for comparison purposes and to evaluate the limits of the TELEMAC 2D model under a configuration adapted to flood modelling and not to low flow rate conditions. As for the mean flow rate condition, the three tools' predictions are compared to the results of the measurement campaign carried out at the first four sections in August 2012 (Figure 8).

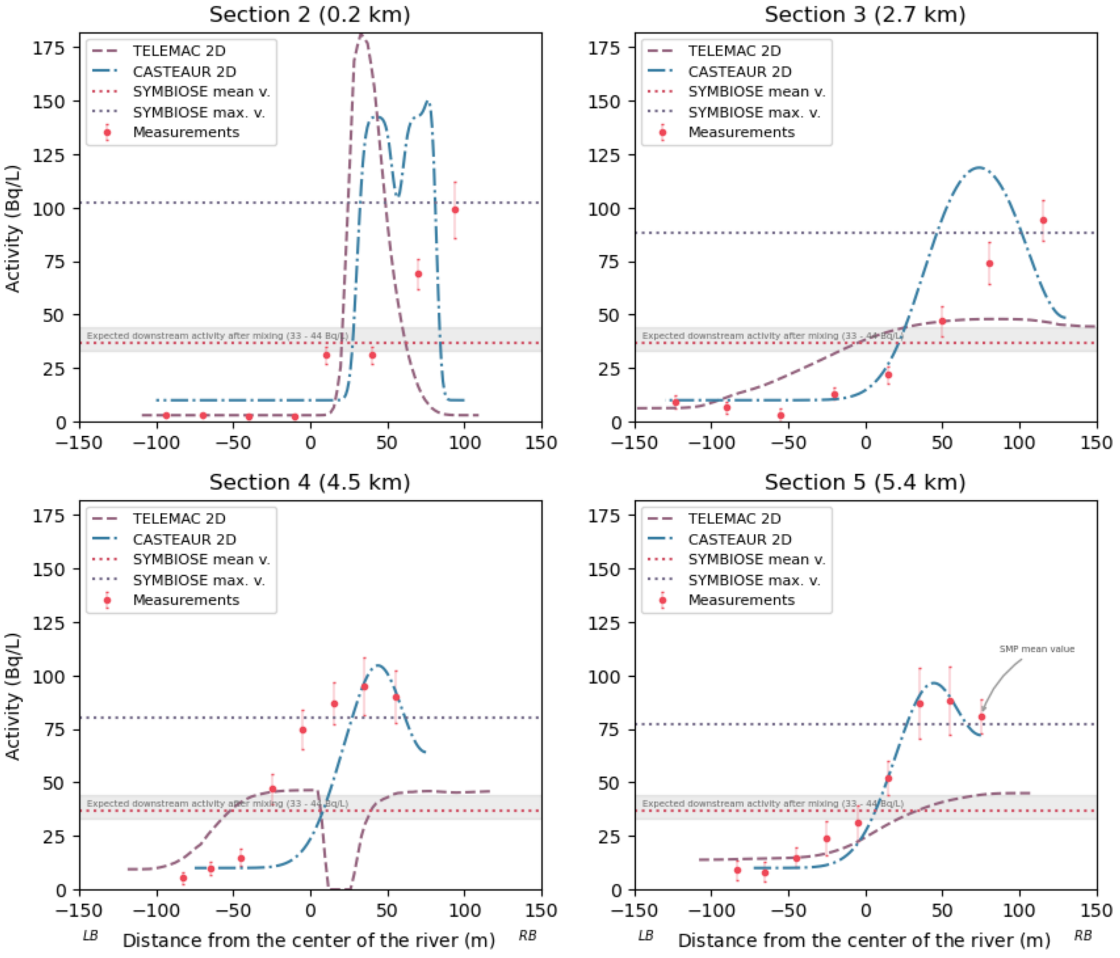

Figure 8: Comparison at the first sections for low river flow rate (Q=69 m³/s)

The results of TELEMAC 2D are higher than the measurements and the other results at Section 2, however, the tritium activity quickly decreases for the next sections to a value lower than expected. Not only is the shape of the profile inadequate, but the results in general seem to be more affected by numerical diffusion than in the previous cases. This can be due to the fact that in low flow rate conditions, the relative error of the numerical diffusion is higher. With smaller amounts of mass in the model, both for water and tritium, sharp gradients are more pronounced. In these cases, numerical diffusion becomes more apparent, causing excessive smoothing and the error introduced is more noticeable. To increase results quality in the TELEMAC 2D model for low flow rate, a recalibration of the existing model for these conditions is required as a first mandatory step due to the conservation of the flood-oriented calibration in this study. Defining a specific friction coefficient calibration may allow to represent in a better way the low-flow rate characteristics of the stream and so, to guarantee the precision of the model from the hydraulic point of view. As a second step, more refining should also be done concerning the riverbed. Perhaps a better alternative would be to configure a specific model with more refinement and with the updated topography of the riverbed specifically for low flow rate conditions. As the mesh definition is, at this point, still influent on the results, a detailed study on the mesh to determine the convergence of the results and estimate then a uncertainty associated with the selected mesh definition may highly increase the overall quality of the model on both hydraulic and numerical point-of-views.

The results of CASTEAUR 2D are higher than the measurements in Sections 2 and 3 and have a very different profile shape. However, for Sections 4 and 5 the results are more satisfactory, with Section 4 presenting only a lateral shift to the right, and Section 5 matching all the measurement points in their uncertainty ranges. The mean value obtained with SYMBIOSE is located inside the range of expected downstream activity after mixing. The maximum values for each section in SYMBIOSE are also good, with a tendency to be lower than the maximum value of the measurement point while still being within its uncertainty range.

5.4. Results for the high flow rate case study

The results obtained for a high flow rate condition in the Loire River with the three tools' predictions are compared only between each other as no measurement data was available for such condition. The results are presented below at the same sections than for the low and mean flow rate conditions (Figure 9).

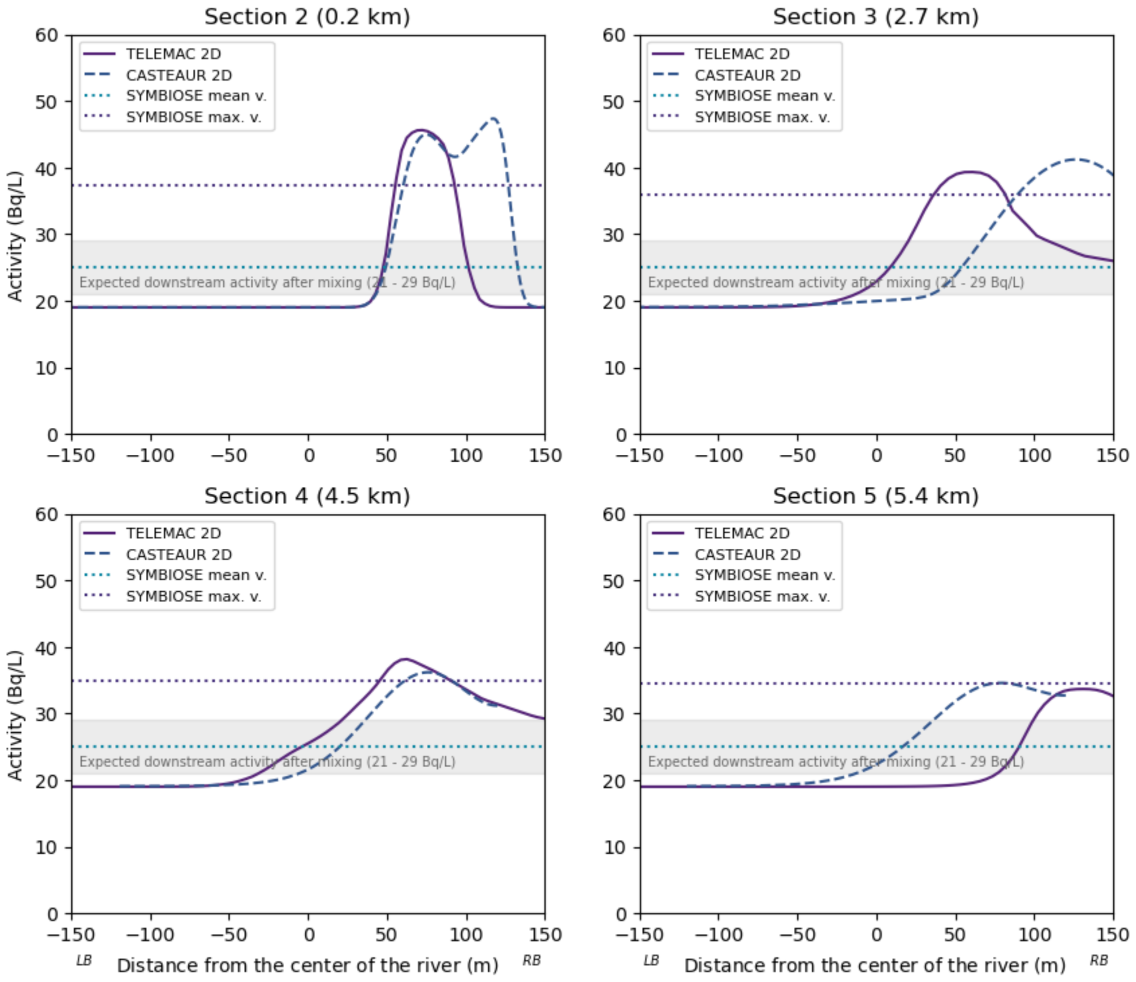

Figure 9: Comparison at the first sections for high river flow rate (Q=1500 m³/s)

The results of TELEMAC 2D and CASTEAUR 2D for this high flow rate case seem to be similar for most of the sections. At Section 2, the peak obtained in TELEMAC 2D matches well the first peak obtained with CASTEAUR 2D. Sections 3-5 seem to have a similar shape but to be shifted laterally. In this case, even at Section 5, TELEMAC 2D seems to be diffusing less than in the case with mean flow rate. While for mean flow rate at Section 5 the maximum value obtained with TELEMAC 2D was almost 40 Bq/L lower than the value obtained with CASTEAUR 2D, in this case the difference between the maximum value predicted by both tools is less than 2 Bq/L. This indicates that the numerical diffusion of TELEMAC 2D is less evident. This can be caused because for a higher discharge rate, the tritium diffusion that occurs as a result is already important, and the gradients in the model are lower. Numerical diffusion tends to be less evident in regions with smoother gradients, and for that reason the error introduced by numerical diffusion might not be as noticeable. This is satisfactory as the intended use of the TELEMAC 2D model that was adapted during this study is for high flow rate conditions and flood modelling. In these two cases the 2D results that TELEMAC provides have more importance as the focus is more on generating maps of the areas flooded and of the tritium activity in those areas.

All the mean values provided by SYMBIOSE are within the expected downstream activity after mixing, the maximum values however, are lower in the first three sections than the maximum reached by the two other tools.

6. DISCUSSION

This comparison makes it possible to position the three tools according to different conditions and scenario of discharge of radioactive liquid effluent into rivers. The main conditions of liquid discharges include the cases of low flow rate conditions where water remains confined to the main channel, mean flow rate conditions characterized by sustained main channel flow and high flow rate conditions causing water to spill out of the main channel, and flooding scenarios where water inundates the floodplain. The main scenarios concern the routine cases where the codes could be used in a monitoring context, the crisis cases which are often degraded situations where all the data and parameters are not necessarily available and the required response times are short, and the expertise cases, where the codes are used to evaluate a specific problem such as, for example, change in discharge procedure, discharge device, etc. The information that could be required for these different cases is shown in Table 5:

Table 5: Outputs needed from the modelling process according to the reference scenario and type of flow rate condition.

Scenario	Low/Mean flow rate	High flow rate/ Flooding
Routine	Mean and Maximum Values 2D activity concentration profiles	Mean Value, Maximum values 2D activity concentration profiles
Crisis	Mean Value, Maximum value 2D activity concentration profiles	Mean Value, Maximum values 2D activity concentration map
Expertise	Mean Value, Maximum value 2D concentration map	Mean Value, Maximum values 2D activity concentration map Information of the 2D spatial evolution in time of the release

A 2D activity concentration map is in general not needed for every routine release; however, it can be important for an average case of a typical routine release. For example, when performing dose assessments for populations, a 2D activity concentration map could help to ensure that the pumping sites for drinking and irrigation water is not affected by the releases. These types of maps can also help to ensure that the tritium plumes do not reach the floodplains that are used for crops.

Knowing the differences between the tools in the modelling process is important to present a final recommendation of the criteria to consider for prioritizing the tools according to the situations encountered at the IRSN. Table 6 summarizes the knowledge obtained for each tool as a result of the studies completed in the present work.

Table 6 : Characteristics of the tools at different aspects related to the modelling process.

		SYMBIOSE	CASTEAUR 2D	TELEMAC 2D
Inputs	Calibration	By site	By site By type of flow	By site May require calibration by type of flow depending on the river
	Flow type	Permanent flow Variable flow	Only permanent flow	Permanent flow Variable flow
	Basic data required (Hydraulics)	River model River hydrograph Tributaries and distributaries flow rates.	Satellite view of the river at a similar flow rate condition. Tributaries and distributaries flow rates.	Topography. Boundary conditions (River hydrograph, stage discharge curve, etc.).
	Basic data required (Tracer)	Discharge flow rate. Discharge activity concentration. Discharge location. Tracer activity concentration at the boundary / background noise.	Substance discharge flow rate. Discharge location. Tracer activity concentration at the boundary / background noise.	Discharge flow rate. Discharge activity concentration. Discharge location. Tracer activity concentration at the boundary / background noise.
Outputs	Results	1D in space. Mean value and maximum value. Variations in time.	2D in space (rectangular channel). Activity concentration profiles. No time dimension.	2D in space (real features). Activity concentration maps and profiles Variations in time.
	Extent and complexity of the domain	A large extent can be modelled, but with low complexity.	Short extent of the domain with low complexity.	Large extent with high complexity.
Requirements	Time required for the simulations	From some seconds to some minutes	From some seconds to some minutes	From some minutes to hours depending on the size of the domain and the mesh refinement.
	Complexity of use	Medium complexity. Requires previous knowledge of the use of SYMBIOSE.	Low complexity. Only requires some knowledge of the cells to modify.	High complexity. Requires previous knowledge of the use of TELEMAC and its pre- and post-processing software.
	Computational requirements	Access to the SYMBIOSE platform.	Excel Macro-Enabled Workbook. QGIS, ArcGIS or Google Earth.	Access the IRSN server with TELEMAC 2D installed or have a local installation. BlueKenue (Pre- and post-processing). Postel + Jupyter Notebooks, or QGIS for post processing.
	Operational capabilities required (Modification of existent model)	Modify the scenario.	Modify the scenario. Run the macro-enabled workbook.	Modify the steering file. Launch a run on the server or in the local installation.
	Operational capabilities required (Creation of new model)	Characterize the scenario. Select the model and connect the variables. Create the river network. Calibration of the model.	Use of Google Earth (or GIS) for drawing the reaches. Measure the reaches. Modify the macro-enabled spreadsheet. Visualizing results in excel. Calibration of the model.	Use of BlueKenue. Mesh Creation. Map the topography to the mesh. Geometry file creation. Boundary conditions file creation. Steering file creation. Extraction and visualization of results. Calibration of the model.
Other	Other capabilities	Can consider: - Radioactive decay - Concentration in sediments - Concentration in suspended solids - Concentration in elements of the food chain (coupled with other modules of SYMBIOSE) - human/non-human biota dose assessments accounting for river use (coupled with other modules of SYMBIOSE)		Can consider: - Effects of rain, evaporation, and wind - Coupled with WAQTEL can consider Radioactive decay Deposition of radionuclides in sediments Resuspension of radionuclides

From the experience obtained working with the three tools, and considering what was presented in Table 6, the following analysis can be made for each of them:

SYMBIOSE. It offers rapid results, making it particularly suitable for emergency situations such as crisis due to accidental releases, for any river flow rate condition. However, its results are limited to 1D at any given distance downstream the release, providing only mean and maximum values of radioactive activity concentration across the section. It lacks the capability to generate activity concentration profiles, rendering it unsuitable for cases requiring precise plume position in the river information. Yet it allows to model a large domain in space and time with a small computational time. It must be kept in mind that while only the radionuclide transport model of SYMBIOSE was used in this work, it is not the primary and sole purpose of the platform, the tool modelling the transfer and fate of radionuclides in the wider environment encompassing notably atmosphere, agricultural land, forest, and allowing to perform human and non-human biota dose assessments. When utilized in conjunction with other SYMBIOSE modules, it becomes a more potent tool.

CASTEAUR 2D. This tool delivers fast results across various reference scenarios, albeit with a somewhat longer model preparation time (still not as long as for TELEMAC 2D). The model setup process is user-friendly, requiring only a basic understanding of tools like Google Earth, QGIS, and Excel. Access to the model is straightforward through a Macro-enabled worksheet. The results, applicable to all river flow rate conditions, provide activity concentration profiles at the chosen sections. Even if it assumes the river as a series of rectangular channel reaches, which is an important simplification, CASTEAUR 2D's outcomes are suitable for most cases and recommended due to their acceptability.

TELEMAC 2D. This numerical modelling software is ideally suited for in-depth analysis of accidental and crisis releases once the critical events have occurred and the comprehensive assessment of reasons and consequences is required. It is primarily recommended for scientific research, as it offers more complexity and superior refinement possibilities. The use of TELEMAC 2D requires operational proficiency and more grasp of numerical modelling principles. Model setup involves a complex process, demanding additional data such as domain topography and validation data. While its calibration takes more time, when prepared with the sufficient refinement, and with a correct calibration, it allows to process a wider range of application than the other tools. TELEMAC 2D provides 2D models, providing results that include activity concentration maps and temporal variations, and the value of the studied variables at each point of the mesh. However, it is not designed for quick results unless a preconfigured model is readily available. Model refinement should differ for varying river flow rate conditions, distinguishing between high flood and low flow rate scenarios. The detailed nature of the results that TELEMAC 2D provides makes it the tool of choice between the three options in the cases where water inundates the floodplain, as it allows the creation of maps of activity concentration. Nevertheless, it may be noticed that TELEMAC-2D coupling with tools such as meta-models, as already achieved for flood studies [18], may be an option in the future to make an operational TELEMAC-2D model fit with operational and crisis situation requirements to reduce the computing time.

In summary, the choice of the appropriate tool depends on the specific scenario and flow rate conditions under consideration. SYMBIOSE's speed and emergency readiness, CASTEAUR 2D's ease of use and acceptable results, and TELEMAC 2D's robustness and in-depth analysis capabilities offer a range of options in the field of radioactive discharge dispersion analysis.

7. CONCLUSIONS

The comparative examination of the three modelling tools— SYMBIOSE (referring only to its dispersion in the river module), CASTEAUR 2D, and TELEMAC 2D—has revealed their strengths and applicability in the domain of radioactive discharge dispersion studies within riverine systems. SYMBIOSE's quick-response efficacy makes it indispensable in crisis scenarios and unexpected discharge events, irrespective of the river flow rate conditions. However, it limits results to mean and maximum values of radioactive activity concentration within a 1D framework. In contrast, CASTEAUR 2D emerges as a pragmatic selection due to its accessible model setup process, and the facility to obtain results in steady state situations. Nevertheless, its simplifications in approximating river geometry, combined with its lack of full 2D outcomes, require more consideration for applications that require a more detailed 2D information of the activity concentrations in the river. The role of TELEMAC 2D becomes relevant in its capacity for post-crisis in-depth analysis as it offers authentic 2D models, with results that include activity concentration maps and temporal dynamics. Even though its computational demands are substantial, involving more technical knowledge, extended data requisites, and a longer refinement and calibration process, the benefits of more detailed analyses are evident.

From the adaptation process of the existent TELEMAC 2D model can be concluded that mesh refinement has an important influence on model outcomes. Additionally, the disposition in the model mesh of the discharge device generates noticeable changes in the results, particularly observable at the river sections closer to the discharge points. The choice of advection schemes is fundamental, with Scheme 4 (N distributive scheme) being a good choice when coupled with the locally semi-implicit predictor-corrector scheme (LIPS). From a broader perspective, TELEMAC 2D emerges as the tool of choice for high flow rates and flooding situations, due to its capacity in capturing nuanced activity concentration distribution across floodplain inundation scenarios. This comprehensive assessment aims to serve as a guide in the selection of the modelling tools in line with contextual necessities, supporting radiological surveillance initiatives and facilitating the decision-making process within the IRSN's mandate.

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