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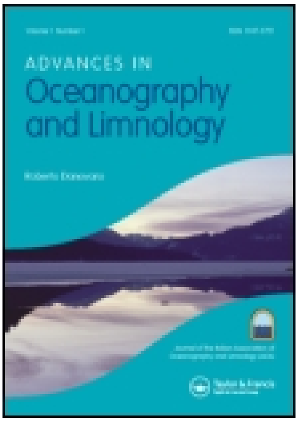

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Salinity and its variability in the Lagoon of Venice, 2000-2009

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Salinity and its variability in the Lagoon of Venice, 2000–2009

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Yearly averages computed from monthly and bimonthly salinity data collected between 2000 and 2009 from 13 broadly spaced stations in the Venice Lagoon were analysed in view of 30 min data collected semi-continuously during 2009 at nine similarly located stations. Data from all stations and all years indicate that, based on yearly averages, the lagoon may be divided along its major (long) axis into three areas: 1) a northern, freshwater impacted area ($S = < 28$ PSU) of high, tidally-caused, variability, 2) a southern, marine, zone of $S > 32$ PSU of low, tidally-caused, variability, and 3) an intermediate zone. Salinity changes are closely associated with rainfall events, and the incoming freshwater is consistently distributed throughout the lagoon by tidal action. Much variability is simply a result of the forward and backward motion of the tides and is not caused by a salinity change in the water itself. The consistency of the 2000–2009 data and the historical (to 1961) watershed record support the hypothesis that the Venice Lagoon has been and is currently at steady-state with respect to its salinity distribution. As such, it is conducive to the development of (at least) three separate ecosystems.

Keywords: Venice Lagoon; salinity; steady-state

1. Introduction

Salinity is a fundamental descriptor of marine waters and estuaries in particular, and has been related to diversity of animal and plant species that reside in them [1]. It has been pointed out that the large physico-chemical gradients found in estuaries promote a diversity of organisms that are important to the exchange of biomass and energy between freshwaters and the sea [2]. However, according to Attrill [3], 'The major environmental factor influencing the distribution of organisms in estuaries is salinity variation, rather than the absolute salinity tolerance. . ..'.

It is well-known that the physico-chemical properties of the waters of the Venice Lagoon are spatially and temporally variable [4,5]. Recently, Ghezzo *et al.* [6] used a two-dimensional (2D) hydrodynamic/dispersive model to simulate lagoon-wide salinities for the years 2003 and 2005. Significant inter-annual variation in salinity, standard deviation of salinity, and hydrodynamic residence times were found. What is less known, however, is whether the temporal variations in salinity during the last decade have been sufficiently small to consider the lagoon at steady-state (e.g., small changes from the

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*Corresponding author. Email: azirino@ucsd.edu mean are permitted but the system tends to return to its average value) and thereby conducive to the development of separate ecosystems [7]. In this work, we hypothesize that the Venice Lagoon is presently at steady-state and examine the available 2000–2009 record to: (a) either confirm or disprove our hypothesis, b) determine if and how climatic drivers may have affected the spatial and temporal variability of salinity over the last decade, and c) establish the past patterns of salinity and its variability in order to be able to better assess and predict the impact of current and coming alterations to the lagoon's morphology [8].

1.1 Background

The Lagoon of Venice is a large (550 km^2), shallow ($\sim$1.5 m), bar-built estuary bordered on the north by an agricultural/industrial drainage basin whose area is roughly three and a half times that of the lagoon and on the south by that section of the northern Adriatic Sea known as the Gulf of Venice. There are three entrances to the lagoon: Lido, the northernmost, Malamocco, at the centre, and Chioggia, to the south. Except for these openings, the lagoon is isolated from the Gulf of Venice and Adriatic Sea by sandy barriers and, at places, by a 4 m seawall. Three urban centres border and affect the lagoon: the city of Mestre which adjoins the lagoon on the north via its port, the borough of Porto Marghera (total population ca. 170,000) and the historical city of Venice (pop. ca. 60,000 including major islands) not counting daily commuters. The geographical layout of the lagoon with the historical city at its centre can be seen in Figure 1.

Starting in about 1700, the full flow of the major rivers emptying in the lagoon was rerouted to prevent filling by river-borne sediments. Nevertheless, at present, portions of several major rivers and canals still flow into the lagoon (Figure 1). While this freshwater inflow is estimated to be only about a few per cent of the saltwater inflow from the Adriatic, the dimensions and bathymetry of the lagoon allow for the presence of a salinity gradient perpendicular to its major axis, increasing from the northern (mainland) margin to the southern entrances, with especially large changes in salinity in the areas where rivers and canals discharge. In the lagoon, salinity ranges from about 20 PSU at the northeastern mainland edge to about 34–35 PSU at the three entrances to the Adriatic Sea [9].

The Lagoon of Venice has been the object of hundreds of separate works and studies spanning from the present to perhaps the fifteenth century. Recent efforts have centred on the safeguarding of the lagoon from the physical impact of the *acque alte*, namely, the frequent autumn and winter floodings of the historic city of Venice caused by storm surges. For this purpose, the Italian government via the Magistrato alle Acque, Venezia (MAV), and its concessionary, the Consorzio Venezia Nuova (CVN), commissioned the building of a system of protective barriers known as MOdulo Sperimentale Elettomeccanico (MOSE). These devices, which at the time of writing are approximately half completed, are designed to seal off the Venice Lagoon from the Adriatic Sea a dozen or more times per year to prevent inundation of the irreplaceable historical city (see http://salve.it/it/soluzioni/acque/f_mose.htm).

The prospect of closing off the lagoon has given rise to several projects designed to provide data for the ecological assessments of its well-being. Notable among these are CVN's MELa (Monitoraggio Ecologico Lagunare) programmes and the establishment of a set of semi-continuous monitoring stations carried out by the MAV's Anti-Pollution Service (SAMANET). With the exception of 2006, when no data were collected, the various (1–5) MELa programmes spanned from September 2000 to December 2010, and initially aimed for maximum spatial coverage of the lagoon. The extensive sampling and the

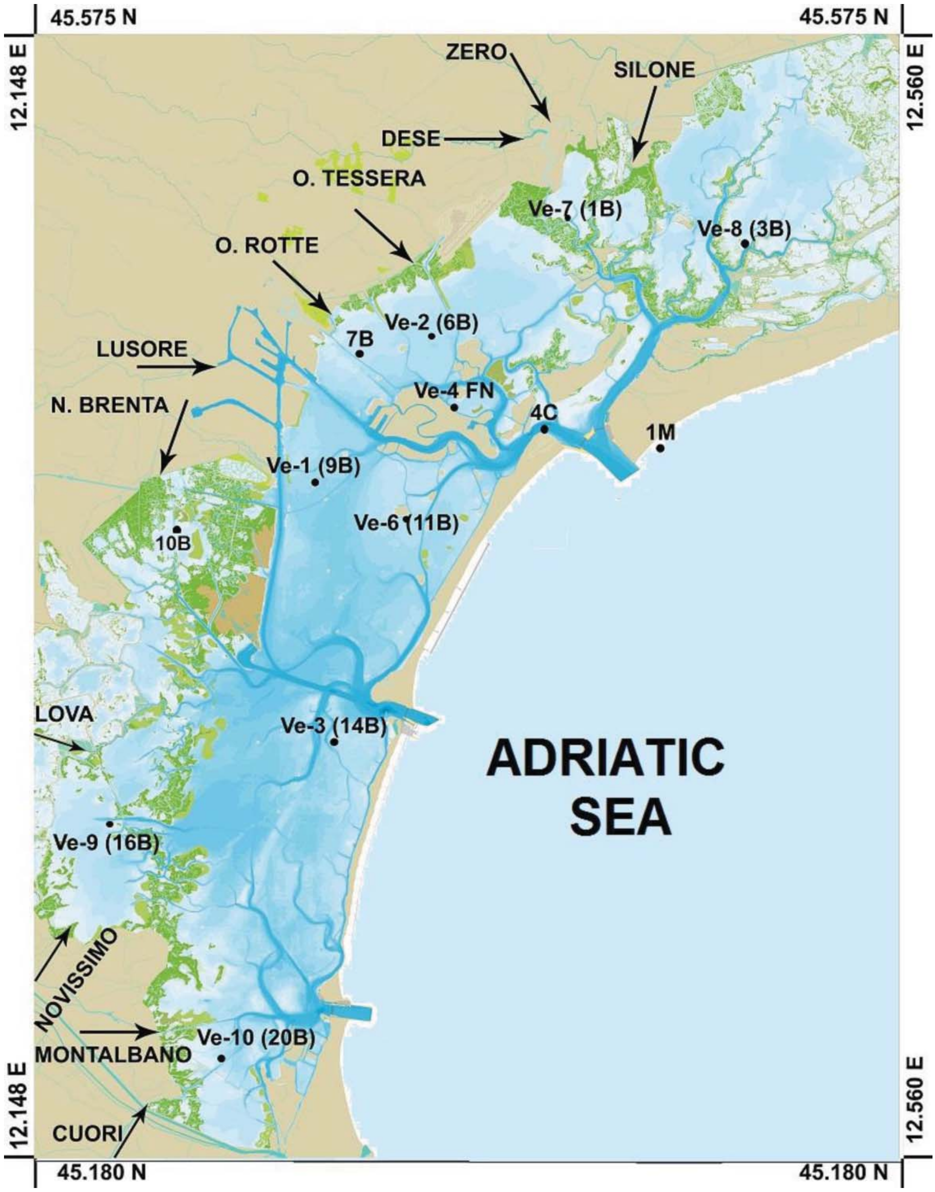

Figure 1. Location of stations and major river/canal discharges discussed in this work. ‘Ve’ stations collect data in place every 30 minutes. Adjoining MELa stations sampled monthly and/or bimonthly are shown only by name or number. River and canal names are connected to their discharge points by arrows. The historical city of Venice borders Station Ve-4 (FN).

measurement of water quality (WQ) variables conducted monthly, and occasionally bimonthly, provide the longest continuous monitoring record of the lagoon and provide the data for this report. However, over the decade, the number of stations was reduced. The initial MELa 1 sampling programme was the most complete: it included 31 stations more or less evenly distributed in the lagoon, plus two ‘marine’ stations located just outside of the Lido and Malamocco entrances. The measurements performed included

21 water quality parameters[1] related to eutrophication and seven heavy metals plus arsenic (As)[2]. Over nine years, the programme was gradually reduced to 24 stations, only 13 of which were part of the original 31. Most of the remaining stations were located in the central lagoon; the others were chosen to give a reasonable areal coverage of the lagoon.

In 2005, the Magistrato alle Acque installed five semi-continuous monitoring stations (SAMANET) in which seven WQ parameters were measured with a conductivity, temperature, depth (CTD) probe every 30 min [10]. The number of stations was progressively increased, reaching 10 in 2009. Nine of these high-temporal-resolution stations were located near the corresponding (monthly) MELa stations and supplied complementary data. These two series of measurements comprise the most complete set of WQ data available for the Venice Lagoon. However, of all of the variables available, this study deals only with the measurement of salinity (the conservative variable). Here we analyse the salinity data available for the 13 'permanent' MELa stations for the 2000–2009 period in light of the features revealed by the 2009 data from the nine automated, semi-continuous, SAMANET stations. As with many studies of the lagoon [11–13], we also consider it to be two-dimensional, namely, that there are no vertical gradients. Data from the MELa 1 programme verified that this approximation is justified [14].

2. Methods and materials

2.1 Sampling

Figure 1 shows the approximate locations of the 13 stations discussed herein. 'Ve' stations are the semi-continuous SAMANET stations and the adjoining MELa stations are shown by their number. Four MELa stations have no temporal high-resolution counterparts (stations 1M, 4C, 7B, and 10B). In the MELa programmes, from December 2000 to December 2009, monthly, and occasionally bimonthly, salinity measurements were carried out from a small vessel at neap tide by means of a CTD (IDRONAUT Ocean 7, Brugherio (Mi), Italy) calibrated according to the manufacturer's specifications. The CTD was lowered in the water to mid-depth and a measurement was recorded when the conductivity signal stabilized. Bottle samples were also collected and preserved for the later measurement of nutrients, DOC, etc., in the laboratory. Station FN was sampled only from 2005. Each of the 10 semi-continuous SAMANET stations consisted of an IDRONAUT Ocean 7 CTD suspended in the water column from a tower firmly positioned in the lagoon floor. Measurements of pressure, temperature, conductivity, dissolved oxygen, redox potential, and pH were performed every 30 minutes. The stations were serviced every two weeks and the sensors were cleaned, re-calibrated, and replaced, if needed. The two SAMANET data files available to us (2009 and 2010) were very similar and we chose to work with the 2009 file because it could be compared directly to the 2009 MELa file.

2.2 Rainfall, evaporation, and river flow

During 2009 rainfall was collected daily at seven additional SAMANET meteorological stations distributed over the lagoon. All seven stations recorded rainfall at similar times

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[1] Temperature, salinity, dissolved oxygen, pH, Eh (redox potential), turbidity, chlorophyll-a and phaeopigments, total suspended solids, nitrogen as NH_4^+, NO_2^-, NO_3^-, total inorganic nitrogen (TIN), total dissolved nitrogen (TDN) and dissolved organic nitrogen (DON), phosphorus (as PO_4^{3-}), total dissolved phosphate (TDP), dissolved organic phosphate (DOP), and carbon as total organic carbon (TOC), particulate organic carbon (POC), and dissolved organic carbon (DOC).

[2] Cu, Hg, Pb, Zn, Cd, Cr, and Ni

although the amounts could vary slightly from station to station. Rainfall from the seven stations was averaged and the average rainfall in millimetres per day over the lagoon was calculated.

Yearly evaporation over the 550 km^2 lagoon was estimated to be approximately 1.3×10^6 m^3/d from the latitude-dependent value of 84 cm/y calculated from the radiation balance equations of G. Wust as reported in McLellan [15].

The approximate yearly-average freshwater flow into the lagoon from 2000 to 2010 was measured with an acoustic Doppler instrument and obtained from CVN records (G. Cecconi, unpublished) and is shown in Table 1. Additional daily inflow data for several water conduits into the lagoon during 2009 was obtained from the Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto (ARPAV). River height measurements were performed daily but had many gaps. Height was converted to flow/time by means of calibrations made previously. All the available 2009 data received from ARPAV were plotted on the same graph and all rivers and canals in the Venice watershed data tended to display peaks at similar times. Measurements of daily flows of the Taglio di Mirano, a minor canal that feeds into the Naviglio del Brenta, were the most complete and this channel was chosen to verify the correspondence between rainfall and river flow.

2.3 Hydrodynamic model

Two simulations of the lagoon's salinity field were generated with a 2D hydrodynamic / dispersive model known as MODMEF, a semi-implicit finite element model developed to solve shallow-water equation problems in areas with large intertidal flats. This model simulates the hydrodynamic effects of tide propagation in the Venice Lagoon with great accuracy (A. Garzon, unpublished) and reproduces the actual salinities and distribution of salinities in the lagoon with reasonable accuracy [16]. The model was forced using the typically calm summer conditions of low winds, minimal freshwater input, and recorded tide of 16 July 2004. Plots were generated to show the salinity field 6.3 hours apart at maximum ebb tide and at maximum flood tide. The tidal range was 85 cm with respect to the reference gauge at Punta della Salute.

2.4 Data analysis

Statistical analyses were made using the computer programs EXCEL® and JMP®. Differences between means for the MELa monthly stations and SAMANET stations were computed using analysis of variance (ANOVA) and an *a posteriori* Tukey-Kramer honest significant difference (HSD) test with $\alpha = 0.05$. Principal component analysis (PCA) using the software JMP® was used to display the results of Tukey's HSD mean comparison of all MELa data pairs.

3. Results

Yearly average salinities and their standard deviations at the 13 MELa stations, placed in increasing order of their 2000–2009 average salinity are shown in Table 2. The two right-hand columns show the average and standard deviation of the yearly averages of each station from 2000–2009. The 9-year average salinity ranged from 21.75 ± 2.17 (1σ) PSU at station Ve-7 -1B (Palude di Cona), a shallow station (0.6 m) influenced by freshwater from the Dese Channel, to 33.80 ± 1.16 (1σ) PSU at station Ve-3-14B (San Pietro in Volta) just south of the Malamocco entrance. In general, from year to year, the salinity

Table 1. Average daily freshwater flow in m3/s per channel, per year. Bold values indicate inserted averages.

YEAR	SILONE	OSELLINO TESSERA	OSELLINO ROTTE	LUSORE	NAV. BRENTA	LUGO	CANALE LOVA	NOVIS-SIMO	MONT-ALBANO	CUORI	DESE	ZERO	TOTAL
2000	3.57	2.94	1.56	3.31	3.93	0.17	1.13	3.98	0.46	3.18	**2.51**	**3.28**	30.03
2001	2.63	2.97	1.12	2.56	4.62	0.12	0.91	3.21	0.47	2.78	**2.51**	**3.28**	27.17
2002	3.09	1.59	**1.05**	3.32	7.25	0.17	1.17	3.06	0.82	2.14	3.05	4.29	31
2003	2.09	0.62	**1.05**	1.92	4.88	0.06	1	2.1	0.12	1.23	2.15	3.33	20.56
2004	2.93	1.17	0.28	3.37	3.89	0.09	1.59	4.04	0.59	3.34	3	3.97	28.26
2005	2.79	1.64	0.95	3.04	4.04	0.07	1.38	4.64	0.26	2.54	2.41	3.99	27.75
2006	1.88	0.59	0.96	2.28	3.13	0.14	1.08	2.68	0.12	1.27	2.08	4.08	20.04
2007	2.68	0.53	0.25	2.12	3.01	0.09	0.97	2.2	0.1	1.05	1.97	2.1	16.89
2008	3.4	0.91	0.75	2.86	3.87	0.11	1.96	3.33	0.08	2.13	**2.51**	2.75	24.51
2009	4.11	1.51	1.57	2.5	2.82	0.26	1.04	4.32	0.76	4.78	1.78	2.19	27.65
2010	4.39	1.1	2.02	3.2	3.69	0.28	0.91	4.48	1.55	3.77	3.61	2.8	31.81

Table 2. Averages and standard deviations of salinity at 13 MELa stations from 2000 to 2009 in order of increasing salinity. Right-hand columns: averages and standard deviations of individual yearly averages. Lower panel: Yearly averages and standard deviations of pooled stations. Station locations are given in Figure 1.

Year	2000		2001		2002		2003		2004		2005		2007		2008		2009		2000–2009	
Sta.	Ave.	Std.	Ave.	Std.	Ave.	Std.	Ave.	Std.	Ave.	Std.	Ave.	Std.	Ave.	Std.	Ave.	Std.	Ave.	Std.	Ave.	Std.
Ve-7	19.94	8.77	22.04	4.12	20.43	5.97	24.82	5.95	21.20	6.54	23.95	4.27	24.21	6.68	19.70	6.49	19.50	5.18	21.75	2.17
10B	25.12	3.81	26.65	2.34	24.57	3.76	27.80	5.65	26.56	3.51	27.64	2.40	25.71	2.55	21.36	4.13	23.81	7.11	25.47	2.15
Ve-9	26.21	2.27	28.08	3.00	27.43	3.17	32.62	3.72	27.20	4.43	28.67	2.52	28.72	2.89	26.13	3.06	25.75	2.71	27.87	2.22
7B	25.82	3.71	27.42	2.53	27.63	3.17	31.23	3.86	28.35	3.40	29.58	2.01	29.11	1.59	26.58	2.25	27.48	1.75	28.13	1.75
Ve-2	27.84	4.07	27.69	2.17	28.94	1.90	31.18	3.57	27.99	2.89	29.38	2.05	29.36	1.98	26.54	2.65	26.02	2.26	28.33	1.67
Ve-10	24.88	5.77	26.14	8.33	27.28	6.01	30.31	4.95	27.42	7.55	31.77	2.24	32.00	2.38	29.25	4.48			28.63	2.77
Ve-1	29.29	2.22	29.41	1.92	29.79	2.71	32.17	1.76	30.10	2.42	31.33	1.14	31.50	1.21	29.95	2.64	30.46	0.90	30.45	1.05
Ve-4									30.80	2.14	32.66	1.66	32.18	1.78	29.88	3.40	30.03	1.89	31.11	1.26
Ve-8	30.05	3.17	31.27	1.77	31.89	1.41	33.65	3.97	31.96	2.19	33.42	2.27	33.41	1.87	30.91	3.21	30.52	2.27	31.90	1.43
Ve-6	31.75	2.35	31.97	1.42	32.70	1.56	34.17	2.32	31.92	2.74	33.94	1.18	33.59	1.27	32.05	2.69	32.30	1.65	32.71	1.01
1M	32.84	1.29	32.84	1.95	33.71	1.96	34.84	2.37	33.53	1.85	33.60	1.55	33.74	1.96	31.87	2.70	30.36	3.32	33.04	1.35
4C	31.64	3.46	32.74	1.52	33.43	2.08	34.86	1.72	33.51	1.79	34.65	0.89	34.68	0.99	32.57	2.30	32.25	2.03	33.37	1.25
Ve-3	32.75	1.75	33.24	1.21	34.08	1.92	35.59	1.97	33.75	1.66	34.42	2.16	34.65	1.19	33.86	1.15	31.90	2.13	33.80	1.16
Lagoon-wide averages and standard deviations																				
	20.18	3.93	29.12	3.41	29.32	4.15	31.94	3.17	29.56	3.59	31.15	3.17	30.99	3.35	28.51	4.29	28.57	3.95		

order of the stations is maintained while the actual salinities may vary by as much as 1–2 PSU, depending on the year.

Interestingly, for any station, the standard deviation of the 9-year average is only about half that of each individual yearly average, probably because the daily tidal fluctuations about the yearly means are symmetrical and tend to cancel each other out.

The bottom panel shows the yearly averages and standard deviations taken by pooling all 13 stations. (These latter averages are not true indicators of the salinities found in the lagoon because each station does not necessarily subtend an equal volume. Nevertheless, this lagoon-wide indicator gives a useful indication of the relative amounts of freshwater that has entered during the year (*vide infra*)).

Figure 2 shows the 2009, 30 min data from the nine semi-continuous SAMANET stations in grey and red. The red line is the 25 h running average of the recorded data shown in grey. Each profile represents from 1.5 × 10^4 to 1.75 × 10^4 data points. A cursory inspection of Figure 2 indicates that the plots of running averages (in red) at all stations show the same low salinity depressions marking distinct fluvial events in time,

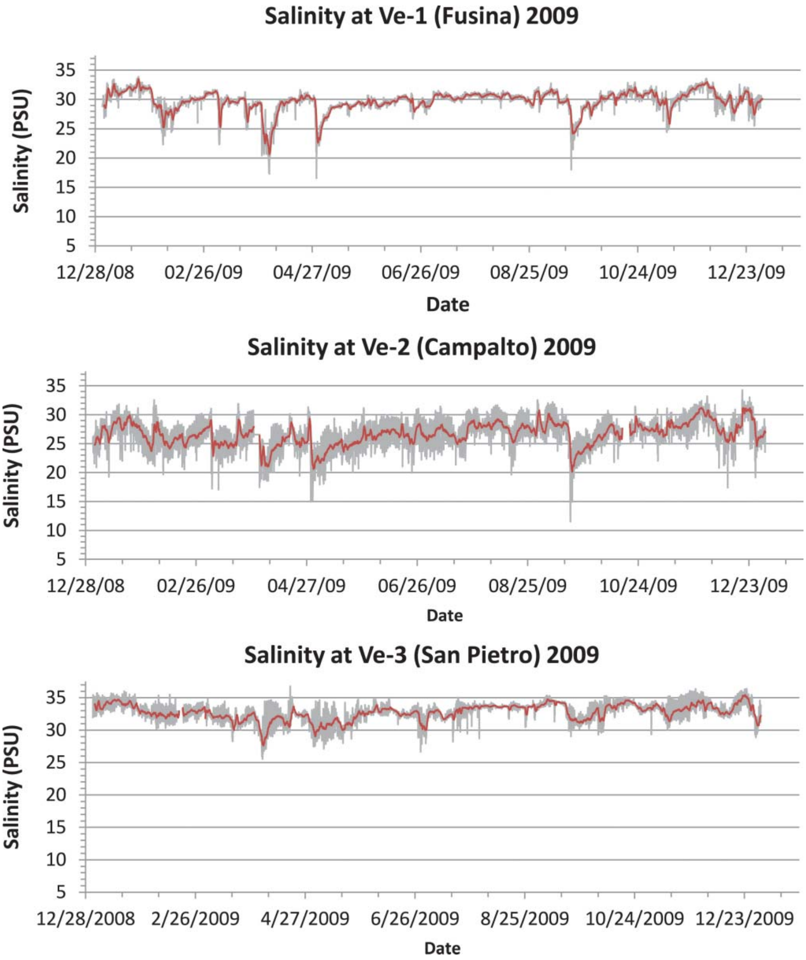

Figure 2. 2009 data from the 9 ‘continuous’ SAMANET stations. Grey: 30 min data; red, 25 h running average.

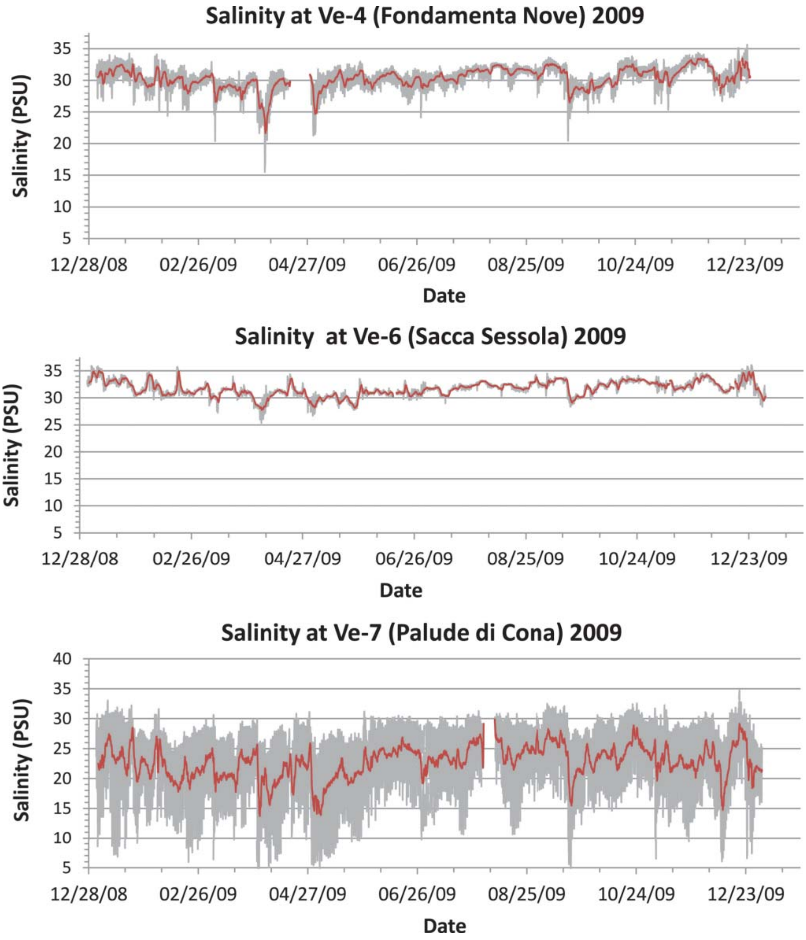

Figure 2. (Continued).

independently of the total salinity. Also, the lower a station's average salinity, the deeper the depression. The depressions in salinity vary from a few days to over a month. Overall, from the end of January to late May, salinity is lower than the yearly mean by about 2 PSU.

Table 3 summarizes and compares the 2009 averages and standard deviations of the MELa and SAMANET stations, before and after removal of the tidal component from the semi-continuous data. With the exception of Station Ve-7 (Dese), MELa and SAMANET stations are within 1 PSU of each other. The MELa average at Station Ve-7 (Dese) is more than 3 PSU less than the SAMANET average, due to the more limited sampling and the wide tidal 'swings'.

3.1 Freshwater flows

Figure 3A shows the 2009 average daily rainfall in m^3/s taken across all SAMANET meteorological stations, superimposed on the daily flow of the Canale Taglio di Mirano. Figure 3B plots salinity at the five outermost SAMANET stations in order in decreasing

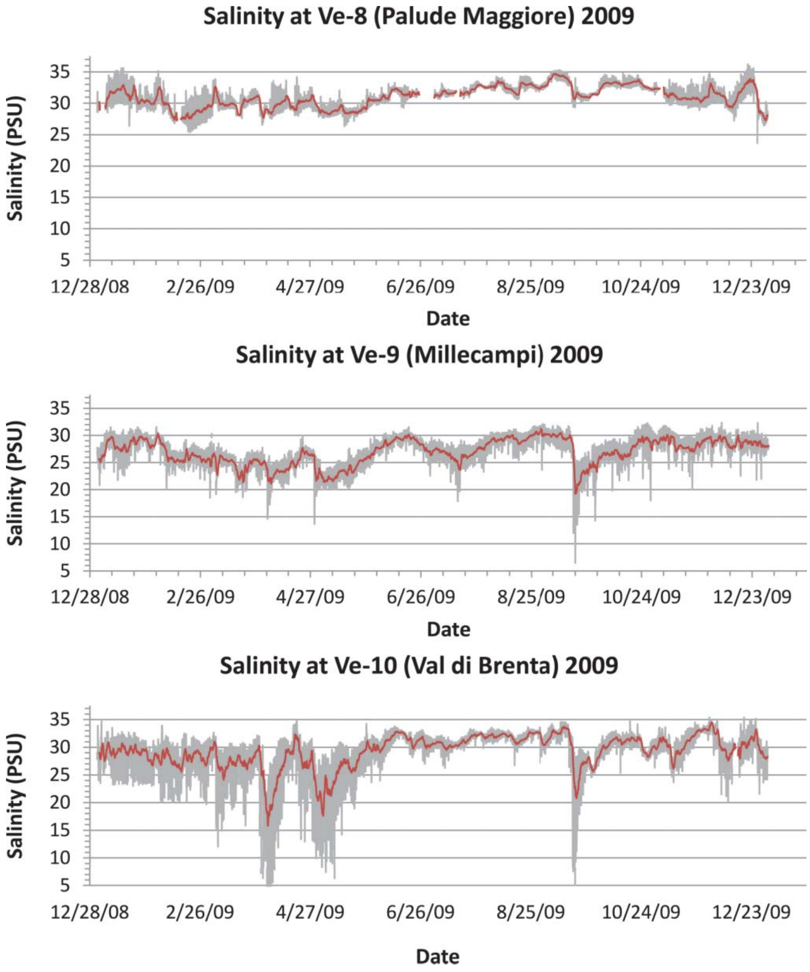

Figure 2. (Continued).

Table 3. 2009 salinity averages and standard deviations of MELa and SAMANET semi-continuous stations. All values are in PSU.

STATION	MELa Average	SAMANET Average	MELa Std. Dev.	SAMANET Std. Dev.	SAMANET Std. Dev. Minus Tide
Ve-7 (Dese)	19.50	22.77	5.18	5.25	2.63
Ve-9 (Millecampi)	25.75	26.99	2.71	2.69	2.34
Ve-2 (Campalto)	26.02	26.60	2.26	2.38	1.89
Ve-10 (Val di Brenta)	No data	29.32	No data	3.63	2.89
Ve-1 (Fusina)	30.46	29.72	0.90	1.84	1.84
Ve-4 (Fondamenta Nove)	30.03	30.34	1.89	1.88	1.55
Ve-8 (Palude Maggiore)	30.52	31.02	2.27	1.83	1.64
Ve-6 (Sacca Sessola)	32.30	31.71	1.65	1.42	1.35
Ve-3 (San Pietro)	31.90	32.75	2.13	1.41	1.19

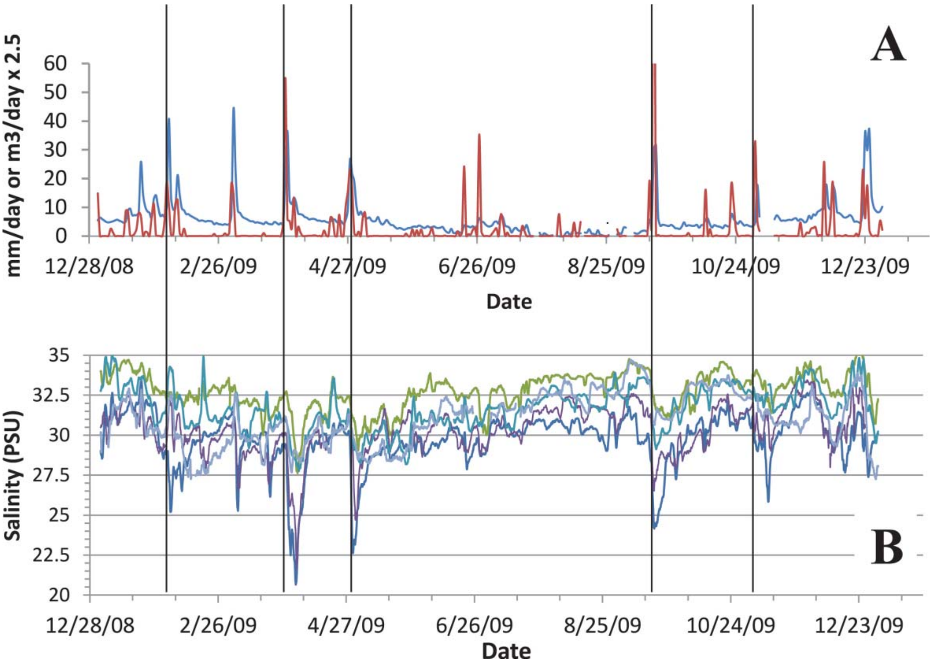

Figure 3. (A) Blue: Daily flow (x2.5) into the Venice Lagoon from the Canale Taglio di Mirano; Red: Average daily rainfall into the lagoon. (B) Figure 3B plots salinity at five outermost SAMANET stations in order in decreasing salinity (Ve-3, Ve-6, Ve-8, Ve-4, Ve-1) with tidal fluctuations removed by employing a 25 hr running average (for clarity, the shoreward, fresher, stations have not been plotted). Vertical lines show the temporal lag between peak rainfall over the lagoon and peak low salinity.

salinity (Ve-3, Ve-6, Ve-8, Ve-4, Ve-1) with tidal fluctuations removed by computing the 25 h running average (for clarity, the shoreward, fresher, stations have not been plotted).

4. Discussion

4.1 Average annual and seasonal salinities

When plotted against the yearly freshwater flows into the lagoon (data from Table 1), the yearly lagoon-wide averages yield a near mirror image of the flows (Figure 4) which suggests that river/channel flow is the dominating freshwater source in the lagoon. (A linear plot of average annual salinity (S) vs. average annual flow (Q) yields $S = -0.182\ Q + 34.45$ with $R^2 = 0.38$). This finding is supported by the available 2009 data: the calculated total freshwater inflow into the lagoon was $2.4 \times 10^6\ m^3/d$ (Table 1); the average rainfall over the lagoon was $1.45 \times 10^6\ m^3/d$ (SAMANET meteo data); the estimated evaporation was $1.3 \times 10^6\ m^3/d$ *op. cit*. Therefore, while rainfall and evaporation are a very significant portion of the freshwater budget, they are distributed over the entire lagoon and also tend to cancel each other out (except for unusually warm years), leaving the riverine input as the principal source of freshwater[3]. This leaves the rivers and canals at the northern edge as the point sources of freshwater into the lagoon. Figures 2 and 3 show these inputs

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[3] Measurements made in 2010 also showed that evaporation and rainfall were nearly equal to each other (G. Cecconi, unpubl.)

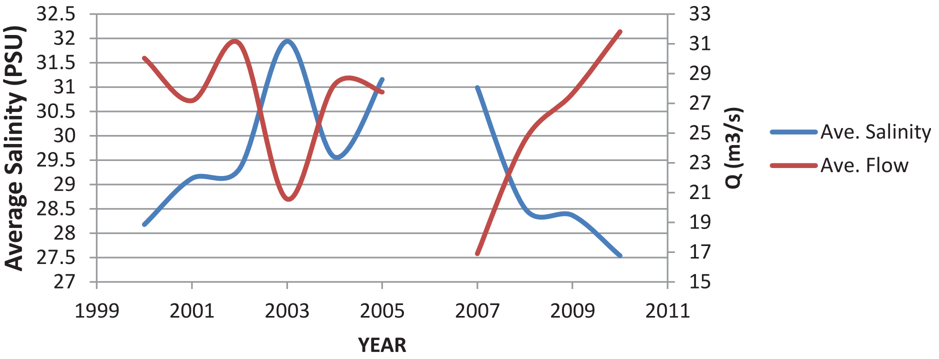

Figure 4. ‘Average’ yearly salinity and average yearly river inflow (2000–2010).

of freshwater as depressions of each station’s salinity with the magnitude of the salinity decrease being, in general, negatively related to its distance from the mainland. These depressions can be major, depending on a station’s proximity to a freshwater source. For example, Station Ve-10 (Val di Brenta) shows salinity depressions of about 15 PSU from March to June. During the same period, Stations Ve-9 (Millecampi), Ve-1 (Fusina) and Ve-2 (Campalto) show salinity depressions of about 10 PSU. At all of these stations a second, prominent freshwater injection, that lowered salinity by about 10 PSU, occurred during the month of September.

One important consideration needs to be mentioned, however. The values shown in Table 1 do not include submerged groundwater discharges (SGD). Estimates of the volume of underground freshwaters entering the lagoon floor vary widely, from 15% of total freshwater flow, measured directly in the northwest of the lagoon near Isola la Cura [17], an area influenced by the river Dese (Sta. Ve-7), to more than 100% across the entire lagoon measured with a technique based on the ratio of naturally occurring radium isotopes [18–20]. However, much of the SGD is recycled lagoon water, which may be the cause of the large variability in the total estimates. The MELa data presented in this work does not distinguish whether river water entering the lagoon comes at or below the surface.

4.2 Salinity structure

The salinity structure, e.g., the spatial distribution of salinity within the lagoon, is controlled by the extent that the input of freshwater mixes with the incoming seawater. The resulting salinity range lies between about 19–22 PSU (Sta. Ve-7) and about 34.5 PSU (Stations Ve-3 and 4C). Station Ve-7 is anomalously fresh and shows extreme tidal variability because it is very shallow [9]. Because the amount of entering freshwater is small in comparison with the entering seawater and in the absence of long periods of strong winds, tidal mixing determines the pattern. That this mixing pattern has been consistent in the Venice Lagoon is supported by the observation that, in general, the 13 stations maintain their salinity order throughout 2000 to 2009 (Table 2). Also, plots of the yearly averages of 12 of the 13 stations from 2000 to 2009 are consistent in their response to freshwater input showing very few intersections between stations (Figure 5). This is also supported by the stations’ seasonal averages, which also show little ‘cross-over’ (Figure 6).

Additionally, Tukey-Kramer’s HSD mean comparison of all pairs showed that 9 of the 13 MELa stations were significantly different from each other. The mean comparison

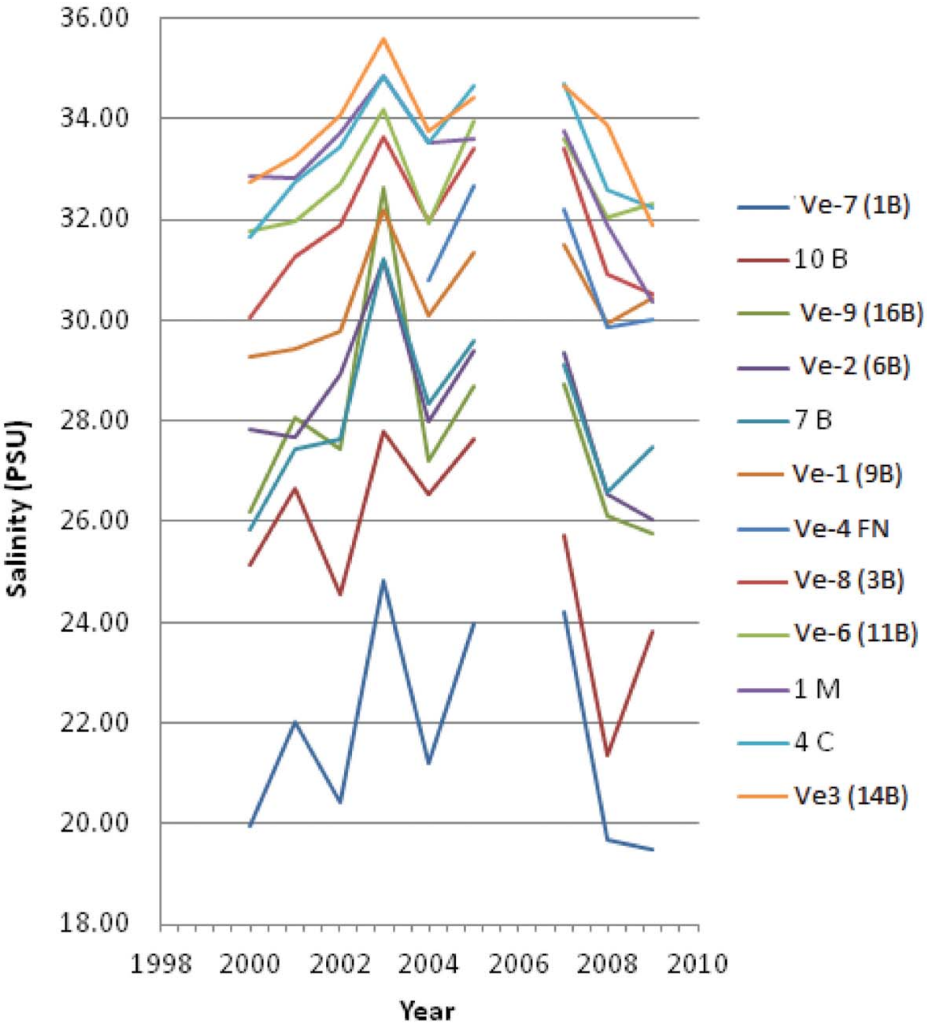

Figure 5. Nine-year (2000–2009) averages of the 13 MELa stations.

of all pairs was further analysed graphically using PCA. The principal components were determined by Euclidean distance on normalized data (mean divided by the standard deviation). PC 1 and 2 combined explain 97.6% of the variation. Figure 7 shows the resulting plot of the PCA scores, identifies similar stations, and groups the stations into approximately three zones. Finally, the 2009 yearly average salinities of the MELa stations were well correlated ($R^2 = 0.97$) to the corresponding SAMANET stations (Table 3) and seven of the nine station averages were statistically identical ($P > 0.05$), indicating that, on a yearly basis, the mixing process is the same for both sets of data.

A close visual examination of the salinity profiles of the SAMANET stations shown in Figure 2 indicates that, at each station, the average salinity is maintained throughout the year, irrespective of season and that in the main, salinity changes are caused by point injections of freshwater. The correspondence between freshwater inflow and lowered salinity in the lagoon is evident in Figures 3A–B, which also show that salinity is related more closely

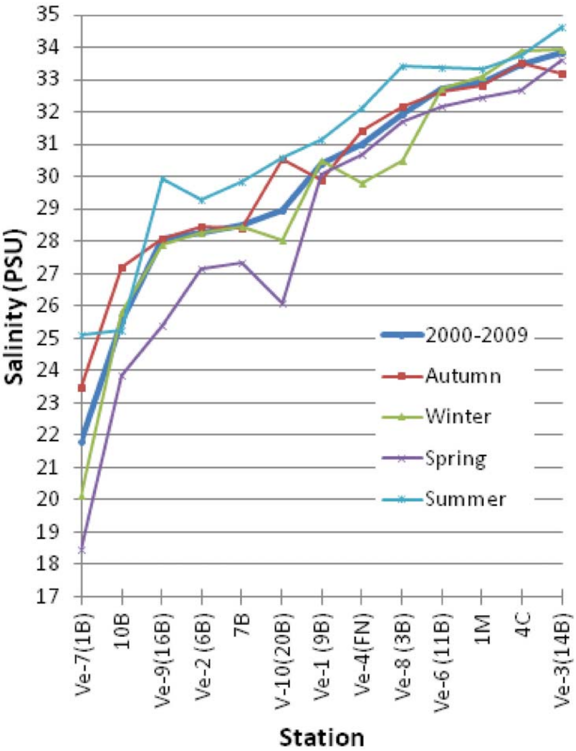

Figure 6. Nine-year (2000–2009) seasonal averages from MELa data. No data was collected in 2006.

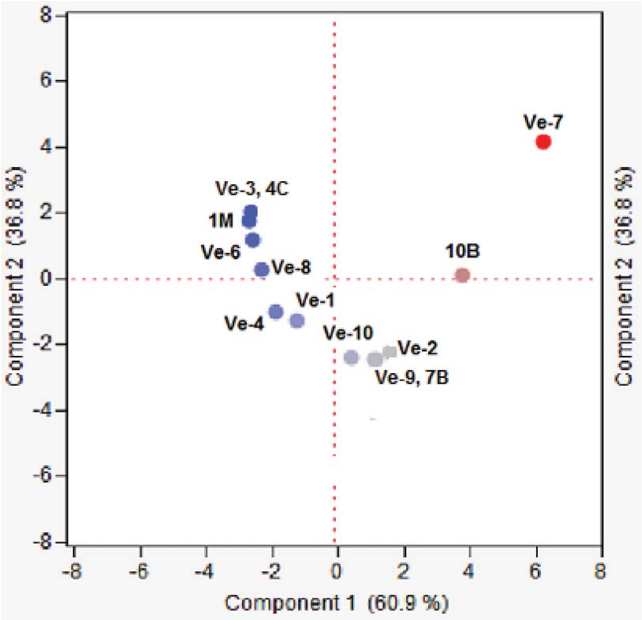

Figure 7. MELa 2009 data: Tukey's HSD mean comparison of all pairs shown graphically in the form of a Principal Component Analysis (PCA). The plot of the PCA scores groups the different salinity zones. Colours indicate progressively increasing salinity from red (lowest) to dark blue, (highest).

to the daily canal flow, as indicated by the Canale Taglio di Mirano, rather than the episodic rainfall events. Also detectable in Figures 3A–B is the several-days' lag from the rain peaks to the salinity troughs. This suggests that it is the collected flow entering the lagoon after a rainfall event in the catchment basin that is evident in the salinity profiles.

4.3 Variability of salinity

The 13 MELa stations can be divided into three distinct groups: those with a nine-year average salinity > 32 PSU (approximately), those with an average salinity of < 28 PSU (approximately) PSU and those with an average salinity between these two values. Percentage standard deviations at salinities < 30 PSU for each year tend to be large, ranging from 4.28 to 8.77 PSU (approx. 20 to 40%) at station Ve-7 (Dese) and from 2.24 to 8.22 PSU (approximately 20 to 30% at Ve-10 (Val di Brenta). On the other hand, stations with salinity at or above 30 PSU have much smaller standard deviations, ranging from 3 to 5%. When all of the 2000 to 2009 yearly averages for each station are combined, the standard deviations narrow, with the standard deviation at station Ve-7 being 2.17 PSU (10%), and 2.77 PSU (9.6%) at station Ve-10 (Val di Brenta) while the stations *with* > 30 PSU have relative standard deviations of 3–4% (Table 3). The large variability of the MELa yearly means occurs because *measured* salinities are not corrected for tidally driven movements. These can be seen in Figure 2 (in grey). Also, at each station, the magnitude of the semidiurnal salinity shift appears to vary independently, but is actually caused by the interaction of three factors: 1) presence of a salinity gradient around the station - large gradients occur near points of freshwater discharge and tend to vary if the discharge is intermittent; 2) tidal currents must move the water backwards and forwards past the station; and 3) the local bathymetry that may funnel flow and speed currents.

Figure 8 shows the result of the modelled, tidally-forced, landward/seaward shift of the salinity field and the compression and dilatations of the large salinity gradients that

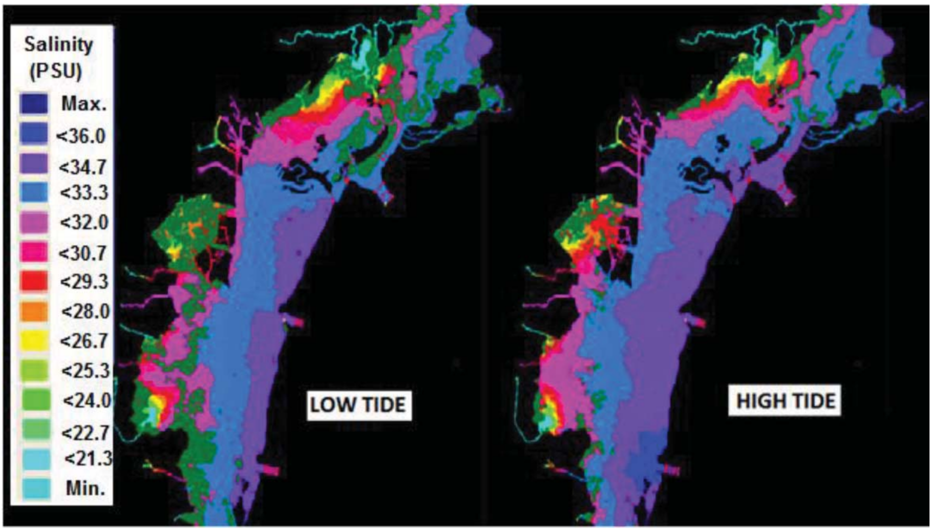

Figure 8. MODMEF-generated contour plots of salinity in Venice Lagoon during one tidal cycle, on 16 July 2004: average freshwater input, low wind, and slack water. Left: ebb, (-45 cm). Right: flood, (+40 cm), with reference to the gauge at Punta della Salute.

surround the near shore stations under low energy conditions, e.g., average freshwater input, low wind and slack water. While the volume of freshwater entering the lagoon is understood to be very small (< 2% of the total), the areal changes in salinity during a tidal cycle are major. Nevertheless, these tidal shifts do not change the salt content of the lagoon's water but affect the determination of salinity by increasing the variation in its measurement.

It is evident that correcting for the tides (Table 3) significantly lowers the standard deviation of most stations. A result of this is that the single monthly values measured in the MELa programme tend to be less representative of the average salinity. This suggests that salinity in the Venice Lagoon is more variable than it is and lessens appreciation for the spatio- temporal order that actually exists. Another consequence of the tidally-induced variability is that benthic organisms residing at the low salinity stations experience more variability than their planktonic counterparts. Similarly, because in the Venice Lagoon nutrients are closely but negatively coupled to salinity [21], stations of high salinity variability experience high semidiurnal nutrient variability as well. At present, it is unclear how this affects the benthic flora and fauna. Similarly, the low salinity (and, by implication, high nutrient) events that occur from March to May and September (Figure 2) and persist for days, weeks, and sometimes, months, may also impact organisms in the water column and on the lagoon floor. Finally, tidally-corrected standard deviations of the high salinity stations, in order of increasing salinity, tend to asymptotically converge to about 1–1.5 PSU. This is probably the extent of the variability in salinity caused by the yearly climatic (temperature) variations in the absence of freshwater flows. This observation is supported by Figure 6, which shows 2000–2009 summer salinities to be about 1 PSU higher than their corresponding average yearly salinities.

Low salinity areas (< 28 PSU) persist because the shallowness of the lagoon floor and the presence of sub-tidal flats restrict flushing by reducing the flow velocity towards the inshore boundary. Conversely, freshwater does not easily mix out of the areas where it is deposited, as indicated by residence times of 20 or so days [6]. On an annual basis, salinity in the lagoon, can be interpreted as being essentially affected by two separate and distinct processes: 1) environmental input, e.g., inflow, rain, and evaporation (the episodic strong winds are too brief to affect the yearly averages), and 2) astronomy, i.e., the tides that efficiently distribute freshwater in accordance with the geomorphology of the lagoon. Because the spatial pattern of salinity is maintained from year to year, the data indicates that the latter process dominates.

4.4 Steady-state

Salinity in the lagoon can be considered as being at steady-state as long as 1) the geomorphology remains unaltered and 2) environmental effects, primarily rainfall, are either too weak or too brief to alter the mixing pattern. Figure 4 provides a measure of the relationship between the freshwater flows and the salinity of the lagoon during the past decade, a relationship that has not altered the mixing patterns of the lagoon. This relationship may also be extended to the past half-century. Figure 9 shows a plot of the yearly annual rainfall in the Venice watershed from 1961 to 2009 as well as a plot of the cumulative average yearly rainfall and the 1961–2009 average of 896 ± 136 mm (1 σ). It can be seen, that after 1970, the cumulative average and the overall average are nearly identical, and that despite its vigorous (short-term) dynamics, both climatological and tidally-forced, the Venice Lagoon appears to be at steady-state. This condition is conducive to the development of separate ecosystems that have different salinity tolerances. This work and the

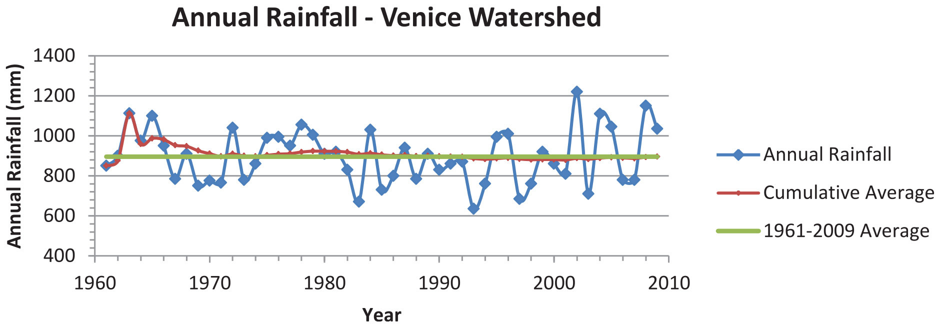

Figure 9. Annual rainfall, cumulative average rainfall, and 1961–2009 average rainfall over the Venice Lagoon watershed (After ARPAV: Bacino scolante nella Laguna di Venezia - Rapporto sullo stato ambientale dei corpi idrici, anni 2008–2009).

work of others [22,23] have identified three ‘permanent’ zones of different salinities and recently Tagliapietra and Sigovini [24] have confirmed the presence of three different and corresponding ecosystems associated with three salinity regions of the lagoon.

On smaller scales, many more distinct ecosystems are possible: the spatial and temporal variability that occurs in coastal lagoons is well known [25]. The modelling efforts of Ghezzo *et al*. [6] indicate that, potentially, the Venice Lagoon can be subdivided into 9 to 14 unique environments (and by implication, ecosystems) based solely on physical data and Solidoro *et al*. [4] were able to subdivide the lagoon into seven groups, based on the similarity of the temporal evolution of nutrients and chlorophyll-a. However, ecosystems are defined by the organisms that populate them and it remains to be seen if the postulated larger number of distinct environments in the Venice Lagoon can be supported by equally distinct differences in floral and faunal data.

Finally, it is unclear how much more monitoring is needed to achieve a finer spatial resolution, beyond the present three tiers. Further studies with mathematical models may help resolve this issue. The combining of (MELa-type) point data with the semi-continuous SAMANET data and the results of hydrodynamic/dispersive models could improve our understanding of the processes that affect the lagoon (and similar environments) considerably.

5. Conclusions

This study of nine years of Venice Lagoon salinity data shows that incoming river-borne freshwater is distributed by tidal action throughout the lagoon with spatial consistency. The lagoon may be divided along its long axis into three areas: 1) a northern, freshwater-impacted area of high, tidally-caused, variability, where $S < 28$ PSU, 2) a southern, marine zone of low tidally-caused variability, where $S > 32$ PSU, and 3) an intermediate zone where S is between 28 and 32 PSU. At the northern and intermediate stations, freshwater injections during spring and autumn may result in major (10–20 PSU) lowerings of salinity. These events occur on time scales of days to a month and may affect local flora and fauna. At some freshwater impacted stations, tidal action itself produces a semidiurnal variability as large as ± 10 PSU. This tidally-caused variability also introduces a large, local, but only apparent, salinity variance when sampling is done monthly.

At present, the distribution of freshwater is overwhelmingly controlled by the astronomical tides and the geomorphology of the basin, independently of the freshwater input.

In a global-warming scenario, this could change. Similarly, MOSE-related morphological alterations to the Venice Lagoon such as the newly-built island at the Lido entrance and the new breakwaters at all the entrances could alter the 2000–2009 salinity pattern [8].

Finally, watershed data from 1961 to 2009 suggests that the lagoon can be considered to be at steady-state: namely, small perturbations in salinity (in response to equally minor changes in the freshwater input) occur, but that, over long periods, salinity returns to its long-term average and maintains its distinct spatial distribution. This is good news for ecologists and water quality managers who need to compare areas of similar characteristics but in different basins.

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