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Technical Note

A Method to Quantify the Drainage Basin Contributions to Transitional Water Bodies: Numerical Modeling Applied to the Case Study of Venice Lagoon

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Abstract: The trophic, chemical and ecological state of a lagoon is strongly influenced by numerous aspects, among which the quantity and quality of the water coming from its drainage basin are a priority. The Source-to-Sea approach directly addresses the linkages between land, water, delta, estuary, coast, nearshore and ocean ecosystems to identify appropriate courses of action to address alterations of key flows, resulting in economic, social and environmental benefits. Hydrodynamic modeling has become a fundamental tool for describing the dynamics of marine environments, and a specific field of development of ongoing research is a detailed representation of the land–coastal–sea fluxes. In the present study, a numerical modeling tool was used in the Venice Lagoon to assess and quantify dominant contributions from the river basin within specific areas of the lagoon. An advective–diffusive model was used to reproduce the transport of passive tracers. The results were analyzed using an automated computational tool, obtaining the average percentage contribution of each input from the drainage basin and mean concentrations of tracer in the different water bodies. Through the proposed methodology, it is possible to support the planning of specific measures, identifying priorities of management intervention and preliminarily exploring different scenarios.

Keywords: Source-to-Sea approach; environmental assessment; water quality; management tool; watershed inflows

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1. Introduction

Globally, the ecosystem status of many lagoons is degraded due to numerous anthropogenic impacts, including excessive nutrient enrichment, habitat destruction [1] and contaminant input [2]. Since the 1960s, anthropogenic nutrient inputs in coastal areas have exponentially increased, causing eutrophication and hypoxia phenomena [3,4]. More recently, a reversal in this trend has been observed following the implementation of measures to reduce agricultural and urban loads (ref. Nitrate Directive, 91/676/EC [5]; Urban Wastewater Treatment Directive, 91/271/EC [6]; Water Framework Directive, 2000/60/EC [7,8]).

The trophic, chemical and ecological state of a lagoon is strongly influenced by the quantity and quality of the water coming from the drainage basin, as well as morphology, hydrodynamics, exchanges with the sea and other stressors. In most cases, however, the main cause of eutrophication is the massive input of nutrients from the drainage basin [9,10]. In addition, the alteration of the trophic status can have a negative effect on species and habitats according to Habitats and Birds Directives ([11] and [12], respectively) and can contribute to the failure to achieve the good chemical and ecological status of lagoon Water Bodies (WBs) according to the Water Framework Directive (WFD, [7]).

As stated by Mathews et al. [13], only quite recently, new insights into the complex relationship between different ecosystems have led to understanding the many important linkages between land, freshwater, deltas, estuaries, nearshore and oceans. The "Source-to-Sea approach" and its contribution to addressing key challenges for sustainable development was proposed as a process of six steps (characterize, engage, diagnose, design, act and adapt). The first step is to characterize the key flows, prioritizing those that will be necessary to work on and determining the system boundary.

Ongoing research projects seek to integrate, scale up and enhance existing observation efforts conducted by satellites or in situ experiments together with numerical simulations to better study the land–sea interface, where terrestrial and marine habitats meet (e.g., the Horizon Europe funded project, [14]).

As reported by Ménesguen-Lacroix [15], since the 2000s, the use of numerical tracers has become more and more popular to track the fate of various nutrient loadings, either considered as simple passive and conservative dyes [16,17] or as active and form-changing variables [18–21].

In this contribution, consolidated modeling tools were used to evaluate the quality of the lagoon as a function of contributions from its drainage basin, and tools to analyze numerical results were proposed to synthesize information useful for the management of the drainage basin.

In particular, the Venice Lagoon and its river basin were used as a study area (Figure 1). The Venice Lagoon is one of the largest Mediterranean lagoons (approximately 550 km^2). Three inlets (Lido, Malamocco and Chioggia) connect the lagoon to the Northern Adriatic Sea. The lagoon basin, which experiences microtidal conditions, is mainly composed of shallow water areas (with an average depth of 1.2 m), with a network of deeper channels leading inwards from the inlets and branching inside each sub-basin. For monitoring and management issues, the lagoon is divided into 11 natural WBs and 3 heavily modified WBs (Figure 1), with key units according to the WFD [22].

The drainage basin of the Venice Lagoon is characterized by an area of about 1986 km^2 [23] and includes several small rivers [24], discharging into the lagoon approx. 30 m^3/s overall in conditions of ordinary runoff (Figure 1). The annual loads of nutrients (approx. 3–5 10^3 tons/y of total nitrogen and 100–200 tons/y of total phosphorous) and any other compounds from river basins depend on the concentration and the flow rate of the main tributaries. The ecological and chemical quality status of the Venice Lagoon is strongly related to the quality of riverine input [25], here considered as the main source [26]. Following the "Source-to-Sea approach", the first step is the identification of the contribution of different regions of the drainage basin. In relation to the above-mentioned WBs, as key units for lagoon management, identification of rivers (or sub-basins) that mainly influence each WB is necessary in such complex environments to design management measures.

A previous investigation of the relationship between the drainage basin–lagoon–sea water system was carried out in the Venice Lagoon by Berto et al. [27] using an isotopic model approach applied to particulate organic matter (POM) to characterize the lagoon water quality and identify the origin of supply (terrestrial–fluvial, marine or autochthonous). Areas and periods with greater relevance of terrestrial-fluvial inputs were also highlighted.

As reported by Umgiesser et al. [28], hydrodynamic modeling has become a fundamental tool for describing the dynamics of marine environments, revealing the human impact on the coasts and promoting sustainable development of marine resources. A specific field of development of ongoing research is a detailed representation of land–coastal–sea fluxes.

In the present study, a quantitative method to assess and quantify the dominant contributions from the drainage basin that prevail in terms of load in each specific WB of the Venice Lagoon is presented. To this purpose, the approach from Feola et al. [29] was applied and adapted to synthesize the large dataset generated by AD numerical modeling.

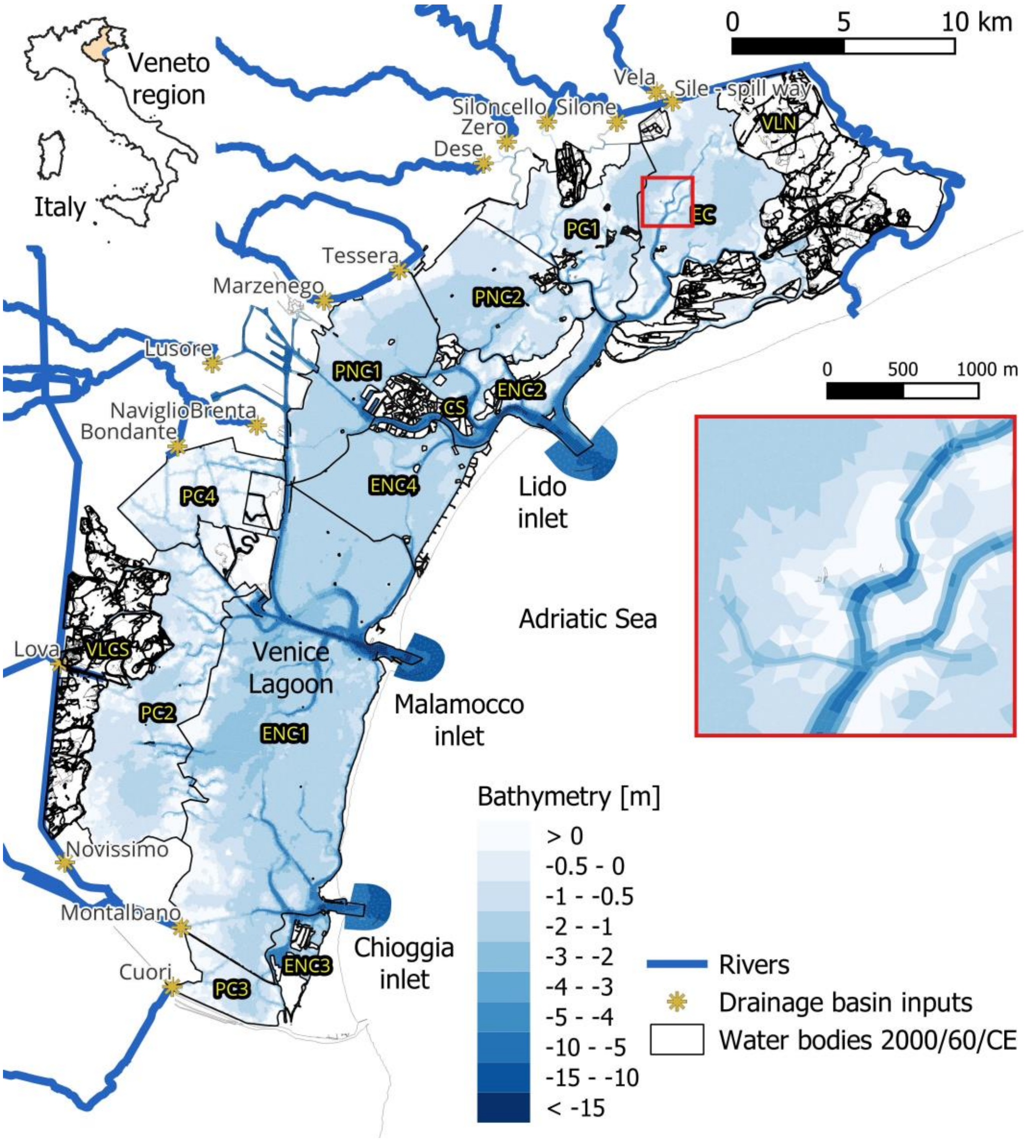

Figure 1. Lagoon of Venice (Italy, Veneto Region) with drainage basin inputs. Water bodies (WBs) according to the Water Framework Directive and bathymetry (data by Interregional Superintendency for Public Works in Veneto) are also reported. See the red box for zoomed-in details.

2. Materials and Methods

2.1. Numerical Model Setup

The study area is the Venice Lagoon (Italy, Veneto region) and its river basin (Figure 1). Bathymetry, derived from data from 2021 collected and shared by the Interregional Superintendency for Public Works in Veneto, is also reported in Figure 1.

A two-dimensional hydrodynamic model was implemented to reproduce the hydraulic regime for the entire lagoon. The adopted numerical model is the MIKE suite developed by DHI, a modeling system created for complex applications within oceanographic, coastal and estuarine environments [30]. The hydrodynamic module simulates changes in level and current in response to the different types of considered forcings (temperature, salinity, tidal effect, wind effect, heat exchange with atmosphere, Coriolis's force, waves and river inputs).

The calculation code is based on the numerical solution of the Navier–Stokes equations under conditions of hydrostatic pressure. For details on the derivation of the two-dimensional shallow water equations, see [31]. The model solves the equations of continuity, momentum, temperature, salinity and density. The spatial domain was discretized using a cell-centered finite volume method. In the horizontal plane, an unstructured grid was used, consisting of triangles or quadrilaterals, respectively, for the flood plains and channel zones.

The time integration is performed using an explicit scheme. This choice, unfortunately, determines a heavy computational effort in the solution of differential equations with consequences on minimum detail reproduced in the computational grid. Interface convective fluxes are calculated using an approximate Riemann solver. The two-dimensional shallow water equations are obtained by integrating the Navier–Stokes equations over water depth.

Transport of temperature, salinity and any solute follow the general advection–diffusion equation, with depth-averaged temperature (T), salinity (S) and concentrations. For T, a source term due to heat exchange with the atmosphere is added.

The transport of a scalar quantity is governed by the conservation equation:

$$\frac{\partial hC}{\partial t}+\frac{\partial huC}{\partial x}+\frac{\partial hvC}{\partial y}=\frac{\partial}{\partial x}\left(hD_C\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(hD_C\frac{\partial C}{\partial y}\right)-hk_pC$$

where C is the depth-averaged concentration of the generic scalar quantity, and kp is the (eventually) linear decay rate of the scalar quantity. D_c is the diffusion coefficient, here formulated according to a scaled eddy viscosity formulation (Smagorinsky). This approach overcomes the typical issue of D_c as a function of grid size in numerical models.

The discrete solution for the water depth, h, for the velocity components, u and v, and the transport variable, C, are defined at the centroid of the elements in the mesh. The space discretization is performed using the finite volume method. For each element at each stage in the time integration procedure, the water depth is updated, and then the two momentum equations are solved using the Newton–Raphson method.

The approach to the treatment of moving boundaries problems (flooding and drying fronts, which are particularly important in a lagoon environment) is based on the work by Zhao et al. [32] and Sleigh et al. [33]. When depths are small, the problem is reformulated, and only when depths are very small are the elements/cells removed from the calculation. Reformulation is made by setting momentum fluxes to zero and only taking mass fluxes into consideration.

For the flow equations, several different boundary conditions can be applied. Level boundary condition is imposed using a strong approach based on the characteristic theory (see, e.g., [33]). Discharge boundary condition is imposed using both a strong approach based on the characteristic theory (see, e.g., [33]) and a weak formulation using ghost cell technique.

In numerical solution of transport equations, time integration is performed using either a first-order explicit Euler method or a second-order explicit Runge–Kutta scheme (the midpoint method). For details on the time integration methods, see Lambert [34] and Hirsch [35].

Looking at boundary conditions, for lateral closed (solid) boundaries normal convective flux and normal gradient of transport variables are zero. For lateral open boundaries, either a specified value or a zero gradient can be given. For specified values, boundary conditions are imposed by applying specified concentrations for the calculation of boundary flux. For a zero-gradient condition, the concentration at the boundary is assumed to be identical to the concentration at the adjacent interior cell.

The computational mesh (Figure 2), with around 100,500 elements and 61,000 nodes, has a resolution ranging from 250 m at the sea boundary to around 75 m in the inner parts of the lagoon. Quadrangular elements, used to discretize the channels, have a resolution of 100 m and 30 m, longitudinally and transversely to the main flow direction, respectively.

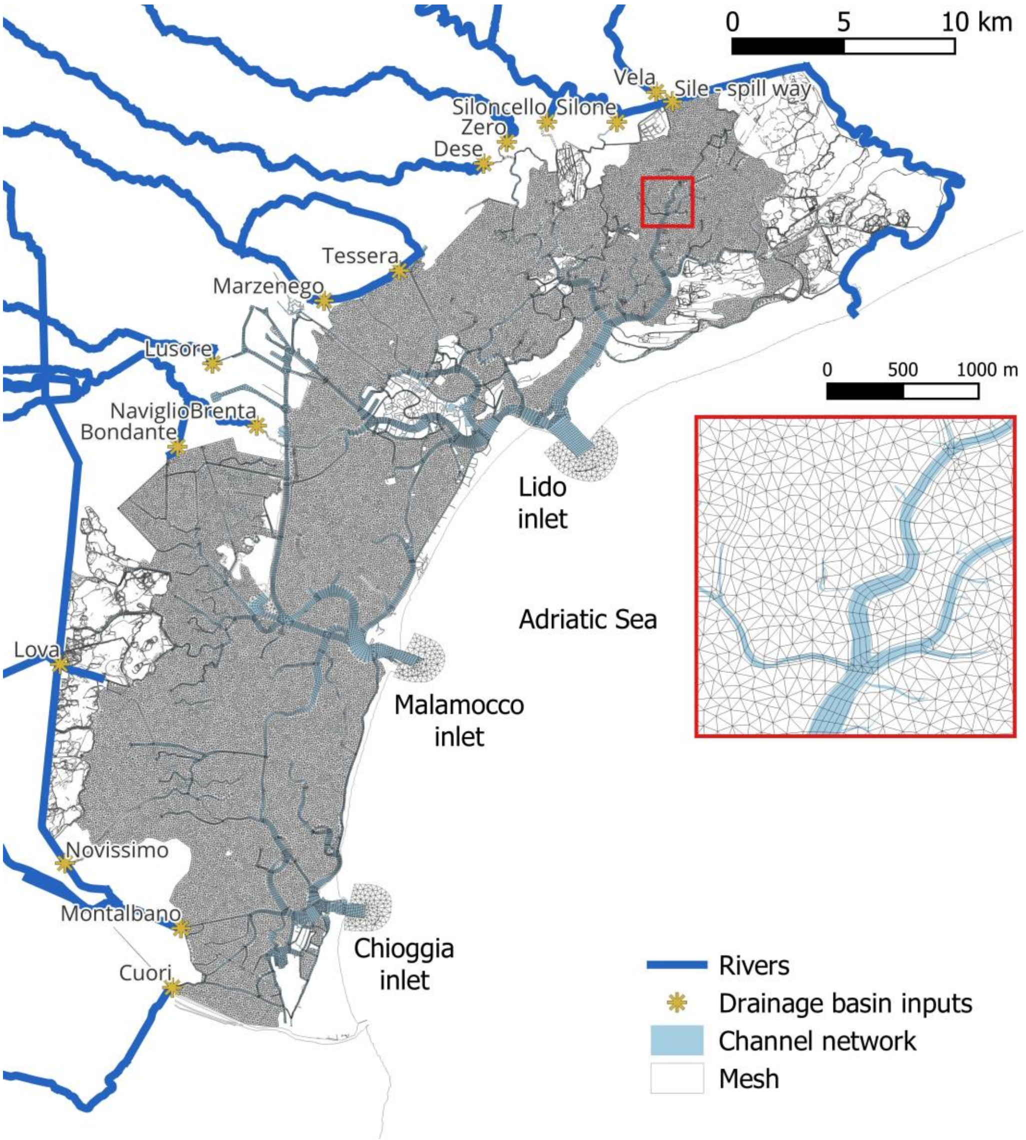

Figure 2. Computational mesh, with around 100,500 elements and 61,000 nodes and a resolution ranging from 250 m at the sea boundary to around 75 m in the inner parts of the lagoon, is represented (see the red box for a zoomed detail). VLCS and VLN, heavily modified WBs, are excluded from the computational mesh.

Water levels at sea open boundaries (Lido, Malamocco and Chioggia inlets; see Figure 2) were acquired using tidal gauges belonging to the Venice Lagoon Tide Gauge Network (ISPRA-RMLV).

Evaluations were carried out for a representative year (2017), characterizing the different tributaries of the drainage basin in terms of discharges introduced into the lagoon (Figure 2). Measured flow rates for many inputs were collected and provided by ARPAV as a continuous time series (daily frequency). Discharge for not-monitored inputs was derived from data from the literature [36,37] and imposed as a constant value. A summary of discharges used in simulations as boundary conditions for the drainage basin inputs is reported in Table 1.

Table 1. Drainage basin inputs: measured discharge. The location of drainage basin inputs is reported in Figure 1.

Drainage Basin Input	ARPAV Continuous Measures (1)	CVN Continuous Measures (2)	Gauge Station Code	Mean Value 2017 for Time Series [m^3/s]	Zuliani [34] (1999) [m^3/s]	Zirino [35] (2000–2010) [m^3/s]	Constant Value [m^3/s] (3)	Information Used Within the Study
Silone		x	CVN_Silone	4.56	4.7	3.05		(2)
Dese		x	CVN_Dese	2.39	7.5	2.51		(2)
Vela	x		G1P_Vela	1.93	3.5			(1)
Zero	x		B2P_Zero	3.35		3.28		(1)
Marzenego	x		C2P_Marzenego	1.11	1.5 (*)	1.05 (**)		(1)
Lusore		x	CVN_Lusore	1.80	2.4	2.77		(2)
Lova		x	CVN_Lova	0.72	1.2	1.19		(2)
Novissimo		x	CVN_Novissimo	4.65	4.7	3.46		(2)
Cuori		x	CVN_CanaleCuori	1.98	1.3	2.56		(2)
Bondante		x	CVN_Bondante	4.63	5.1	4.10		(2)
Naviglio	x	x	(§)	2.68				(1–2)
Tessera					0.7 (+)	1.42 (++)	1.0	(3)
Montalbano					0.7	0.48	0.6	(3)
Siloncello							0.5	(3)
Total				27.13	33.3	25.88		

An “x” is reported for each information used within the study; (*) referenced as Osellino; (**) referenced as Osellino-Rotte; (§) difference between measures from A7P_NaviglioBrenta and CVN_Bondante; (+) referenced as Scolmatore; (++) referenced as Osellino-Tessera.

In the northern part of the lagoon, also the Sile spillway (Figure 2), built after the extreme event of 1966 to protect the town of Jesolo, was considered impulsive overflow events. During significant overflow events during 2017–2018, a considerable volume of fresh water entered the lagoon through this spillway, with peaks of flow rates ranging between 4 and 28 m^3/s, with a maximum of 80 m^3/s, a duration ranging between 4 and 100 h of overflow and an average volume of water spilled into the lagoon of about 500,000 m^3 per event (data collected by Consorzio Venezia Nuova-CVN gauge station; elaboration by ISPRA).

According to Annex II of the WFD ([7]), the Venice Lagoon is a large coastal microtidal lagoon. Salinity ranges can group types of WBs into euhaline (E) or polyhaline (P), while the type “chocked/not choked (restricted)” (C/NC) can explain several hydrodynamic descriptors listed in Annex II of the WFD. In the present study, 12 WBs were considered (11 natural and 1 heavily modified). Table 2 lists the main WB characteristics.

Table 2. Water bodies (WBs) types of the Venice Lagoon (according to WFD [7]) considered in the present study and their main physical characteristics (P = polyhaline, E = euhaline, C = choked, NC = not choked). The location of WBs is reported in Figure 1.

WB Name	Type (Salinity)	Type (Hydrodynamics)	Natural (N)/ Heavily Modified (HM)	Surface [ha]	Mean Depth [m]
EC	euhaline	choked	N	4676.58	−1.11
ENC1	euhaline	not choked	N	13,412.41	−2.14
ENC2	euhaline	not choked	N	1988.93	−4.02
ENC3	euhaline	not choked	N	436.03	−3.55
ENC4	euhaline	not choked	N	2657.81	−1.64
PC1	polyhaline	choked	N	2733.60	−0.89
PC2	polyhaline	choked	N	5013.85	−0.86
PC3	polyhaline	choked	N	995.15	−0.65
PC4	polyhaline	choked	N	2098.73	−0.52
PNC1	polyhaline	not choked	N	3292.78	−1.51
PNC2	polyhaline	not choked	N	3139.73	−1.02
CS	historical center (Venice)		HM	176.74	−7.02

The advective-diffusive model (DHI - Mike Advection Diffusion-AD) was used for the implementation of the transport of non-reactive (passive) tracers based on hydrodynamic characterization performed through the hydrodynamic (HD) model. The AD module allows to reproduce variation in space and time of concentration of a passive (non-reactive) tracer entering the system at given source points inside the model domain.

The introduction of a generic tracer with constant concentration was assumed, and an arbitrary value equal to 100 mg/L was imposed at each lagoon tributary (Figure 2). The contribution of each tributary spilling into the Venice Lagoon was diversified according to the entry point. The initial concentration in the lagoon was set equal to zero.

2.2. Data Analysis

The numerical model was applied to obtain, for each element of the computational domain, the variation in time, over an entire year of simulation (2017), of tracer concentration, characterizing contributions of different tributaries of the drainage basin. Results were analyzed with an automated computational tool [29] to summarize and extract a quantitative characterization of the main features of the system in terms of water quality. Statistical parameters were obtained by integrating information over time and space. The dominant input from the drainage basin, calculated as the contribution that, for most of the time, exceeds other contributions in terms of tracer concentration, was evaluated at each point of the calculation domain. Similarly, the percentage of time of the dominant tracer was also calculated.

Using model spatial results within the WB perimeter, the average percentage contributions, obtained as the ratio between the concentration coming from a single tributary and the sum of concentrations from all tributaries of the drainage basin, were calculated. The mean concentration of the tracer, coming from each input of the drainage basin in the different WBs, was also calculated. Contributions were evaluated as averaged values in time over the representative year of simulation and averaged in space within each WB.

3. Results

Model outputs show the extremely complex variability over time and space of lagoon loads. This variability is influenced by tidal conditions, flow conditions of tributaries and weather and climate conditions that affect hydrodynamics.

Contributions of different inputs of the drainage basin within the WBs, derived from integrated analysis of modeled results, can be evaluated in percentage terms (Table 3).

Table 3. Percentage contributions of the different inputs of the drainage basin within the water bodies (WBs) of the Venice Lagoon (P = polyhaline, E = euhaline, C = choked, NC = not choked, CS: historical center of Venice).

Drainage Basin Input	**Water Bodies**											
	CS	**EC**	**ENC1**	**ENC2**	**ENC3**	**ENC4**	**PC1**	**PC2**	**PC3**	**PC4**	**PNC1**	**PNC2**
Silone	16.8	46.1	3.9	25.6	1.0	14.1	39.8	1.1	0.4	1.9	10.4	21.9
Siloncello	2.6	4.1	0.6	3.6	0.2	2.1	5.1	0.2	0.1	0.3	1.7	3.5
Dese	13.9	9.1	3.7	15.6	1.0	12.2	14.5	1.0	0.4	1.7	13.0	21.8
Vela	8.2	19.0	1.6	12.2	0.4	6.7	18.2	0.4	0.2	0.7	5.0	10.9
Zero	18.7	12.7	4.9	21.1	1.3	16.2	19.7	1.3	0.5	2.0	17.1	29.2
Marzenego	6.9	0.5	2.3	4.0	0.4	6.8	0.3	0.6	0.2	1.1	10.2	2.2
Tessera	3.8	0.5	1.2	2.9	0.3	3.4	0.3	0.3	0.1	0.6	7.1	3.5
Lusore	10.8	0.6	5.8	5.1	1.3	13.0	0.3	1.6	0.5	3.1	12.4	2.4
Lova	0.2		4.2	0.1	3.1	0.3		7.1	1.5	0.4	0.2	0.1
Novissimo	0.6	0.1	29.8	0.3	36.3	1.0	0.0	47.6	19.1	1.2	0.8	0.2
Bondante	7.3	0.5	28.9	3.7	15.4	10.1	0.3	36.5	6.7	81.4	9.3	1.8
Cuori			2.5		26.8			0.1	57.3			
Montalbano			3.0		10.6			0.1	12.4			
Naviglio	9.6	0.5	7.4	4.7	1.7	13.6	0.3	2.2	0.7	5.7	12.6	2.2
Sile spillway	0.5	6.2	0.1	0.9		0.4	1.1				0.2	0.5
Total	100	100	100	100	100	100	100	100	100	100	100	100
N contributors > 10%	4	3	2	4	4	6	4	2	3	1	6	4
Legend	Dominant contributor			Contributor > 10%			WB acronyms: P = Polyhaline, E = Euhaline, C = choked, NC = not choked, CS = historical city center					

The dominant tributary among all inputs from the drainage basin can be defined as the one with the maximum permanence of the highest concentration during the representative year of simulation (Figure 3). To estimate the permanence of the dominant condition, the percentage of time that the tracer, introduced from the dominant tributary, remains higher than others can be evaluated within the domain (Figure 4).

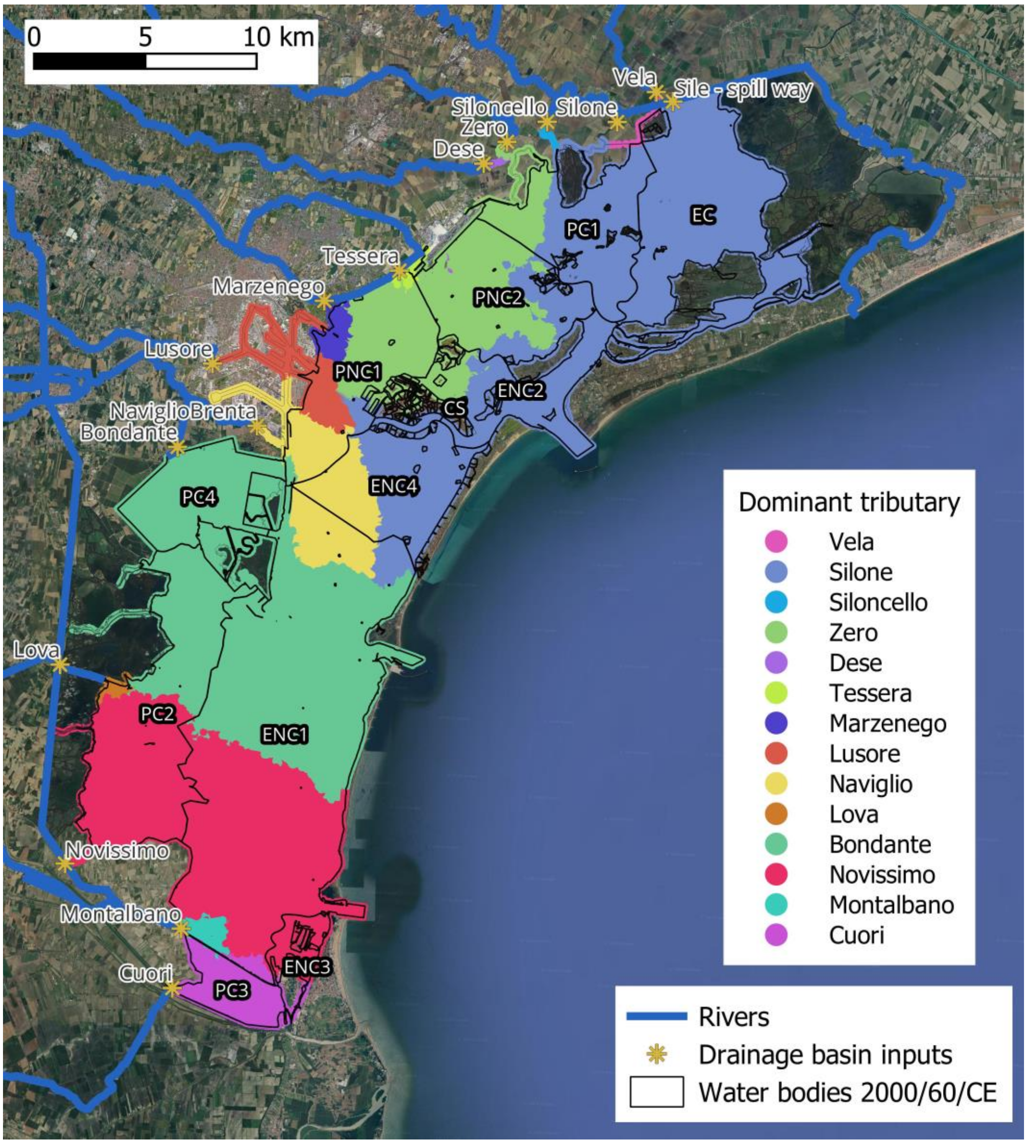

Figure 3. Dominant tributaries of the drainage basin with the maximum permanence of the highest concentration among all the tributaries.

Dominant contributors and tributaries with contributions greater than 10% are highlighted (Table 3).

Analyzing integrated results, the input from Silone river resulted in the major contribution in the Northern lagoon (EC, PC1), while the Zero river mainly resulted in influence areas between the City of Venice (CS—historical center) and Tessera where the airport is placed (PNC1 and PNC2) (Figure 3, Table 3). The Southern Venice Lagoon was dominated by Novissimo (ENC1, ENC3, PC2), Bondante (PC4) and Cuori (PC3) river inputs.

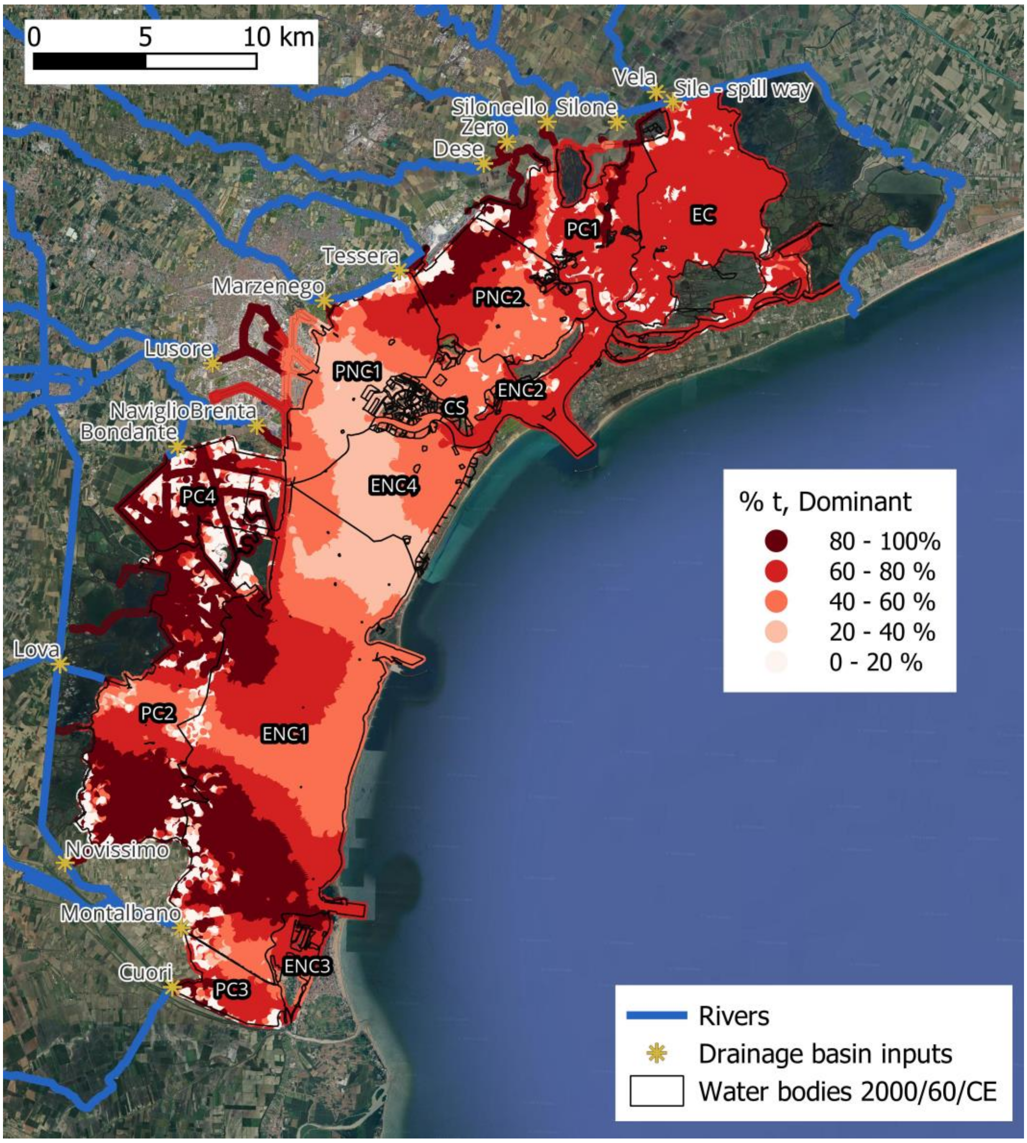

Figure 4. The percentage of time that the tracer, introduced from the dominant tributary remains higher than others. (WB acronyms: P = Polyhaline, E = Euhaline, C = choked, NC = not choked).

Considering a specific WB (values in a column in Table 3), it is possible to evaluate which are contributions in different basins that, with different extents, contribute to the overall water quality (summing up to 100%). The water quality of PNC2, mainly related to the dominating Zero river (29.2 % in Table 3), is also influenced by contributions from Silone and Dese (>20%) and Vela (around 10%). While the water quality of PC4 is mainly related to the single contribution of Bondante (>80%), the water quality of other WBs, like ENC4 and PNC1, is influenced by six different contributors with percentages ranging between 10% and 17%.

In addition to the dominance, the magnitude of each contribution needs to be considered in terms of the mean concentration of tracers to provide a quantitative description of the influence of inputs from the river basin (Table 4).

Analyzing results reported in Table 4, Silone river, the major contributor for EC, ENC2 and PC1, has a tracer concentration greater than 12 at PC1, while it is close to 1 at ENC2. Zero river, the major contributor for CS, ENC4, PNC1 and PNC2, has a concentration greater than 7 at PNC2, while it is close to 1 at CS and ENC4. Similarly, the Novissimo river, contributing with almost 30% or more to ENC1, ENC3 and PC2 (Table 3), shows a concentration close to 20 at PC2, while it is near 2 at ENC3.

Table 4. The mean concentration of tracer within the water bodies (WBs) of the Vencie Lagoon coming from each input of the drainage basin (P = polyhaline, E = euhaline, C = choked, NC = not choked, CS: historical center of Venice).

Drainage Basin Input	**Water Bodies**											
	CS	**EC**	**ENC1**	**ENC2**	**ENC3**	**ENC4**	**PC1**	**PC2**	**PC3**	**PC4**	**PNC1**	**PNC2**
Silone	1.05	7.15	0.27	1.05	0.05	0.97	12.48	0.21	0.05	0.24	1.99	4.28
Siloncello	0.16	0.61	0.04	0.15	0.01	0.15	1.81	0.03	0.01	0.04	0.34	0.72
Dese	0.90	1.29	0.27	0.71	0.05	0.87	5.15	0.20	0.06	0.23	2.66	5.45
Vela	0.51	2.94	0.11	0.51	0.02	0.45	5.81	0.08	0.02	0.09	0.97	2.15
Zero	1.20	1.81	0.35	0.96	0.07	1.16	7.12	0.26	0.08	0.30	3.50	7.33
Marzenego	0.47	0.07	0.16	0.21	0.02	0.53	0.06	0.11	0.02	0.15	2.17	0.36
Tessera	0.26	0.06	0.09	0.15	0.02	0.26	0.06	0.07	0.02	0.08	1.68	0.91
Lusore	0.74	0.08	0.43	0.27	0.07	1.09	0.07	0.32	0.08	0.43	2.02	0.38
Lova	0.01	0.00	0.42	0.01	0.17	0.03	0.00	2.17	0.23	0.07	0.04	0.01
Novissimo	0.04	0.01	3.31	0.02	1.99	0.08	0.01	19.18	2.96	0.21	0.12	0.03
Bondante	0.49	0.06	2.50	0.19	0.83	0.84	0.06	8.04	1.01	22.67	1.45	0.29
Cuori			0.27		1.61			0.02	10.82			
Montalbano			0.45		0.62			0.02	1.97			
Naviglio	0.65	0.07	0.56	0.24	0.09	1.16	0.07	0.45	0.10	0.83	1.98	0.35
Sile spillway	0.03	1.18		0.04		0.03	0.31				0.04	0.09
Legend	Dominant contributor			Contributor > 10%			WB acronyms: P = Polyhaline, E = Euhaline, C = choked, NC = not choked, CS = historical city center					

4. Discussion and Conclusions

The quantity and quality of water coming from the drainage basin can affect the trophic, chemical and ecological state of a lagoon. Moreover, morphology, hydrodynamics, exchanges with the sea and other stressors related to anthropogenic uses of the lagoon can alter it [1,2,8,9]. Numerical modeling, a fundamental tool for describing the dynamics of this complex environment, can be used to evaluate specific aspects.

In this study, consolidated modeling tools were used to evaluate lagoon quality as a function of contributions from its drainage basin, while tools for analyzing numerical results were proposed to synthetize information useful for the management of the drainage basin.

In particular, post-processing analysis of results from numerical modeling was implemented, in the case study of the Venice Lagoon, as a management tool to support the assessment of water quality of the lagoon WBs.

Spatial and temporal characterization of contributions of individual river inputs to transitional water bodies cannot be quantified without using a hydrodynamic model. Indeed, models allow to reproduce variability in space and time of concentrations as a function of the boundary conditions from the drainage basin (flow rates and concentrations of tracer of the inputs) and from the sea (tide levels at the inlets), obtaining the hydrodynamics as the interaction between tidal currents, wind forcing and morphological complexity (channels, shallow waters, intertidal structures).

Results show the influence of various contributors that, in some cases, is not directly attributable to the position of the nearest inputs. This is the case of Zero river, whose influence remains confined in the areas between the City of Venice and the mainland, or the case of Silone river, whose influence extends to the main part of the Northern lagoon.

Statistical comparison of inputs from the drainage basin allowed us to identify major contributions in the different areas, collecting useful elements for the management of intervention priorities.

It is possible to assess, in a specific lagoon area, which is the catchment area that prevails in terms of discharge and what are the contributions of the different basins that, although to a lesser extent, contribute to the overall water quality. In this regard, the results show that there are WBs influenced by a single dominant input (e.g., PC4 influenced by Bondante river) while the water quality of other WBs is related to a high number of contributors (e.g., ENC4 and PNC1 with six different inputs).

Through this methodology, implementation preferences can be established for specific practices, exploring different scenarios of investment and policy interventions by assessing the potential impact of specific measures on the reduction in impacts [38]. It is also possible to evaluate the complex variability of lagoon loads to identify optimal sampling strategies and formulate evaluations to support the interpretation of the monitoring results.

Future developments related to the presented case study may foresee a better description, also through numerical models, of inputs from the drainage basin that are currently not monitored.

The tracer concentration, initially assumed to be constant as a first hypothesis, can be replaced with measurements of specific compound concentrations to assess actual loads.

Certainly, by shifting from hypothetical tracers to actual concentrations of specific substances (e.g., dissolved inorganic nitrogen), the assumption of a 'non-reactive' tracer is inadequate, and the implementation of biogeochemical models to reproduce these processes becomes necessary. However, this approach can still help analyze the influence areas of each sub-basin, excluding the internal processes within the lagoon.

Future research in this field will address other aspects, such as morpho-dynamics, including cohesive sediment transport.

In the context of lagoon river basin management, this approach can support a preliminary analysis of sub-basin contributions, helping to prioritize areas where measures to reduce nutrient loads could have a greater impact on lagoon water quality. This initial analysis can then inform the selection of scenarios, which can be further refined using more complex tools able to reproduce biogeochemical processes.

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List of Abbreviations

Italian National Institute for Environmental Protection and Research: ISPRA; Environmental Prevention and Protection Agency of Veneto Region: ARPAV; WBs: Water bodies; Water Framework Directive: WFD; particulate organic matter: POM; Consorzio Venezia Nuova: CVN; WB acronyms: P = polyhaline, E = euhaline, C = confined, NC = not confined; Advection–Diffusion model: AD; hydrodynamic model: HD.

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