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A Novel EPANET Integration for the Diffusive–Dispersive Transport of Tracers

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Engineering and Physical Sciences Research Council

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Article

A Novel EPANET Integration for the Diffusive–Dispersive Transport of Contaminants

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Abstract: The EPANET model is commonly used to model hydraulic behaviour and water quality within water distribution networks. The standard version of the model solves the advective transport equation by solving a mass balance of the fundamental plug flow substance that considers the advective transport and kinetic reaction processes. Over the years, several versions of the model have been developed, which have made it possible to improve the modelling of water quality through the introduction of additional terms within the transport equation to solve the problem of dispersive transport (EPANET-AZRED) and to consider multiple interacting species in the mass flow and on the pipe walls (EPANET multi-species extension). The present study proposes a novel integration of the EPANET-DD (dynamic-dispersion) model, which enables the advective–diffusive–dispersive transport equation in dynamic flow conditions to be solved in the two-dimensional case, through the classical random walk method, implementing the diffusion and dispersion equations proposed by Romero-Gomez and Choi (2011). The model was applied to the University of Enna "KORE" laboratory network to verify its effectiveness in modelling diffusive–dispersive transport mechanisms in the presence of variable flow regimes. The results showed that the EPANET-DD model could better represent the actual data than previously developed versions of the EPANET model.

check for updates

Keywords: EPANET; EPANET-DD; water distribution network; random walk method; water quality modelling

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1. Introduction

EPANET is the model widely used to simulate the hydraulic behaviour and water quality within water distribution networks. This model was first developed by Rossman in 1994 [1,2] and distributed by the Environmental Protection Agency (EPA). This first version made it possible to solve the system of hydraulic equations implemented in the model (equation of continuity at nodes and pipes, equations of motion) through the method of the "gradient algorithm" [3]. As regards the solution of the water quality equation (advective-reactive transport equation), the conservation equation of the mass of the substance has been solved through the discrete volume element method (DVEM) [4], in which the mass substance is assigned to discrete volume elements once all connections in the network have been partitioned. This way, the concentration within each volume segment is first reacted and transferred to the adjacent downstream part. Suppose the latter is a junction node; the incoming mass and flow volumes mix with those already on the network nodes. Once these processes have been exhausted for all the network elements, the concentration is calculated and released in the first sections of the pipeline with flow out of the node.

In 2000, the model was updated to version 2.0 [5], in which the update concerns the water quality simulation section. Indeed, if in version 1.1, an Eulerian approach was used to solve the advective transport equation (DVEM), in this case, a time-based Lagrangian approach was used to track the fate of discrete water particles as they move along the tubes and mix at the junctions between time phases of fixed length. This significantly reduces the time passage of water quality compared to the hydraulic time passage, as the process is

INTRODUCTION

Simplified advective models such as EPANET are used to model water quality, but this they can not always used due to the dispersion-diffusion phenomena that are intrinsic to transport processes.

Need to use suitable models to simulate water quality within distribution networks.

New model to study the advective–diffusive–dispersive transport equation in dynamic flow conditions

Comparison of the EPANET-DD model to the EPANET and AZRED models

MATERIALS AND METHODS

EPANET model is based on Advection Equation (Rossman, 1993):

$$\frac{\partial C_i(x,t)}{\partial t} = -u_m \frac{\partial C_i(x,t)}{\partial x} - KC_i(x,t)$$

In low velocity flows, dispersion may have an impact on solute concentrations (Axworthy and Karney, 1996):

$$\frac{\partial C_i(x,t)}{\partial t} = -(E + u_m)\frac{\partial C_i(x,t)}{\partial x} - KC_i(x,t)$$

$$D = D_{disp} + D_{diff}$$

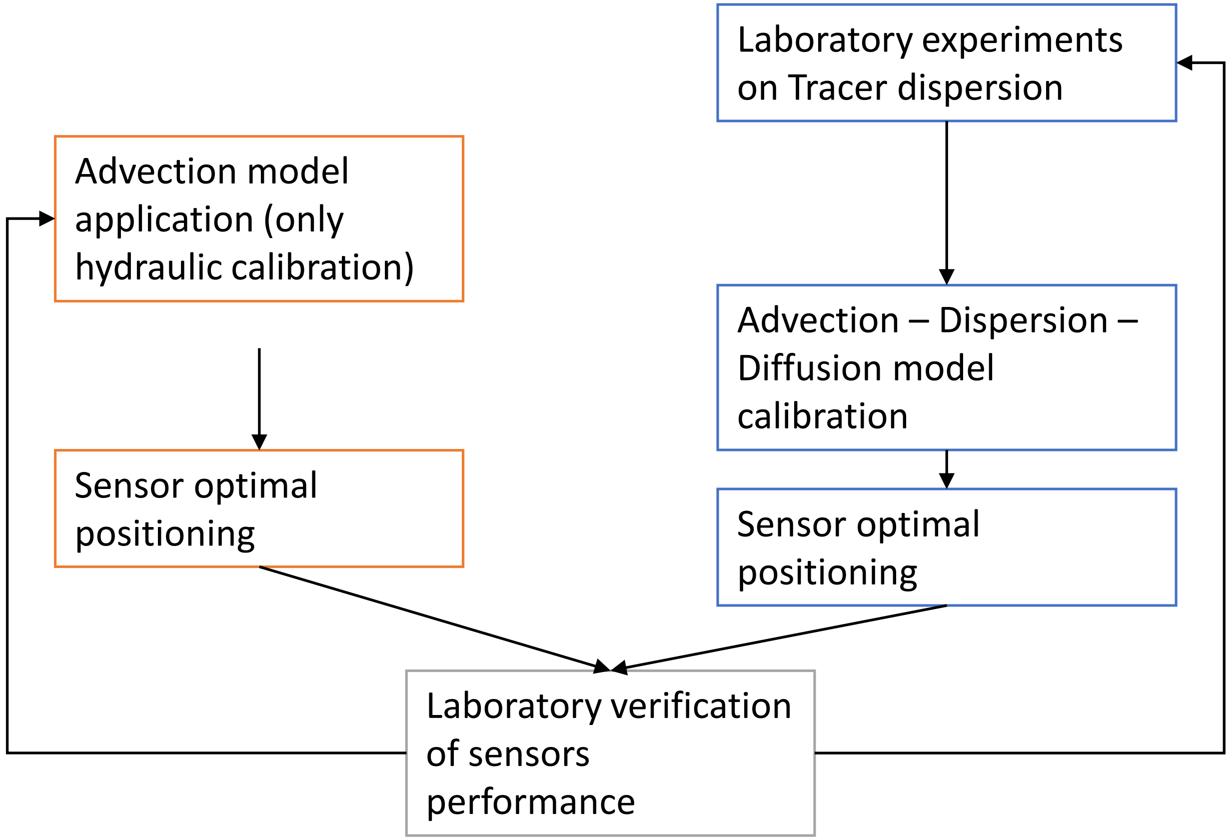
$$D_{disp} = a^2u^2/48\,D_{diff} \qquad D_{disp} = 10.1au_*$$

Dispersion coefficients are different backward and forward with respect to flow direction (Romero-Gomez and Choi, 2011):

$$\frac{\partial C_i(x,t)}{\partial t} = \frac{1}{\Delta x}\left(\phi_b - \phi_f\right) - u_m \frac{\partial C_i(x,t)}{\partial x} - KC_i(x,t)$$

$$\phi_b = -E_b \left.\frac{\partial C}{\partial x}\right|_b \quad and \quad \phi_f = -E_f \left.\frac{\partial C}{\partial x}\right|_f$$

MATERIALS AND METHODS

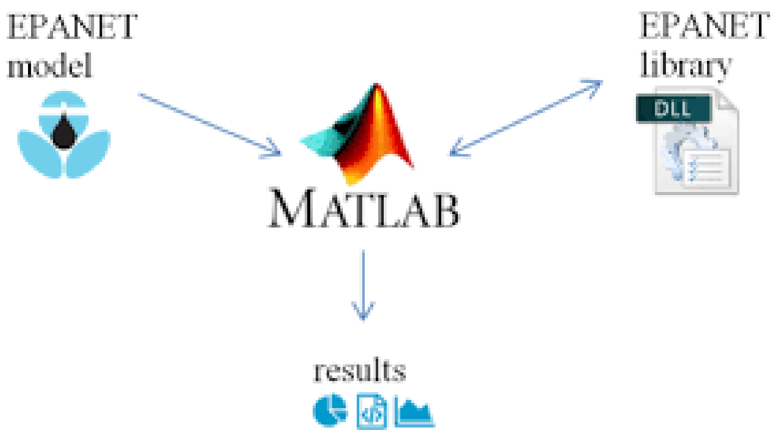


MATERIALS AND METHODS

Hydraulic analysis: EPANET-Matlab-Toolikt solving Gradient Method

$$H_i - H_j = h_{ij} = rQ_{ij}^n - mQ_{ij}^2$$

$$\sum_j Q_{ij} - D_i = 0 \quad for\ i = 1, \dots, N$$

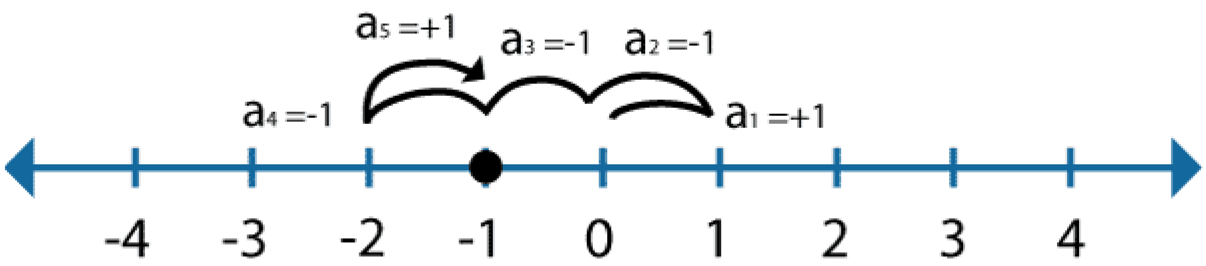


Quality analysis: Classical Random Walk Method

$$x(i,1) = x(i,1) + \frac{3}{2}u_x\left(1.001 - \left(\frac{y(i,1)}{\frac{d}{2}}\right)^2\right)dt + \sqrt{2 \cdot E_{f\ or\ b} \cdot dt}$$

$$y = y + u_y dt + \sqrt{(E_f + E_b) \cdot dt}$$

$$C = C + \frac{C \cdot n}{\frac{L}{\Delta x} \cdot \pi \frac{d^2}{4}}$$

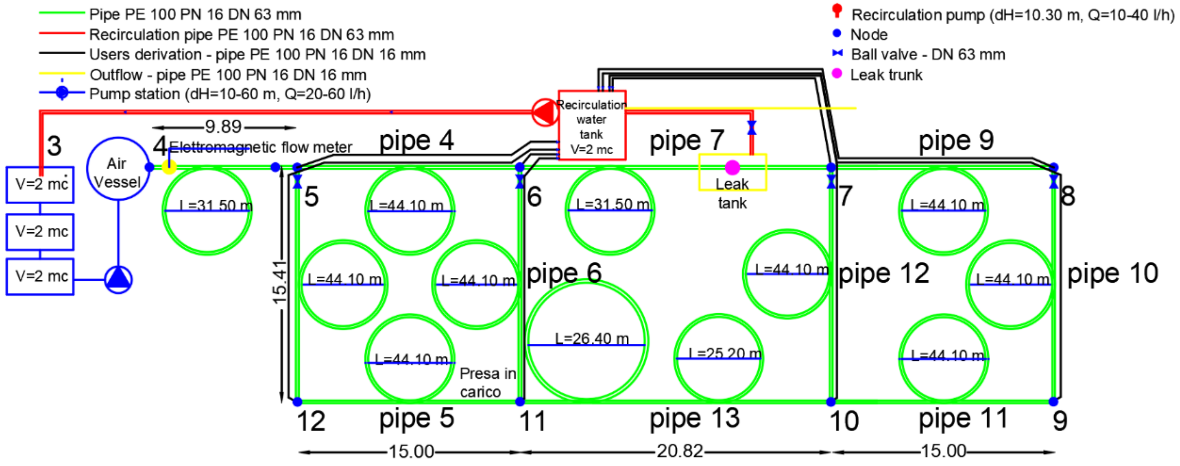


CASE STUDY

University of Enna, KORE

Environmental Hydraulic Laboratory

HDPE pipelines
DN 63 mm
Thickness 5.8 mm
Pipe length 45 m
Scale 1:1



EXPERIMENTAL SETUP: UKE NETWORK

Electromagnetic flow meters

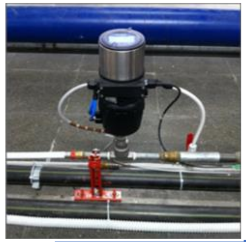
- 1 flow meter in the inlet pipe
- 6 flow meters in the internal pipes
- Accuracy of 0.1%

Pressure cells

- 8 piezo-resistive pressure transducer in all the internal nodes
- Range 0-6 bar
- Accuracy of 0.1%

Multi-jet water meters

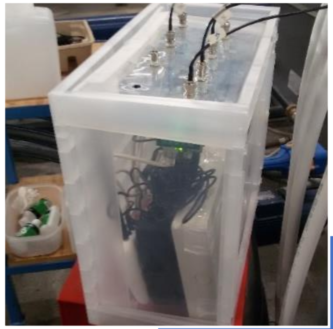
- 8 new water meters in all the internal nodes
- 1 is located in the node connected with the roof tank



Flow control valves

- Each internal node is provided by a FCV

EXPERIMENTAL SETUP: UKE NETWORK



Conductivity sensors

- Wi-Fi real-time
- Wi-Fi routers
- 8 Arduino cards

Conductivity

- 8 conductivity

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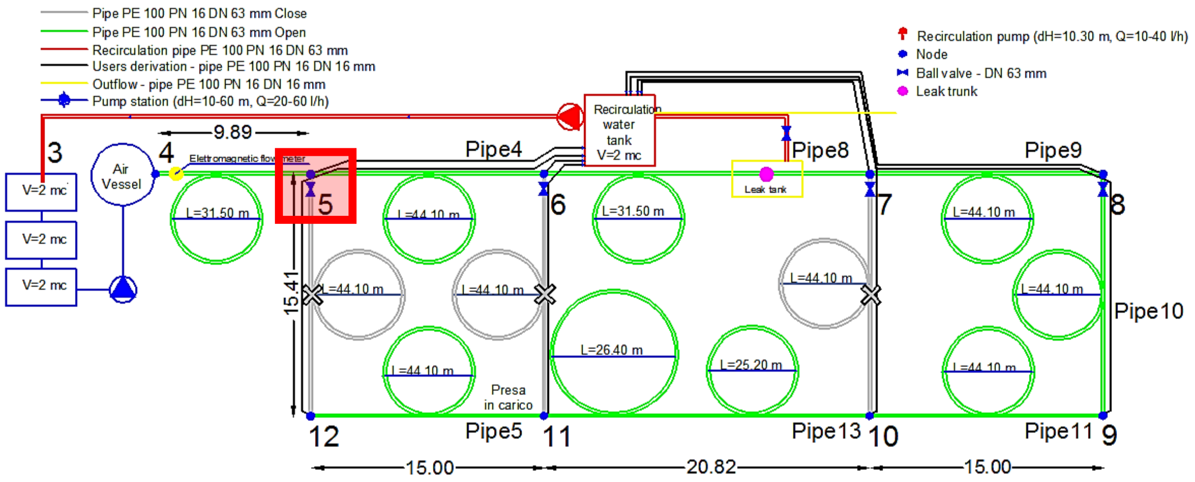
All data are collected by means of WiFi data acquisition cards and sent to the server

EXPERIMENTAL SETUP: UKE NETWORK



Tracer: *Sodium Chloride*

+

- No toxic
- Easy measurable
- Low cost
- High availability

−

- High mass needed
- Need to clean up the network at each test

LABORATORY TEST

Test 1

Simulation data with EPANET model

Tracer concentration: *4600 mg/l*

Injection duration: *3 minutes*

Simulation duration: *3 hours*

Test 2

Simulation data with AZRED model

Tracer concentration: *4600 mg/l*

Injection duration: *3 minutes*

Simulation duration: *3 hours*

Test 3

Simulation data with EPANET-DD model

Tracer concentration: *4600 mg/l*

Injection duration: *3 minutes*

Simulation duration: *3 hours*

Test 4

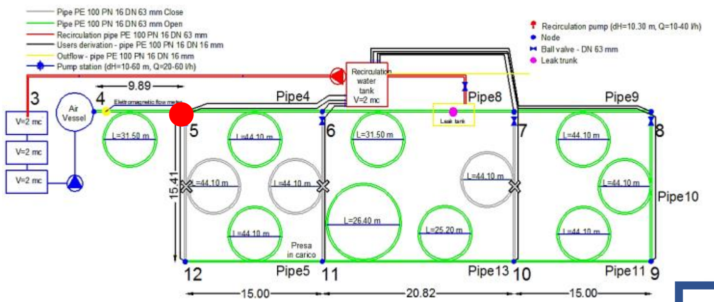
Experimental data

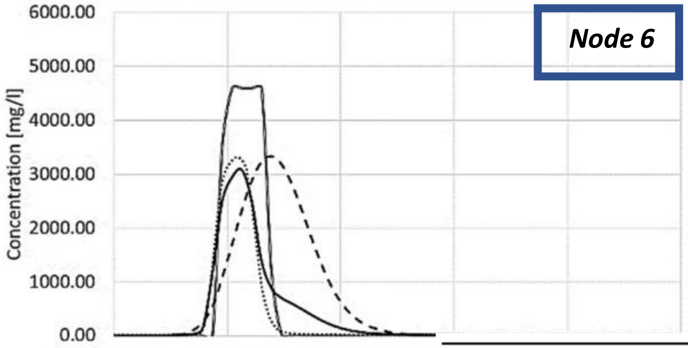
Tracer concentration: *4600 mg/l*

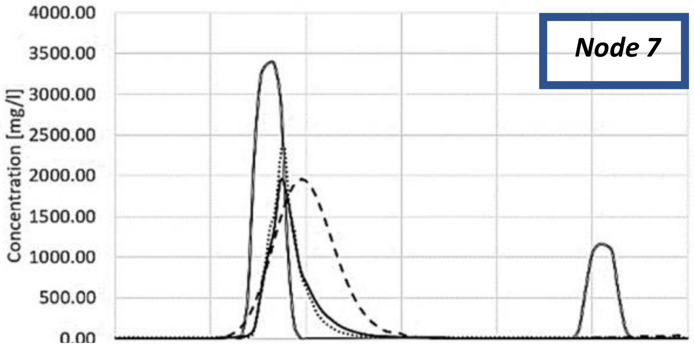
Injection duration: *3 minutes*

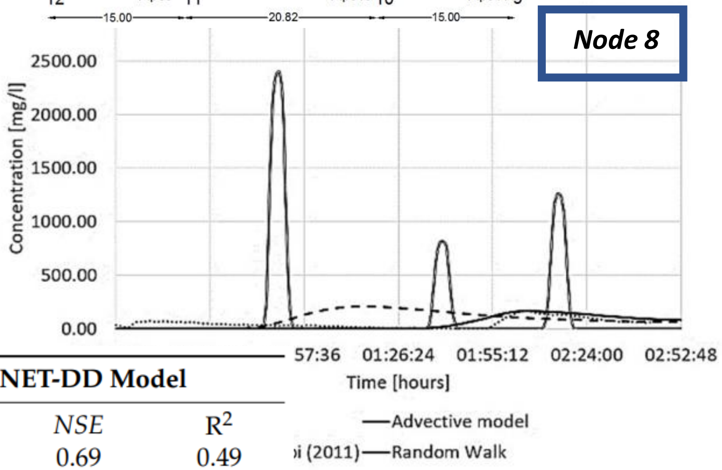
Simulation duration: *3 hours*

RESULTS

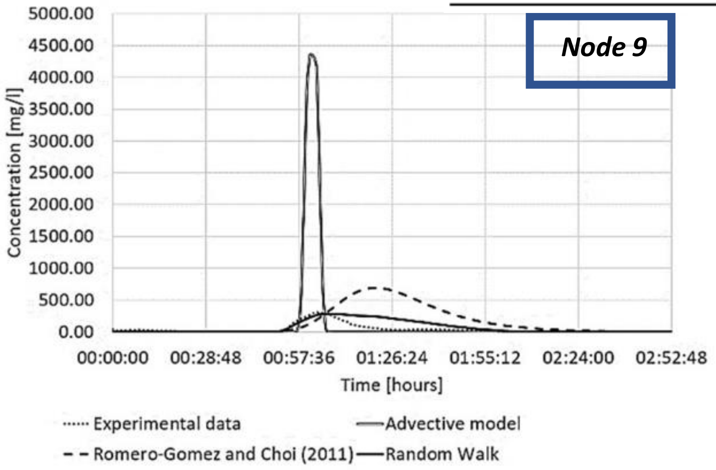


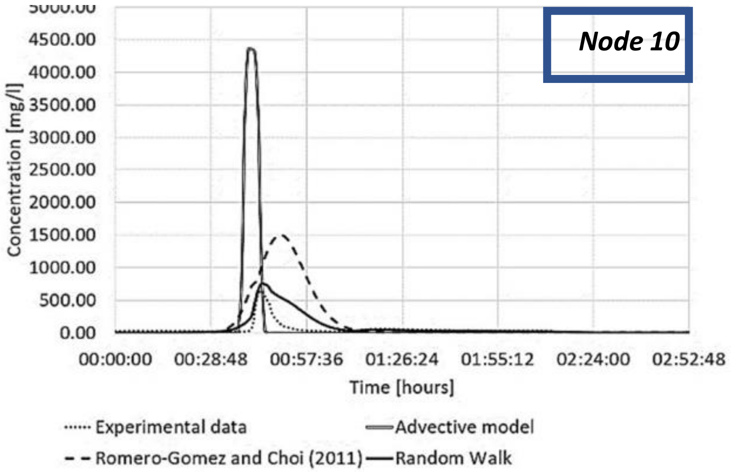


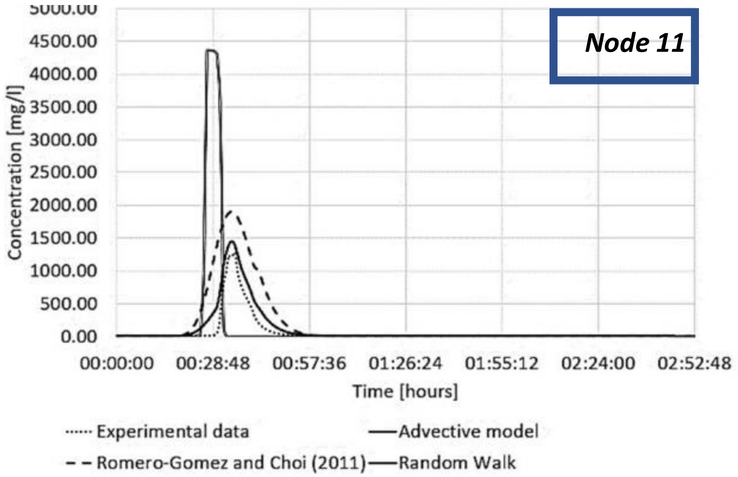




Node	Advective Model			Romero-Gomez and Choi (2011) Model			EPANET-DD Model		
	KGE	*NSE*	R^2	*KGE*	*NSE*	R^2	*KGE*	*NSE*	R^2
6	0.44	0.52	0.29	−0.60	−0.72	0.21	0.63	0.69	0.49
7	0.25	0.59	0.68	−0.08	−0.15	0.12	0.81	0.84	0.76
8	−0.55	−1.50	0.08	0.01	0.35	0.04	0.45	0.43	0.92
9	0.22	0.18	0.43	−1.58	−5.57	0.13	0.29	0.35	0.17
10	0.34	−0.01	0.19	−4.35	−14.81	0.09	−0.15	−0.54	0.55
11	−0.30	−0.62	0.05	−0.94	−1.18	0.79	0.42	0.76	0.90







CASE STUDY

Huysmans and Dassargues (2005)

$$Pe_1 = \frac{V_e L}{D_L} = \frac{V_D L}{n_e D_L}$$

$$Pe_2 = \frac{V_e^2 T}{D_h}$$

$$Pe_3 = \frac{V_e \Delta m}{D_h}$$

$$Pe_4 = \frac{V_e d}{D_e}$$

$$Pe_5 = \frac{V_e R}{D_e}$$

$$Pe_6 = \frac{V_e d}{D_d} = \omega Pe_4$$

$$Pe_7 = \frac{V_e b}{D_d}$$

$$Pe_8 = \frac{V_D \sqrt{k}}{n_e D_d} = \frac{V_D \sqrt{\left(K \frac{\mu}{\rho g}\right)}}{n_e D_d}$$

$$Pe_9 = \frac{V_D x}{nRD_{app}} = \frac{V_D x}{nD_e}$$

Péclet number << 1 diffusive mass transport is predominant

Péclet number >> 1 the advection mass transport is predominant

No univocal Péclet number threshold

CASE STUDY

EPANET

$$\frac{\partial C_i(x,t)}{\partial t} = -u_m \frac{\partial C_i(x,t)}{\partial x} - K C_i(x,t)$$

EPANET-DD (Dynamic-Dispersion)

$$x = x + \frac{3}{2} u_x \left(1 - \left(\frac{y}{\frac{d}{2}} \right)^2 \right) dt + \sqrt{2 \cdot E_{f\ or\ b} \cdot dt}$$

$$y = y + u_y dt + \sqrt{(E_f + E_b) \cdot dt}$$

Péclet Number

$$Pe = Sc \cdot Re$$

Pipe lengths vary in a range of 1 - 20 m

Pipe diameters vary in a range of 0.010 - 0.080 m

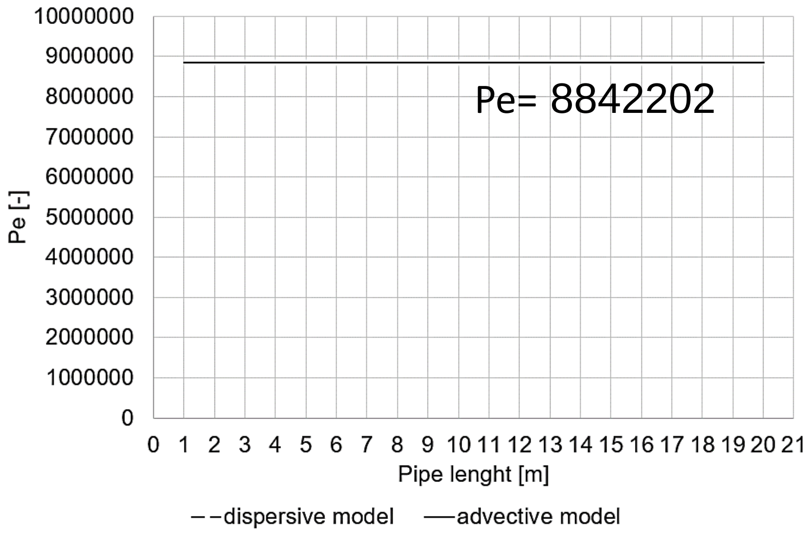
Flow rate vary in a range of 0.000087 - 0.00098 mc / s

Gaussian type concentration pattern of sodium chloride

CASE STUDY

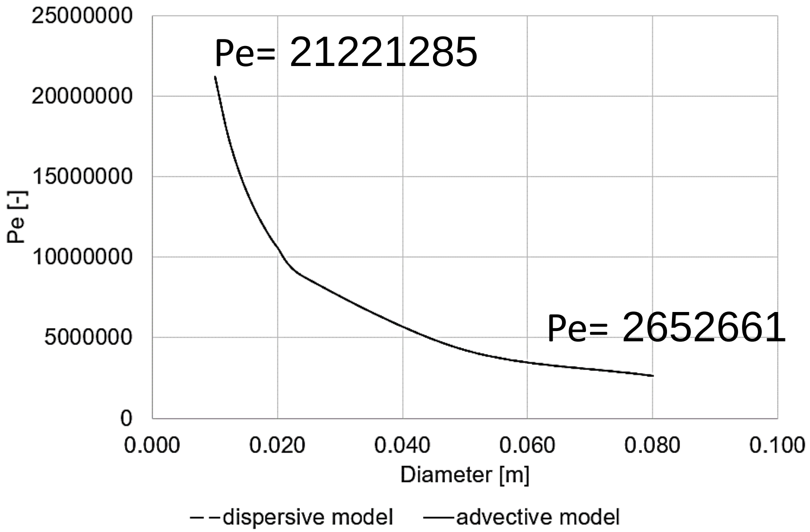
Scenario 1	Scenario 2	Scenario 3
pipe lengths vary in a range of 1 - 20 m	diameters vary in a range of 0.010 - 0.080 m	flow rate is variable in the range of 0.000087 - 0.00098 m^3 / s
Diameter = 0.024 m	pipe lengths = 20 m	Diameter = 0.024 m
flow rate = 0.0002 m^3 / s	flow rate = 0.0002 m^3 / s	pipe lengths = 20 m

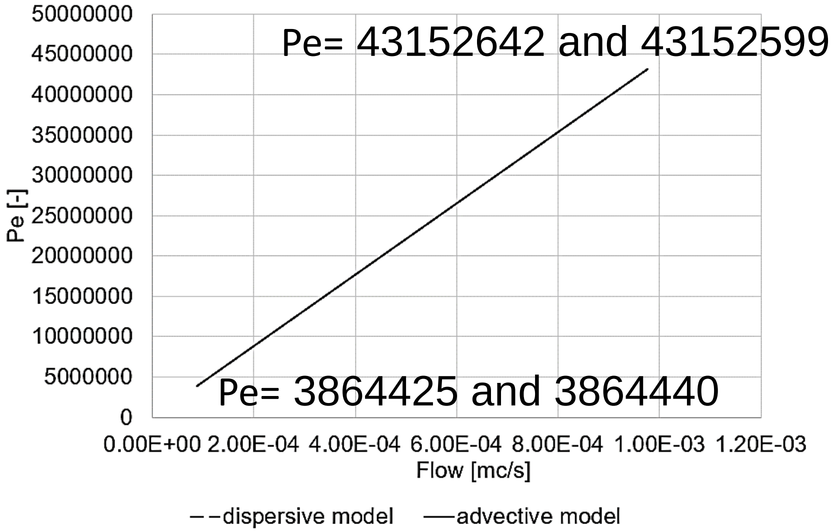
RESULTS



Scenario 1

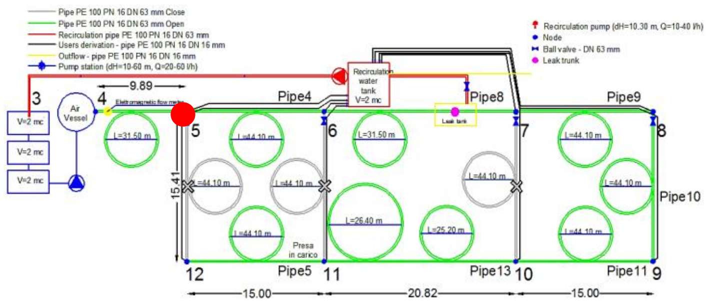
Scenario 2

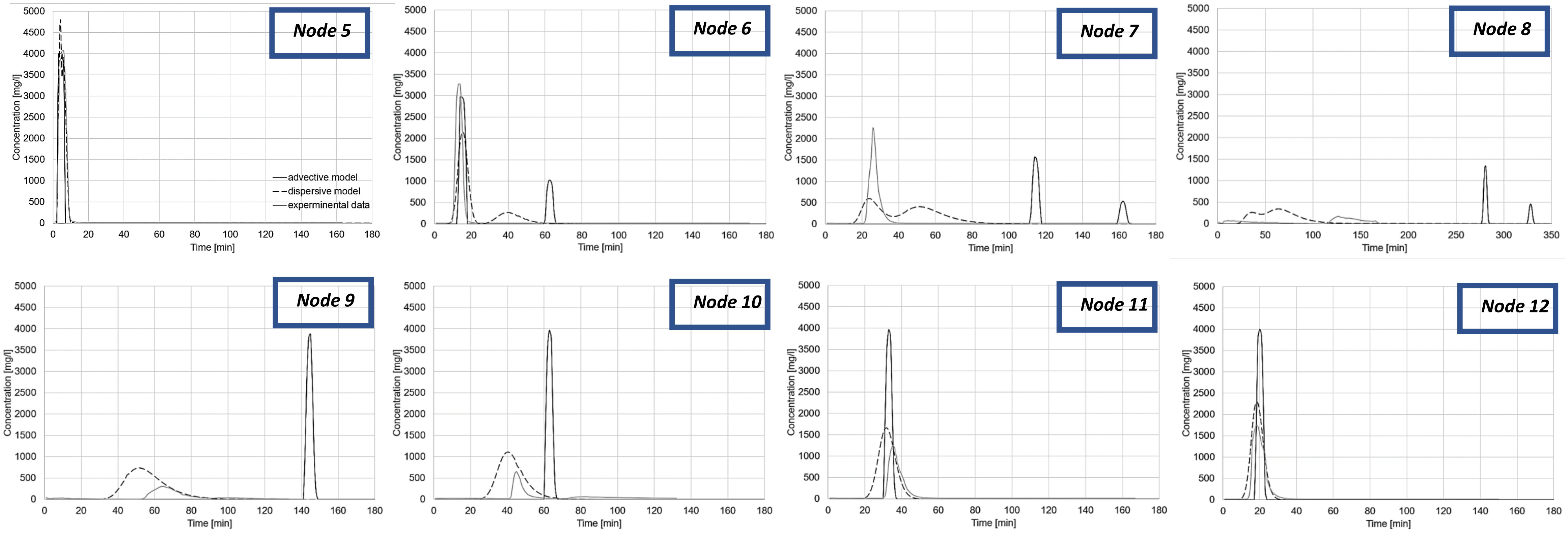




Scenario 3

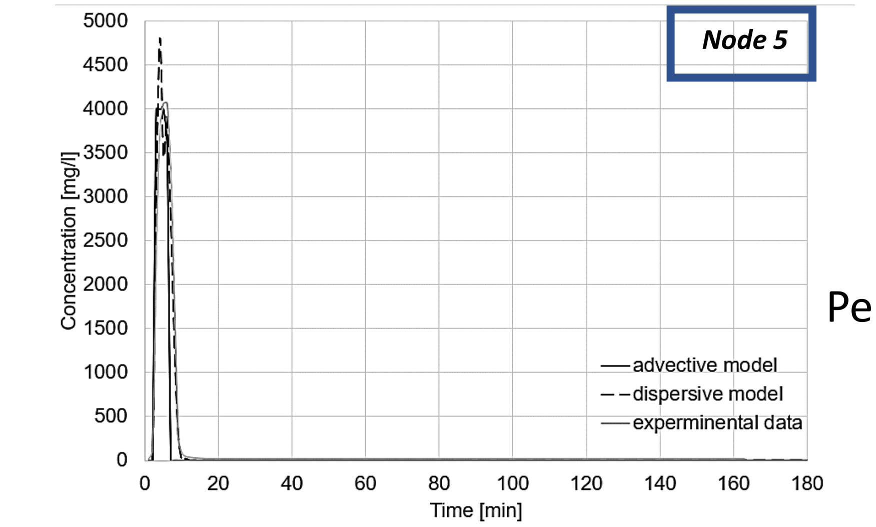
RESULTS





	Node 5	Node 6	Node 7	Node 8	Node 9	Node 10	Node 11	Node 12
Pipe length [m]	13	8.7	6.1	3.9	11.1	4.7	7.1	17
Flow [mc/s]	0.00015	0.00002	0.00001	0.00002	0.00001	0.00020	0.00002	0.00001
Diameter [m]	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
Reynolds [-]	14986	2286	1524	2032	1016	20066	1651	1524
Peclet [-]	12488333	1905000	1270000	1693333	846667	16721667	1375833	1270000
Flow Regime	Turbulent	Laminar	Laminar	Laminar	Laminar	Turbulent	Laminar	Laminar

RESULTS



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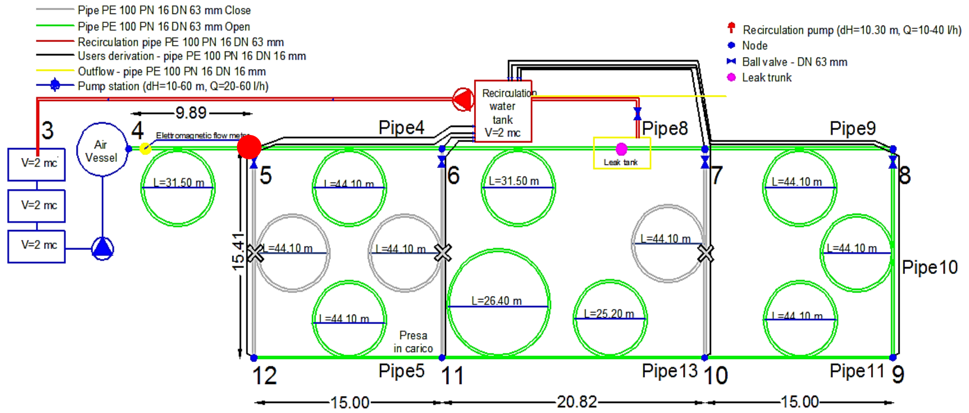

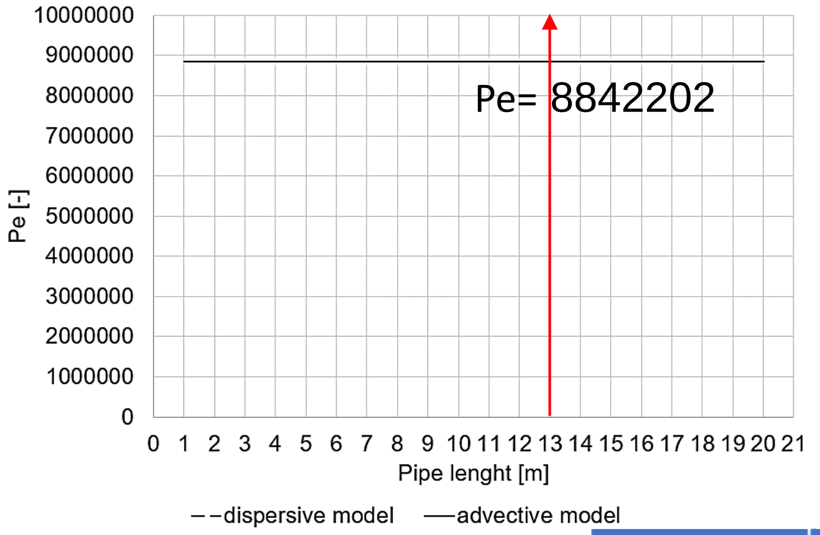

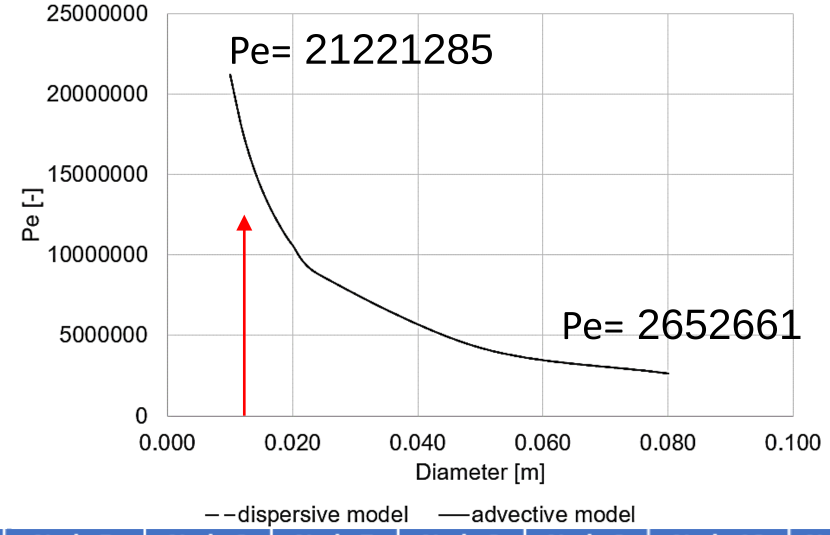

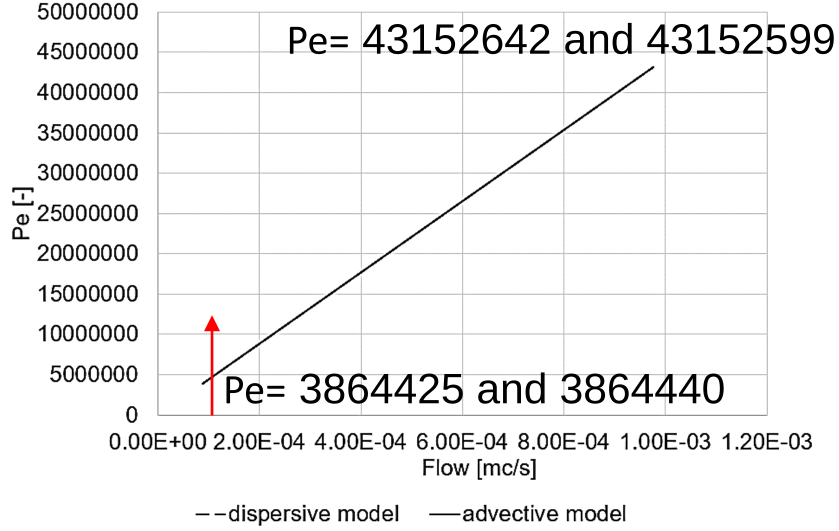

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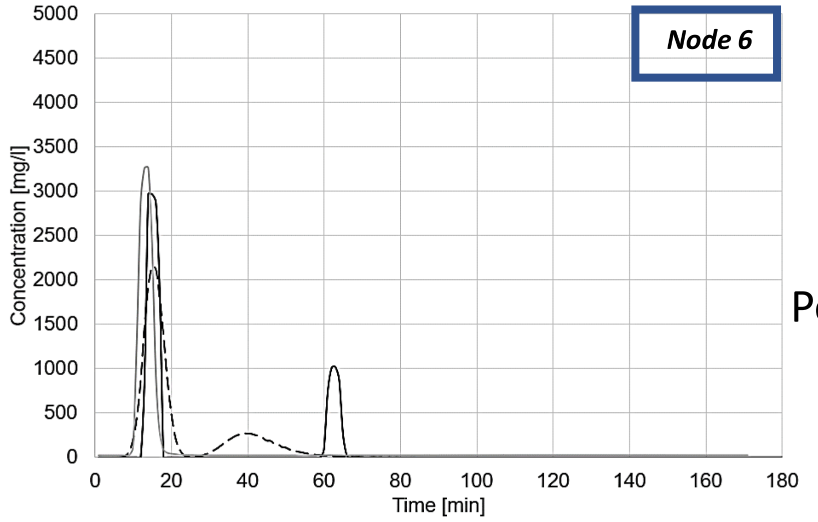
Flow Regime	Turbulent	Laminar	Laminar	Laminar	Laminar	Turbulent	Laminar	Laminar

RESULTS



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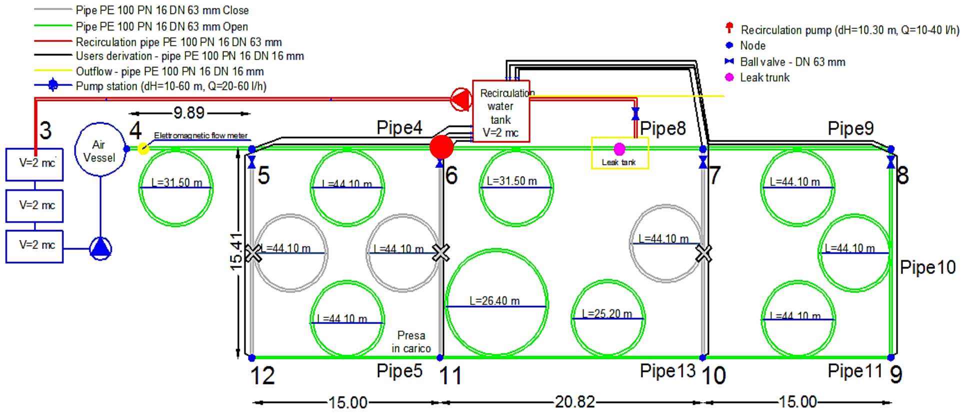

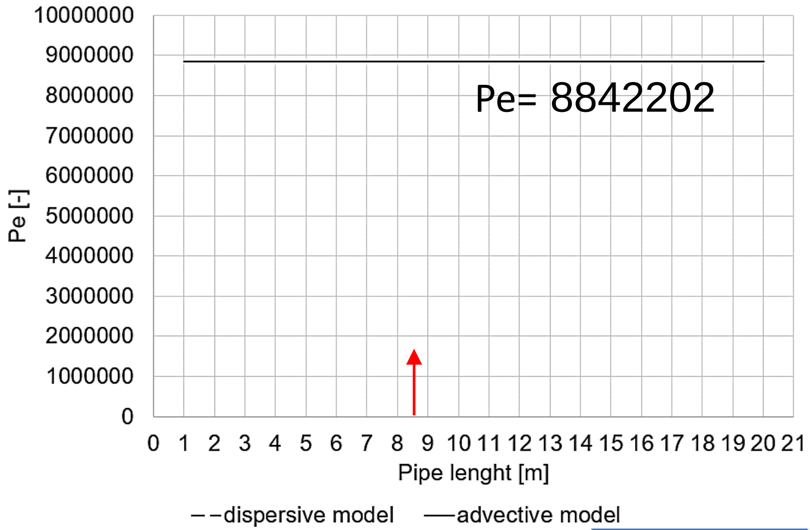

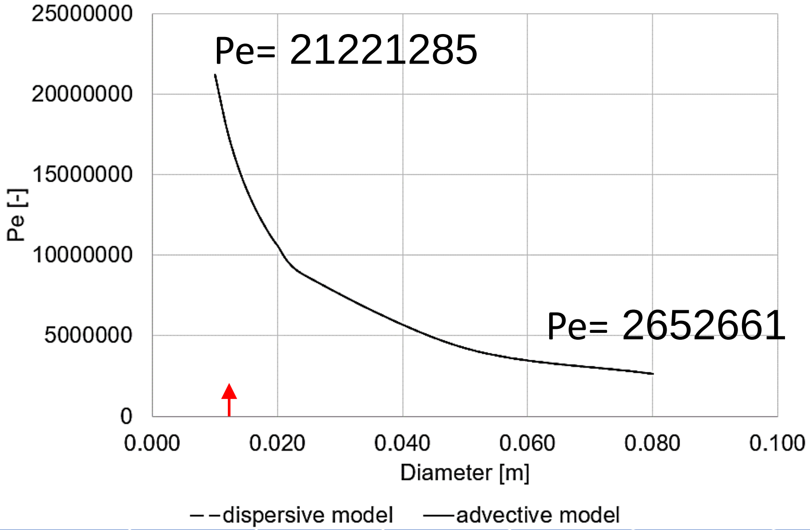

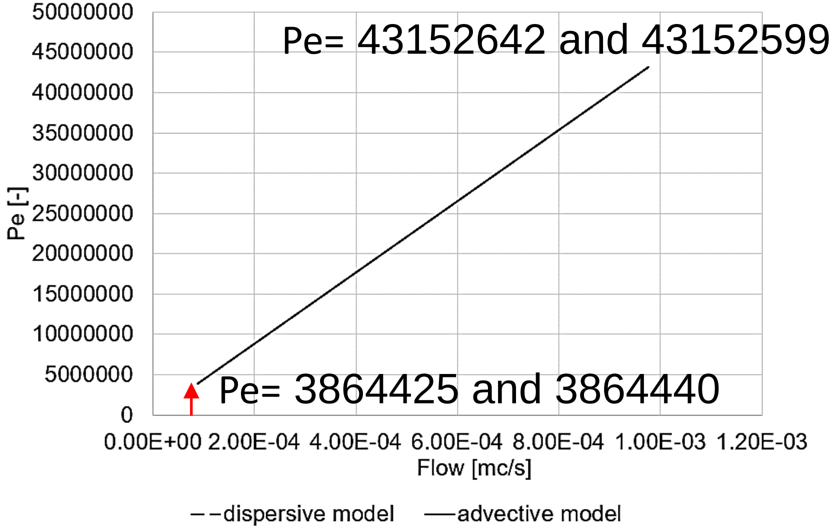

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Diameter [m]	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
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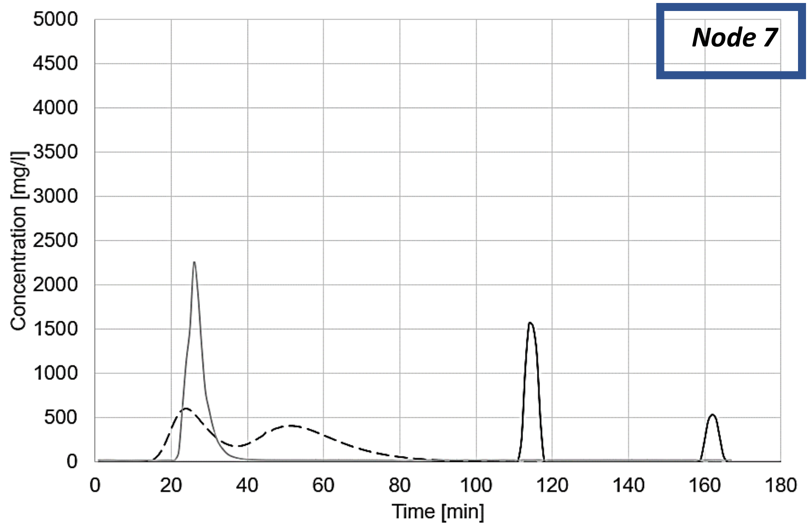
Flow Regime	Turbulent	Laminar	Laminar	Laminar	Laminar	Turbulent	Laminar	Laminar

RESULTS



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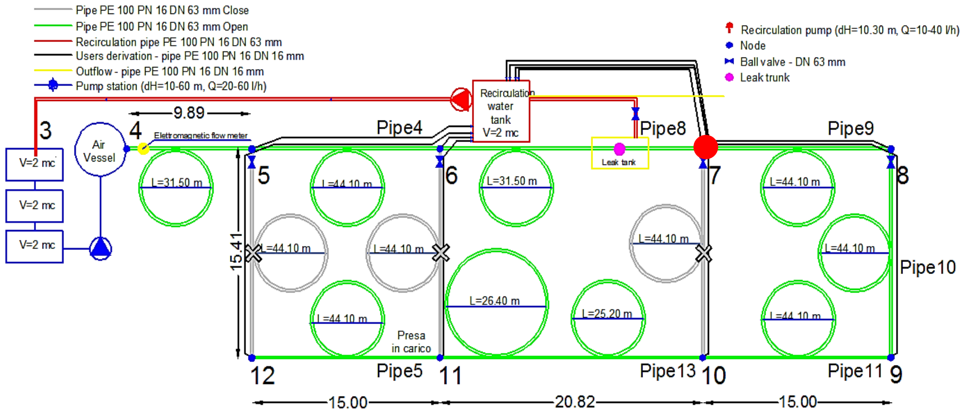

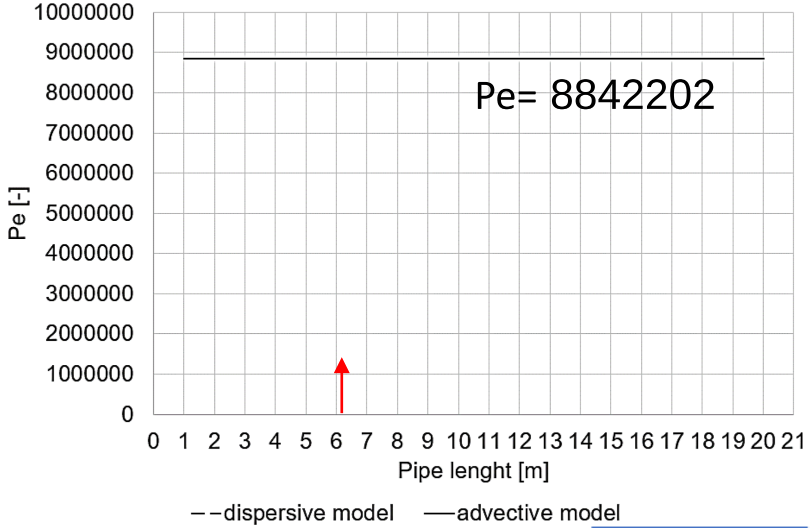

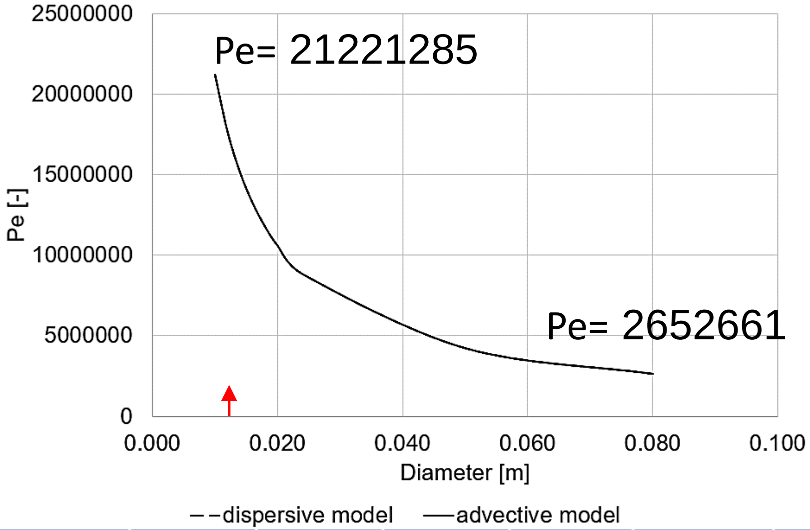

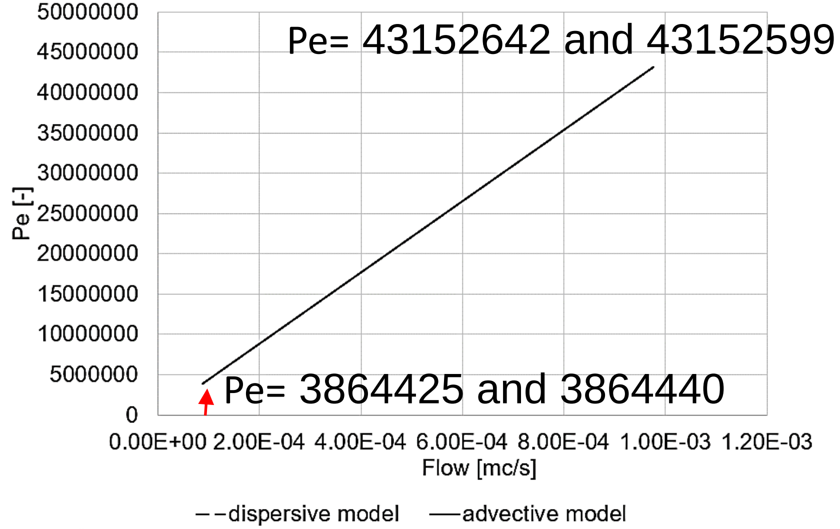

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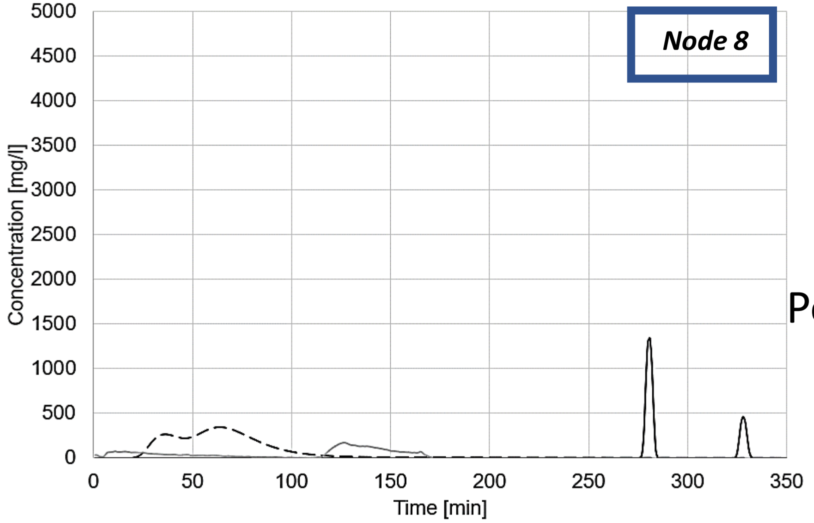
Flow Regime	Turbulent	Laminar	Laminar	Laminar	Laminar	Turbulent	Laminar	Laminar

RESULTS



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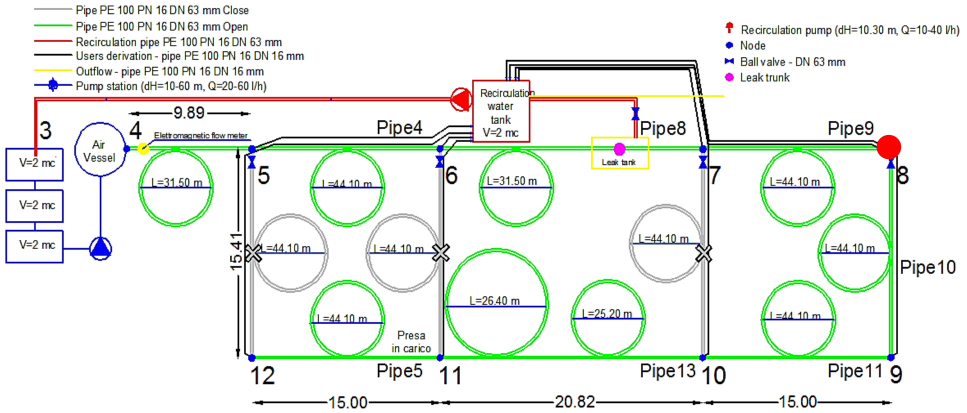
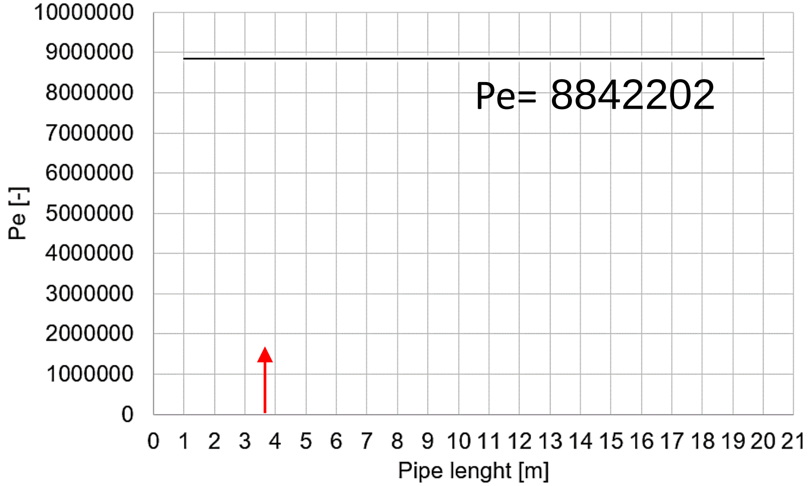
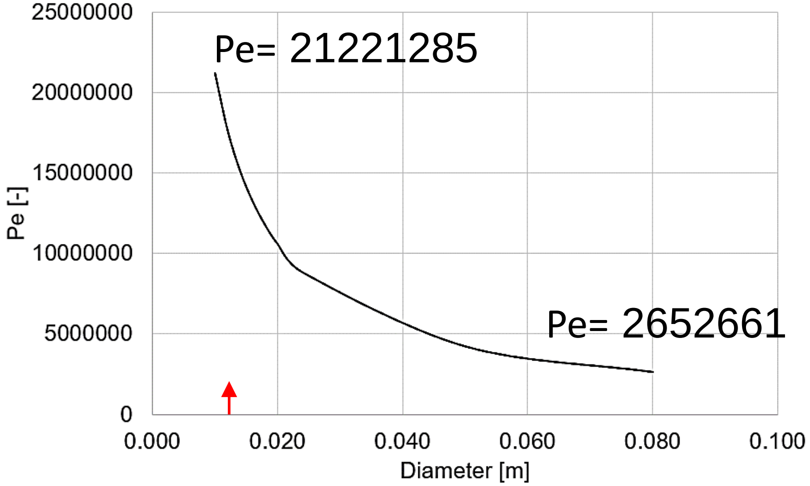
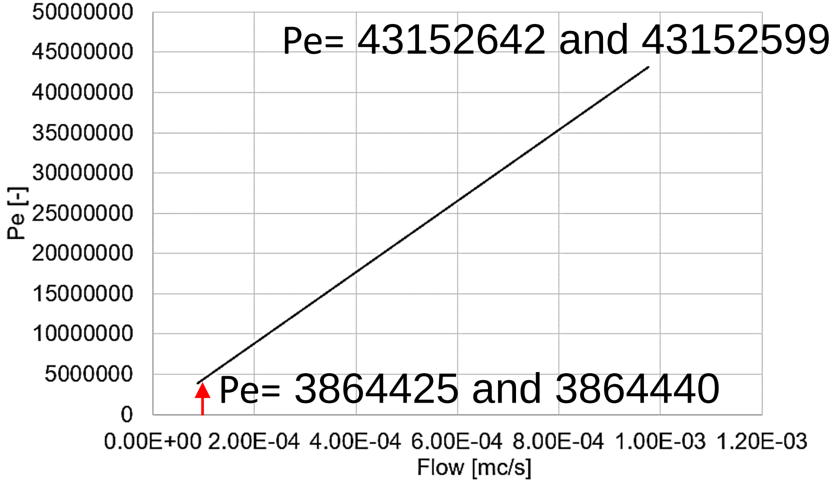




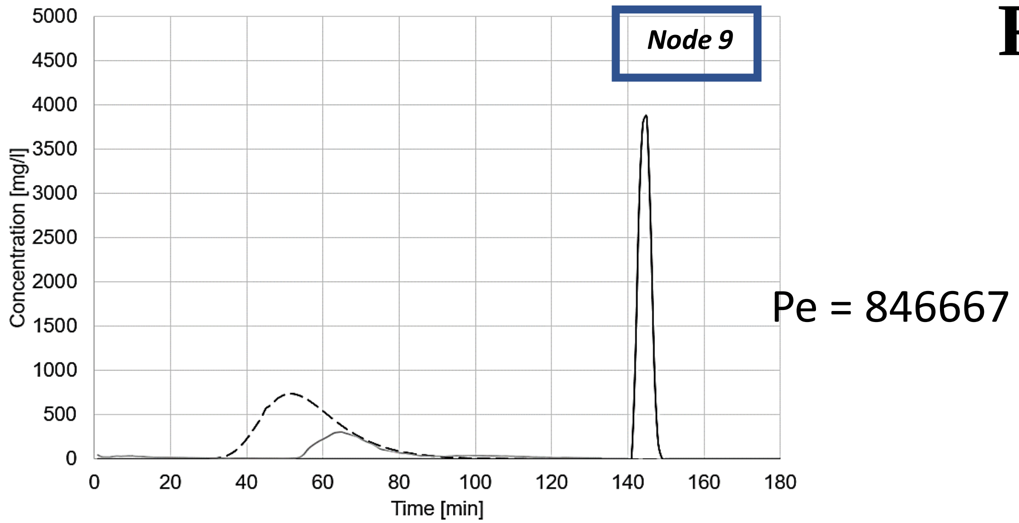


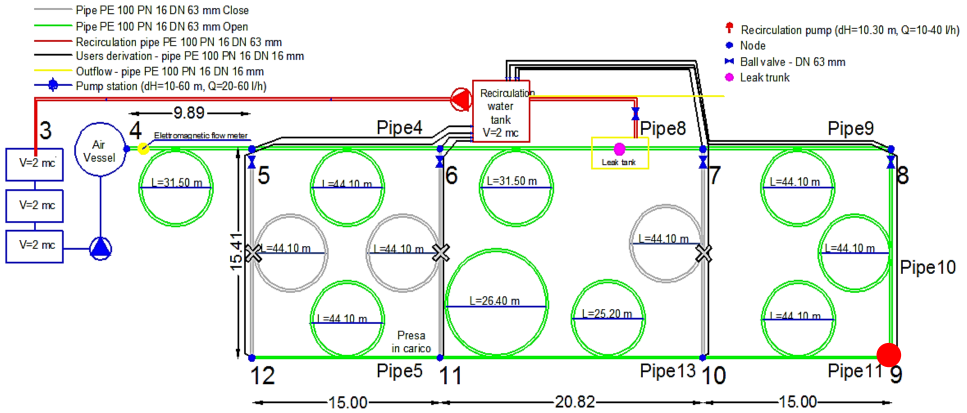


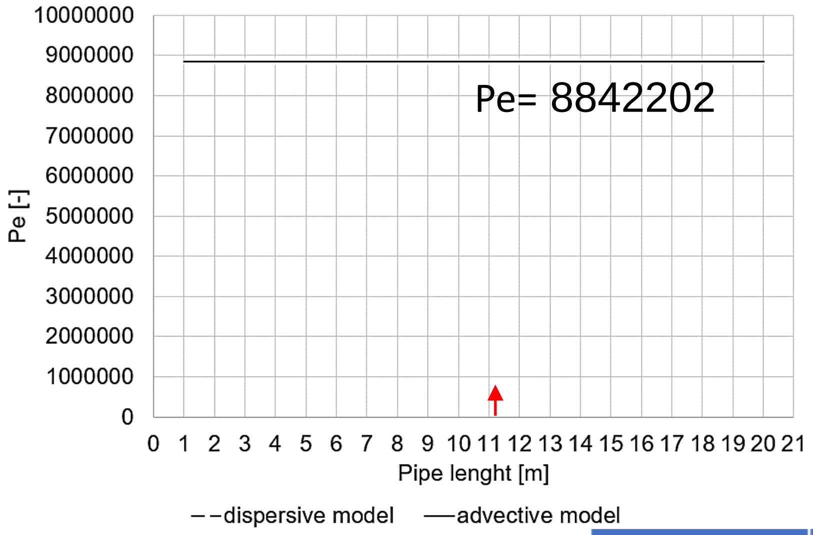
– –dispersive model ——advective model

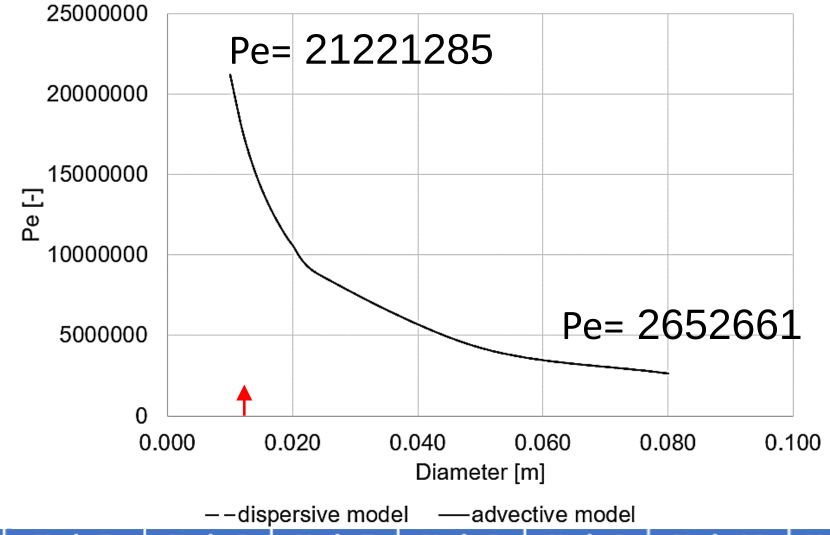
	Node 5	Node 6	Node 7	Node 8	Node 9	Node 10	Node 11	Node 12
Pipe length [m]	13	8.7	6.1	3.9	11.1	4.7	7.1	17
Flow [mc/s]	0.00015	0.00002	0.00001	0.00002	0.00001	0.00020	0.00002	0.00001
Diameter [m]	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013
Reynolds [-]	14986	2286	1524	2032	1016	20066	1651	1524
Peclet [-]	12488333	1905000	1270000	1693333	846667	16721667	1375833	1270000
Flow Regime	Turbulent	Laminar	Laminar	Laminar	Laminar	Turbulent	Laminar	Laminar

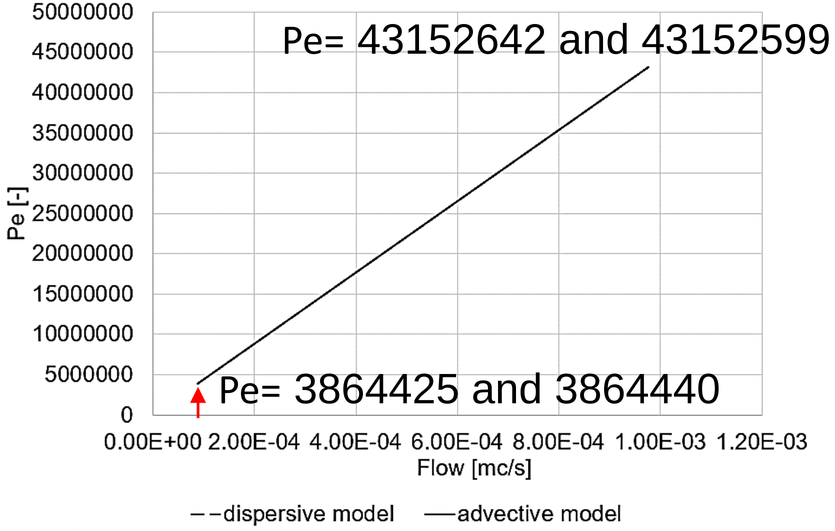
RESULTS











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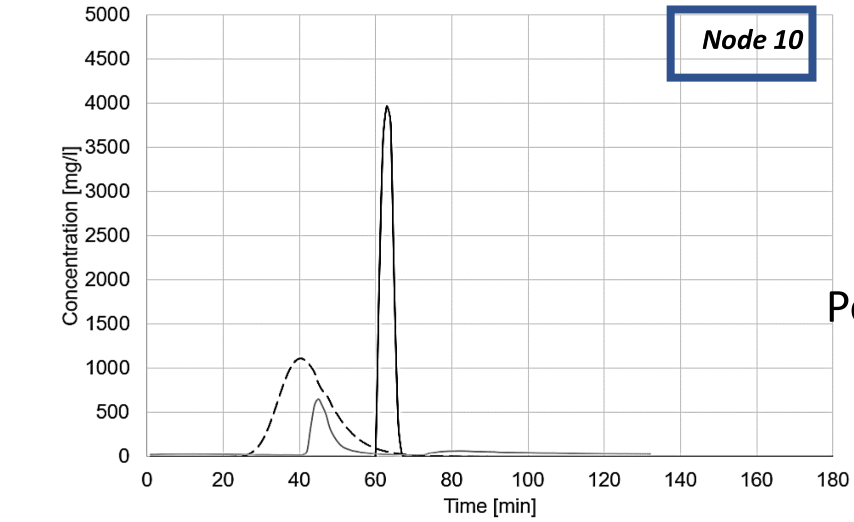
Flow Regime	Turbulent	Laminar	Laminar	Laminar	Laminar	Turbulent	Laminar	Laminar

RESULTS



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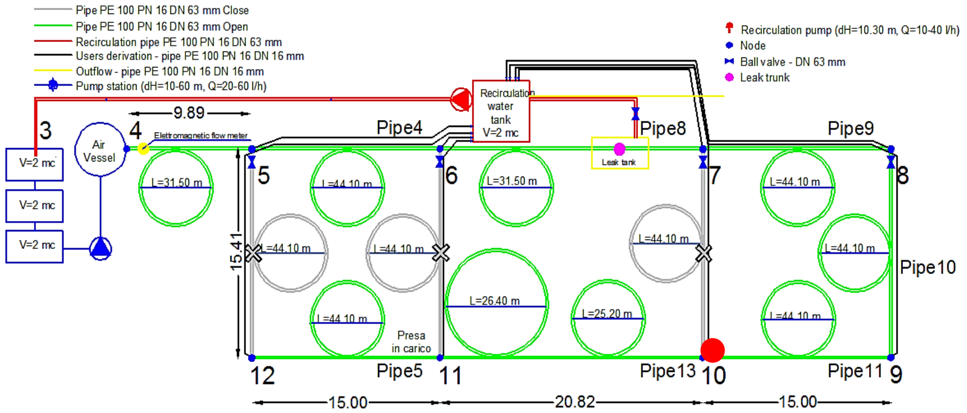

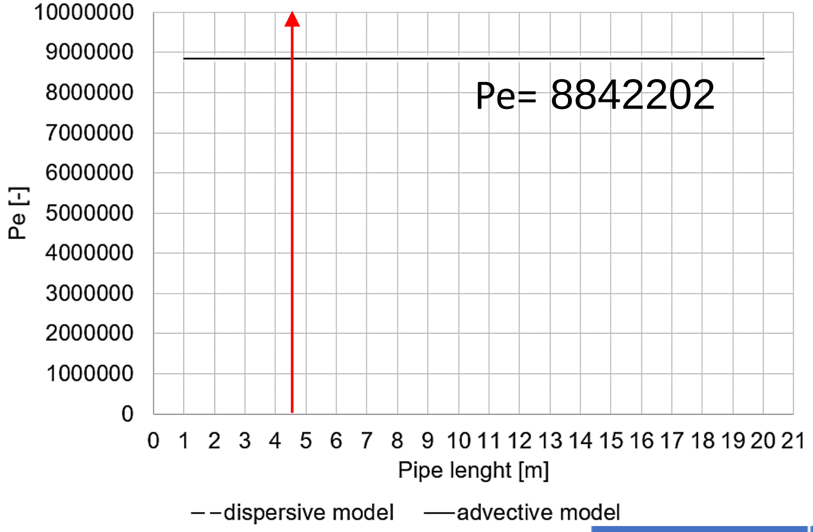

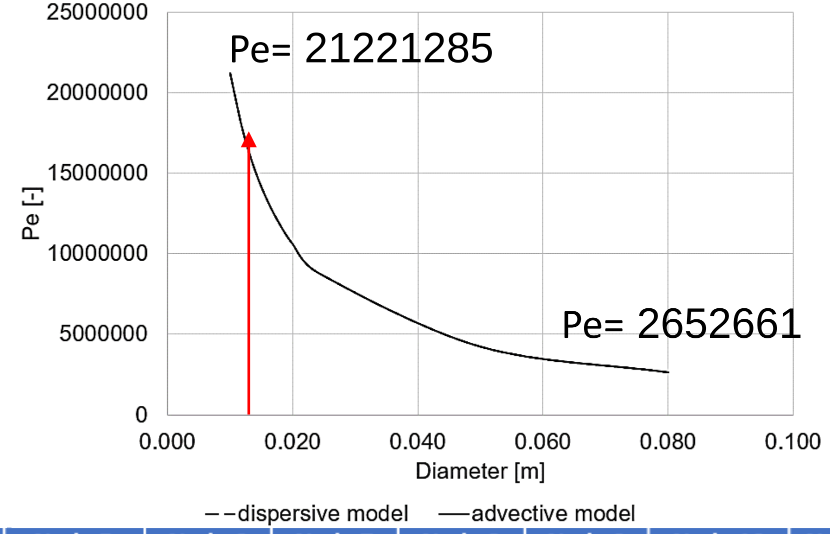

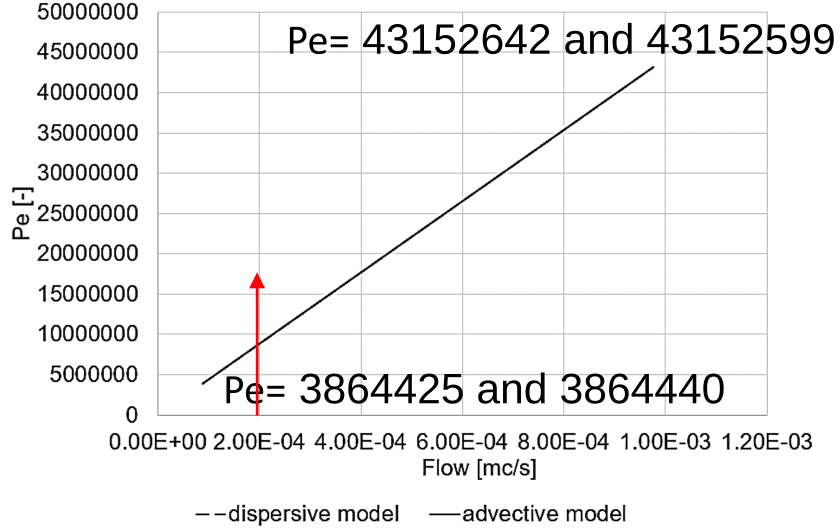

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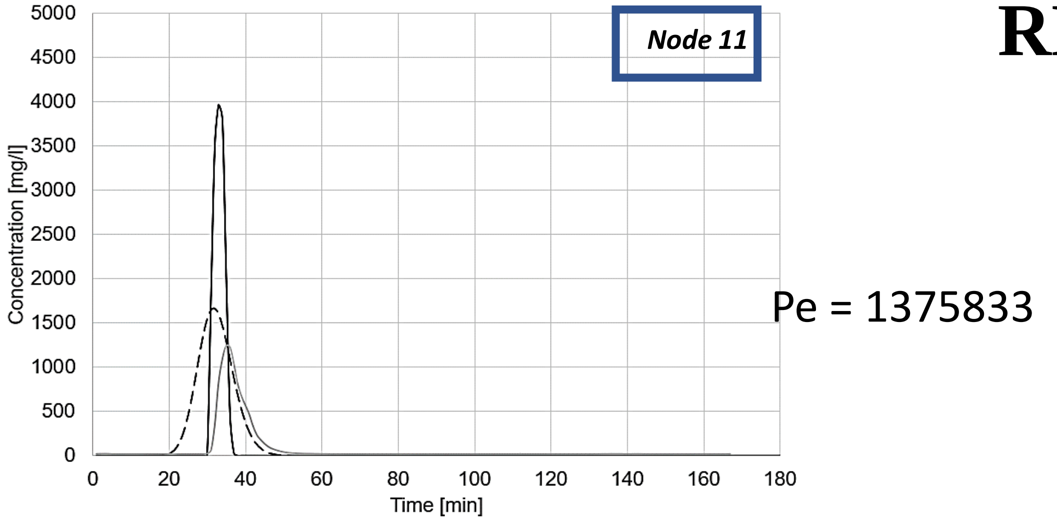
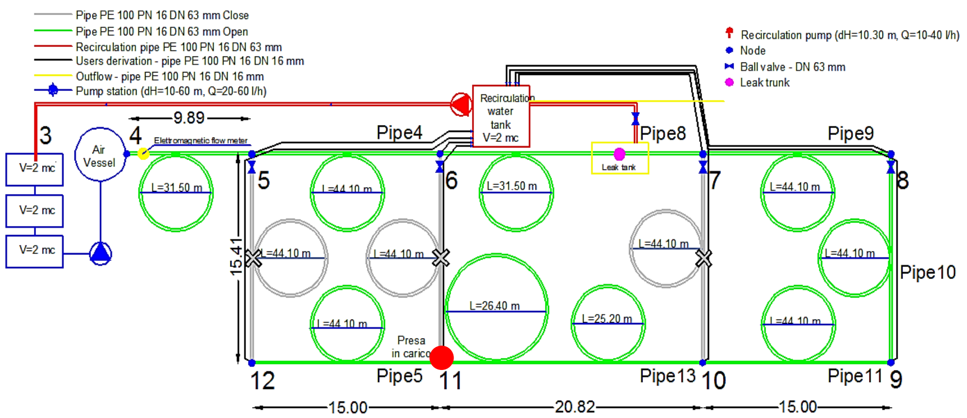
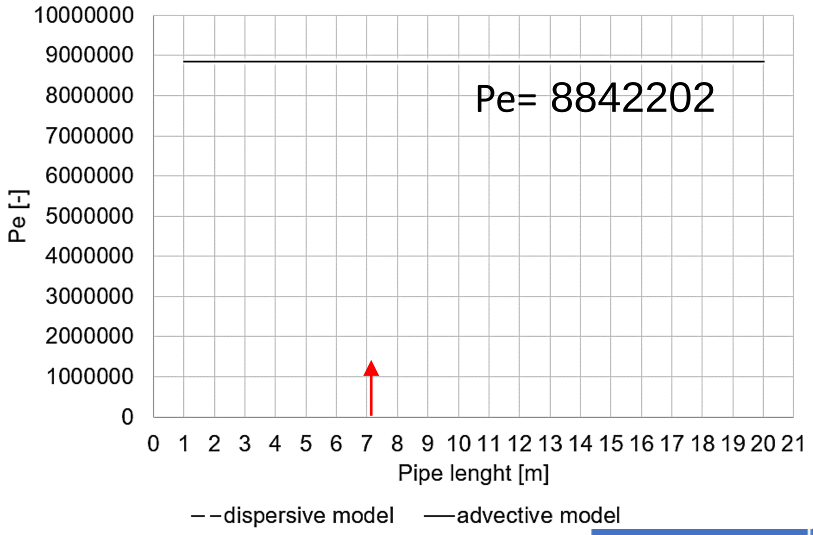
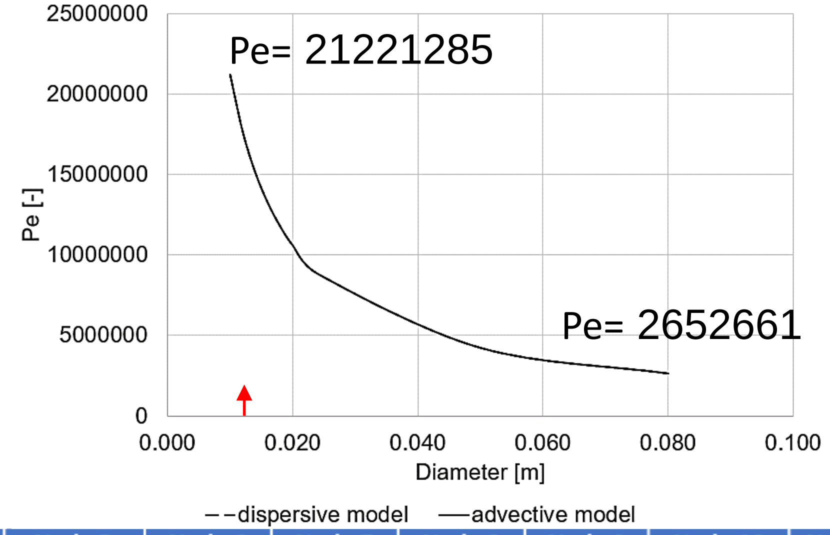
Flow Regime	Turbulent	Laminar	Laminar	Laminar	Laminar	Turbulent	Laminar	Laminar

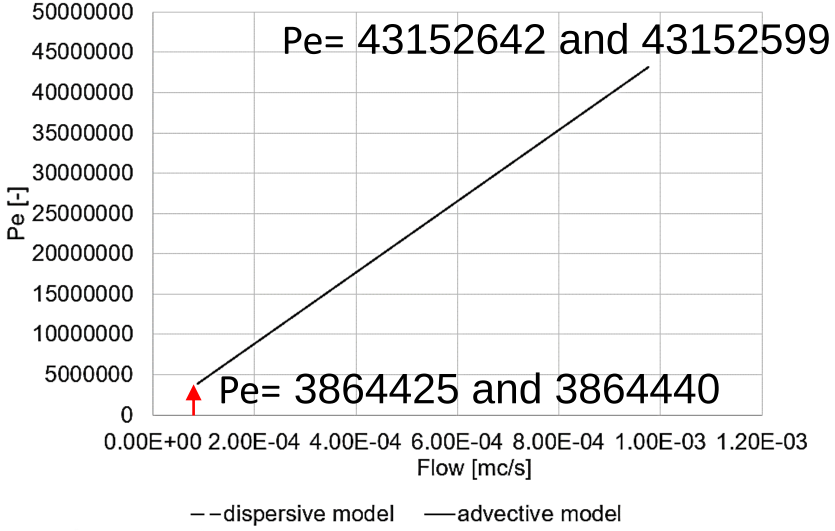
RESULTS











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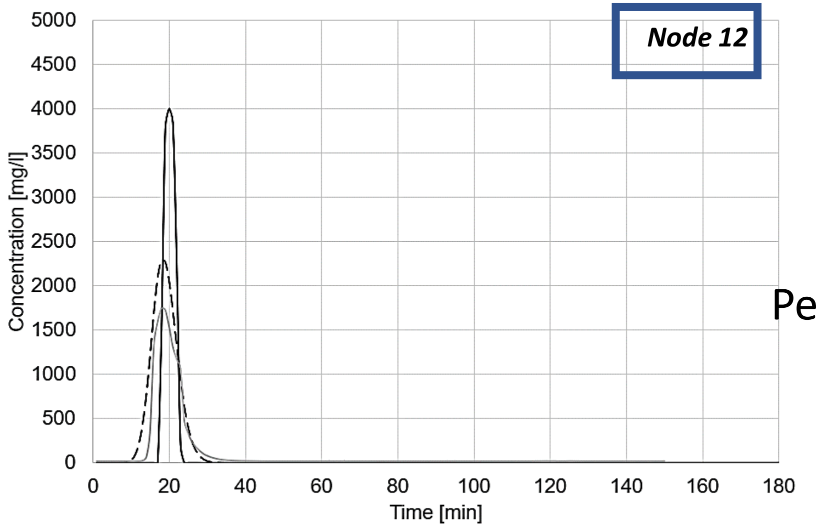
Flow Regime	Turbulent	Laminar	Laminar	Laminar	Laminar	Turbulent	Laminar	Laminar

RESULTS



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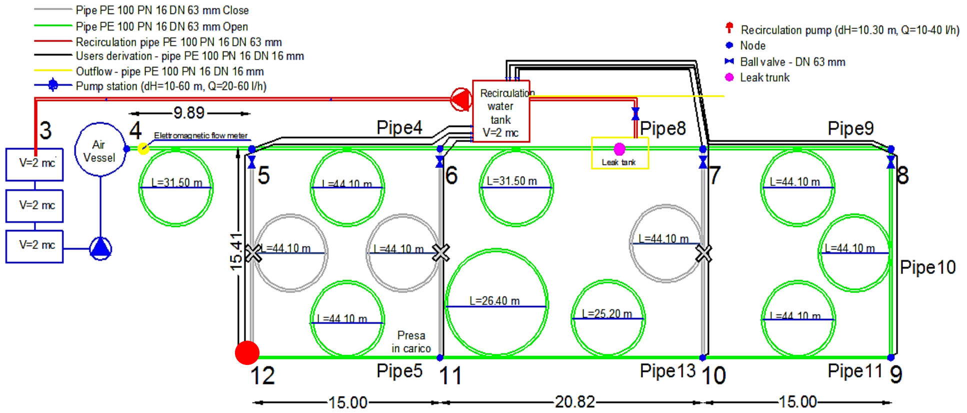

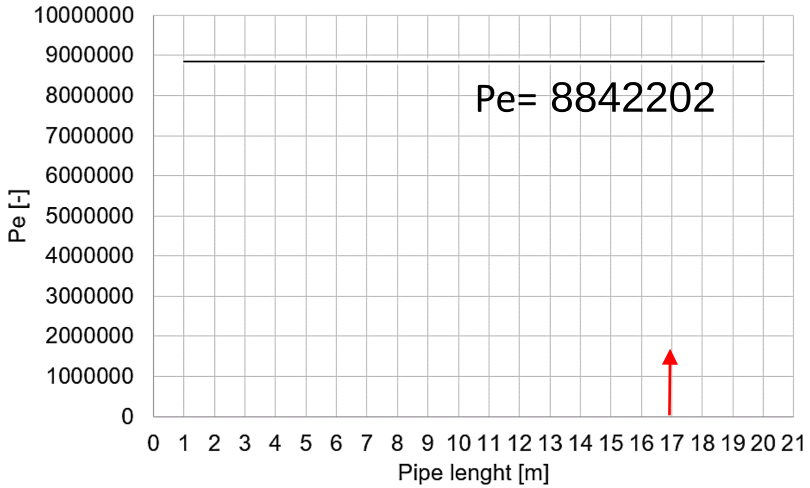

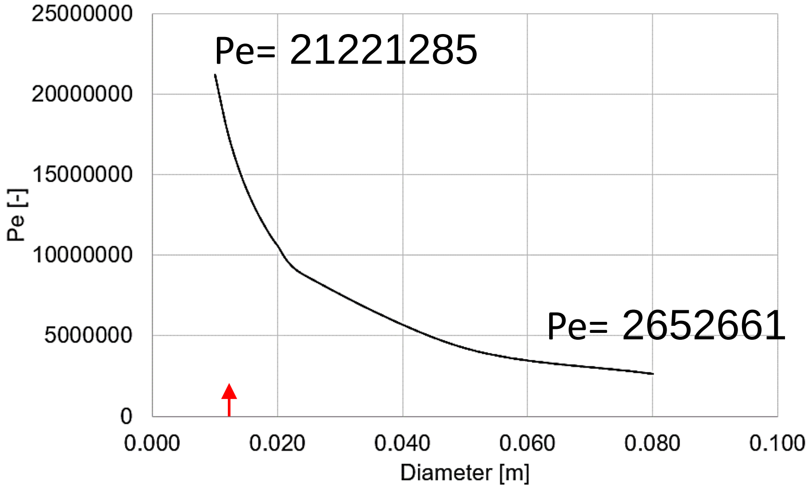

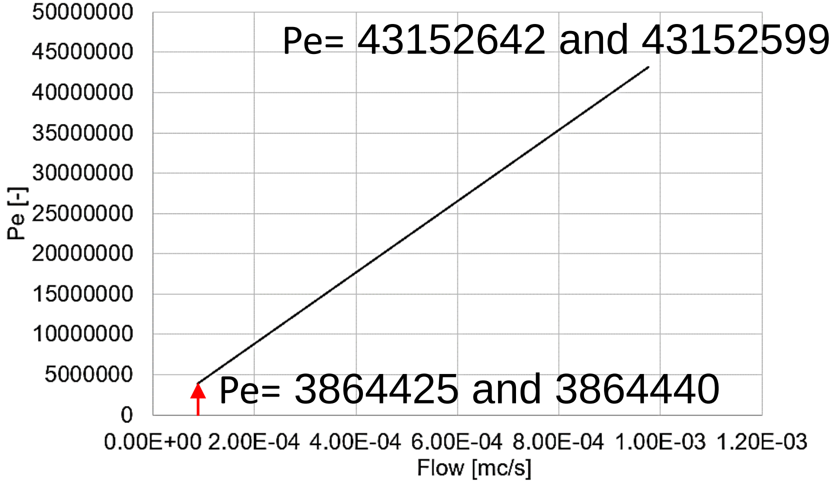

– –dispersive model ——advective model

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Flow Regime	Turbulent	Laminar	Laminar	Laminar	Laminar	Turbulent	Laminar	Laminar

CONCLUSION

- The advective model works well only in locations close to the Injection node, where it can intercept the Injection's peak even for lower values. In fact, relatively high values of the KGE, NSE and R2 coefficients were observed at node 6 near the Injection node (0.44, 0.52, 0.29 respectively).
- In all other cases, the Injection event was anticipated and had a shorter duration than that detected by the experimental campaign. As a result, much lower or even negative values of the three coefficients were obtained.
- The Romero-Gomez and Choi model can represent the dispersive behaviour of the Tracer. Still, it poorly represents the experimental data regarding delay or anticipation of the Injection peak and overestimating the Tracer mass. This was confirmed by the coefficients KGE, NSE, R2 which resulted in some nodes (6, 7, 9, 10) being worse than those obtained using the advective model.
- The new EPANET-DD model produced the best results in terms of adaptability with the experimental data. It simultaneously represented the peak time and provided better accuracy than the Romero-Gomez and Choi model. In fact, the coefficients considered were very high and, in some cases, close to unity.

CONCLUSION

- Keeping the flow rate and the diameter of the pipeline constant, by varying the **length**, the Péclet number was kept constant and equal to 8842202.
- By varying the **flow rate**, a linear relationship was observed, in which the Péclet number assumes a minimum value equal to 3864425 and 3864440, with a difference between the two values equal to 15.42, and a maximum value equal to 43152642 and 43152599, with a difference between the two values equal to 43.42, respectively using the EPANET-DD model and the EPANET model.
- By varying the pipeline **diameter**, a hyperbolic relationship was obtained, so that at the smallest diameter considered the maximum value of the Péclet number equal to 21221285 was obtained, vice versa the corresponding minimum value equal to Pe = 2652661 was obtained.
- The analysis on the laboratory network of the University of Enna "KORE" made **it possible to determine its behaviour as a function of the transport mechanisms involved**. It is observed that it is predominantly diffusive-dispersive, since a purely turbulent flow regime occurs only in two sections of the network, while in all the other sections there is a laminar flow regime.
- This was confirmed by the comparison between the values of the Péclet number, calculated for the single sections of the pipeline, and the threshold values, since the values relating to the laminar flow regime all fall below the thresholds determined in the generic condition.

Mixing Processes in Pipes, Sewers & the Natural Environment from Theory to Practice

18th & 19th April 2023, University of Sheffield

THANKS FOR YOUR ATTENTION

Stefania Piazza, Mariacrocetta Sambito, Gabriele Freni

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University of Enna "Kore"
School of Engineering and Architecture

University of Sheffield

UKRI Engineering and Physical Sciences Research Council

IAHR AIRH International Association for Hydro-Environment Engineering and Research