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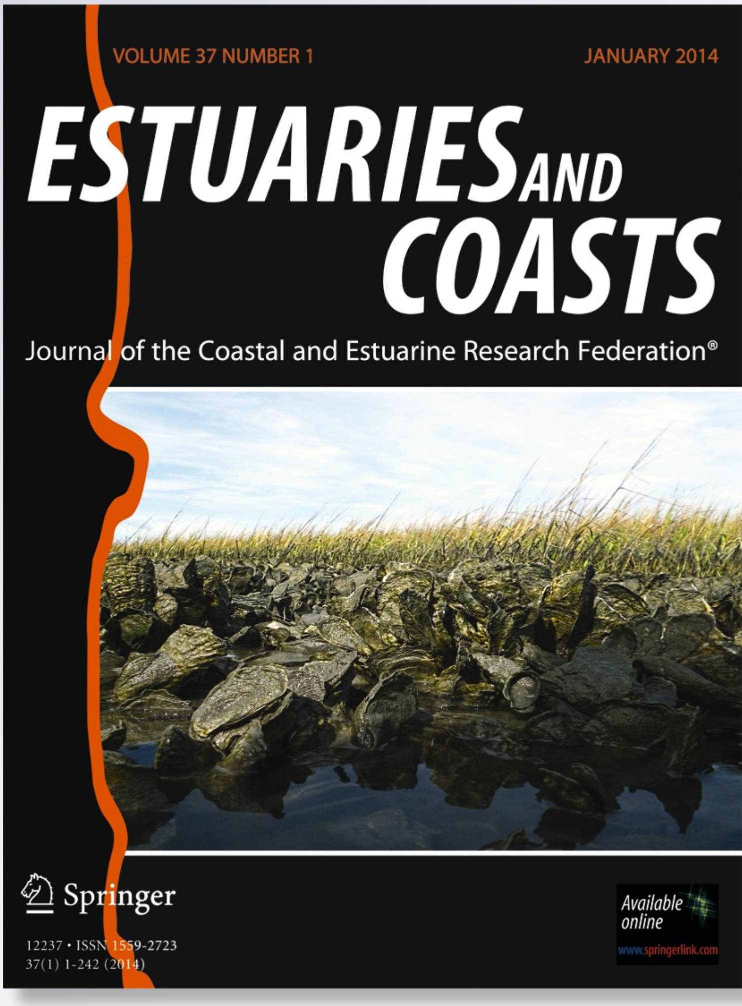

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Hydrological Regime and Renewal Capacity of the Micro-tidal Lesina Lagoon, Italy

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Abstract A multidisciplinary approach that combines field measurements, artificial neural networks, water balance analyses and hydrodynamic modelling was developed to investigate the water budget and renewal capacity of semi-closed coastal systems. The method was applied to the Lesina Lagoon, a micro-tidal lagoon in the southern Adriatic Sea (Italy). Surface water flux between the lagoon and the sea was determined by neural network prediction and used as input in the analysis. Strong seasonal variations in the water budget equation were predicted. Fresh water inputs estimated by the water balance analysis were used as forcing by a calibrated finite element model to describe the water circulation and transport time scale of the lagoon's surface waters. The model highlighted the spatial heterogeneity of the renewal behaviour of the system, with a strong east–west water renewal time gradient. Knowledge of spatial distribution of water renewal times is crucial for understanding the lagoon's renewal capacity and explaining the high spatial variability of the biogeochemistry of the Lesina Lagoon.

Keywords Hydrological regime · Neural network · Water budget · Finite element model · Water renewal time · Lesina Lagoon

Mathematics Subject Classification (2010) MSC 86A05 · MSC 92D40

Introduction

Lagoons are highly productive areas located at the transition between land and sea (Nixon 1988; Kjerfve and Magill 1989). Lagoons were initially exploited by

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humans as strategic sites for fisheries. Later, they became important as protected sites for harbours and settlements. These natural advantages led to the development of lagoon-based industrial, commercial, and recreational activities (Duck and da Silva 2012). Lagoons are subject to rapid morphological evolution in response to sea-level rise, inputs of sediments from continental and marine sources, and the rapidly changing morphology of their associated barrier islands (Viaroli et al. 2007; Tagliapietra et al. 2009). In order to maintain the functionality of these important ecosystems, understanding the processes occurring in these water bodies is of paramount interest (Gonenc and Wolflin 2005; Basset et al. 2006).

Hydrodynamic characteristics determine most of the physical and biogeochemical processes affecting coastal and lagoon environments (Pérez-Ruzafa et al. 2005; Viaroli et al. 2007; Barbone and Basset 2010). These processes can therefore be drastically altered by inter-seasonal and inter-annual variations in hydraulic forcing (Kjerfve and Magill 1989; Gong et al. 2008). Indeed, lagoons and estuaries are characterised by a dynamic equilibrium between the input of fresh water from land and the penetration of salt water (Rapaglia et al. 2012). Surface and sub-surface water flows are transport pathways for nutrients and pollutants and this may be critically important to coastal zone processes (Swarzenski et al. 2006; Moore 2010). The sub-surface flow of water, commonly known as submarine groundwater discharge, is a significant component in the water balance of many coastal systems (Rapaglia et al. 2010; Beck et al. 2007; Burnett et al. 2006).

Investigating the hydrological regime of a lagoon environment requires a large amount of information, which in most cases cannot be collected easily. Several approaches have been used to explore various aspects of a lagoon's hydrology; many of them based on water and salt budget analyses (Kjerfve et al. 1996; Jakimavižius and Kovalenkoviene 2010; Michot et al. 2011), or numerical modelling (Li-Rong et al. 2011; Jia and Li 2012).

The aim of this study is to investigate the hydrological regime and renewal capacity of Lesina Lagoon using a multidisciplinary approach that combines field measurements, artificial neural networks, water balance analyses and hydrodynamic modelling. The approach accounts for fresh water inputs and water exchange between the lagoon and the sea. The renewal capacity of the lagoon was estimated by the computation of the water renewal time.

Study Site

The Lagoon of Lesina (Fig. 1), located on the north side of the Gargano promontory, in the southern Adriatic Sea (Italy), is semi-closed and influenced by both fresh and saline waters. It is an important habitat for numerous plant and animal species, and is an economic resource in terms of fisheries and tourism (Roselli et al. 2009).

The lagoon is a very shallow water body with a flat sea bed. According to recent bathymetric surveys (Brambati 2002), the average water depth is 0.9 m and the maximum water depth is 1.6 m. It has a surface area of about 50 km^2, stretches in an east–west direction nearly 22 km and is 2.2 km wide (Breber et al. 2008). Reed beds characterise the easternmost part of the lagoon, where the sediment is mostly sand and silt, while the central and western sectors are characterised by silty sediments.

The lagoon is separated from the open sea by a 300–2,000-m-wide barrier island (*tombolo*), which hosts an almost pristine dune system. Surface water exchanges with the sea are provided by two small artificial channels having a mean depth of about 1.4 m. The western channel

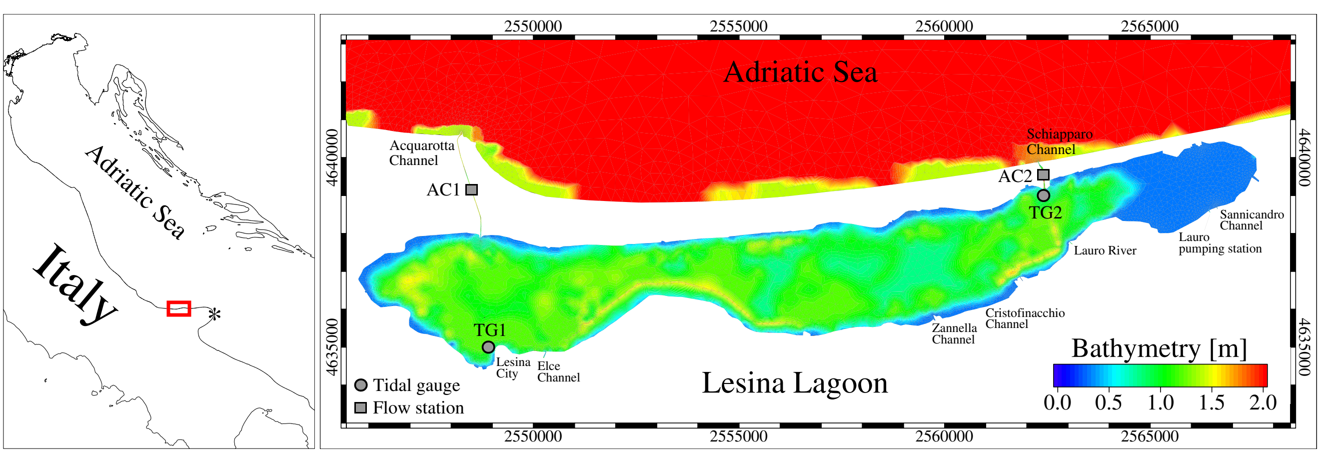

Fig. 1 Bathymetry of Lesina Lagoon and adjacent shore interpolated on the finite element numerical grid (superimposed). Depth values are referred to the elevation datum of the Italian gauge network. *Circles* mark locations of tide gauges (TG1 and TG2). *Squares* indicate locations of flux stations (AC1 and AC2). Outflow points of major tributaries are also shown. The *asterisk* on the *left panel* indicates the location of Vieste measuring station

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(Acquarotta) is 2 km long and has a width of about 10 m. The eastern channel (Schiapparo) is less than 1 km long and about 15 m wide. Currently, the flow in both channels is limited at the lagoon end by sluices and partially obstructed grilles, which were once used for fishing purposes (Roselli et al. 2009).

Small tributaries flow into the lagoon, mostly in the eastern sector (Fig. 1), draining the majority of the surface and sub-surface water coming from the adjacent karstic promontory (Cotecchia and Magri 1966) (the Zanella, Cristofinacchio and Sannicandro channels and the river Lauro). This flow of fresh water is appreciable even during the dry season (Polemio et al. 2000). Partially treated waste water from the lagoon's catchment area, which has almost 30,000 inhabitants, is discharged into the lagoon through the Elce channel, the river Lauro and the Lauro pumping station (Roselli et al. 2009). The surface fresh water discharge from all the above-mentioned watercourses was estimated by (Francavilla 2007) to be 3.3 $m^3\ s^{-1}$. According to (Rapaglia et al. 2012), inputs from diffuse underground discharge along the western margin of the lagoon seem also to be significant.

Due to the limited tidally-driven exchanges between the lagoon and sea, the salinity of the lagoon water is strongly influenced by fresh water input, evaporation and precipitation. It ranges from 30–35 in summer (with peak values of nearly 50 in particularly dry seasons) to 5–15 in winter (Roselli et al. 2009; Rapaglia et al. 2012). According to the cited authors, an east–west salinity gradient is commonly found, with lower salinities at the eastern end of the lagoon, into which the small tributaries flow.

Materials and Methods

The methodology comprises a combination of field measurements, neural network predictions, water budget analyses and numerical modelling. A schematic representation of this fourfold approach and its associated connections is shown in Fig. 2. Surface water flows between lagoon and sea were determined by neural network prediction and used as input in the lagoon water budget. Fresh water inputs estimated by water budget analysis were used as a forcing factor by the model to describe the transport time scales of the lagoon's surface waters.

Field Measurements

A monitoring programme was performed from May 2010 to August 2011. As shown in Fig. 2, the available data set was used to build the neural networks, to assess the water budget of the lagoon and to implement the hydrodynamic model.

Water level and water temperature were measured hourly at stations TG1 and TG2 (circles in Fig. 1) with the use of Sea-Bird Electronic SBE-39 pressure and temperature recorders. Open sea level and sea surface temperature were measured hourly in Vieste (located at about 50 km from the eastern end of the lagoon) by the Italian Institute for Environmental Protection and Research (ISPRA). Water level data acquired in the lagoon refer to the elevation datum of the Italian gauge network. In order to investigate tidal propagation in the lagoon, harmonic analyses were performed on the water levels recorded at the TG1 and Vieste stations. The water level time series were analysed with the TAPPY tidal harmonic analysis package (Cera 2011).

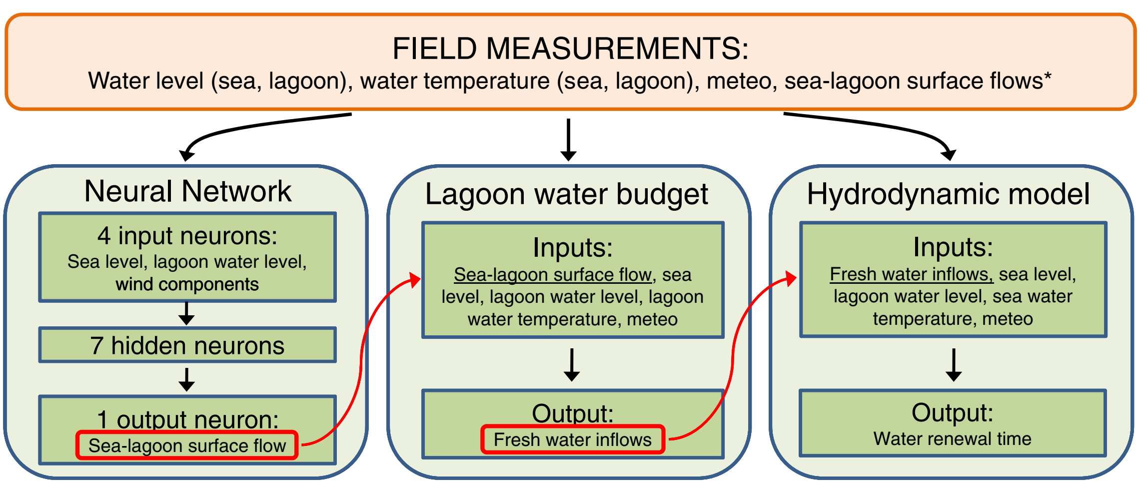

Fig. 2 Schematic representation of the multidisciplinary methodology adopted to investigate the hydrological regime and renewal capacity of Lesina Lagoon. The term "*meteo*" comprises all variables measured at the meteorological station close to the city of Lesina (wind speed and direction, precipitation, relative humidity, air pressure, air temperature, solar radiation and cloud cover). *Surface sea–lagoon flux data acquired at station AC1 and AC2 were used to calibrate the neural network prediction

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Flow data for the Acquarotta (station AC1) and Schiapparo (station AC2) seaward channels (squares in Fig. 1) are available for about 20 days in various periods of the year (five periods: S1–S5). About 470 flow measurements were performed at stations AC1 and AC2 with the use of a 1,200-kHz RDI Workhorse Rio Grande acoustic Doppler current profiler (ADCP). The instrument was mounted on a remote-controlled trimaran, which carried out measurements along transects across the channel. Each flow datum was taken as the average of four consecutive ADCP transects. Details of the flow surveys are given in Table 1.

Wind speed and direction, precipitation, relative humidity, atmospheric pressure, air temperature, solar radiation and cloud cover were obtained from a meteorological station located near the city of Lesina (about 7 km from the lagoon).

Water Fluxes Through the Seaward Channels—Neural Network Prediction

It is reasonable to assume that the water flow through the seaward channels (Q_{ss}) is mainly determined by the water level gradient between the lagoon and the open sea. However, a simple linear regression between Q_{ss} and hydraulic gradient would not fully account for tidal asymmetry, due to different bottom friction effects during the ebb and flood tides. Moreover, as the water levels are not measured at the ends of the tidal channels, the flow equation in the channel can not be solved with the available data set. In order to obtain a long-term hourly time series of surface water fluxes from the available observations and to overcome the above-mentioned limitations, two artificial neural networks (one for Schiapparo and one for Acquarotta) were assembled.

The artificial neural network (ANN) library used in this study is based on the Fast Artificial Neural Network (FANN) library developed by (Nissen 2003). FANN is a multilayer artificial neural network, which uses a back-propagation training algorithm (RPROP), and a symmetric sigmoid activation function (Nissen 2003). Each of the two ANNs receives, as input, water level time series in the lagoon and the open sea, and the zonal and meridian components of the wind. Each of these input variables represents one input neuron. The neural network is then formed by one input layer, with four input neurons, one hidden layer, and one output layer, with one neuron, which gives the water flux through the inlet.

Available data acquired at stations AC1 and AC2 were split into two sub-samples: one is used in the training phase (surveys S1 and S2), and the other in the testing phase, used to assess the performances of the ANNs (surveys S3, S4 and S5). During the training phase, a minimisation procedure changes the weights of the connections between the neurons and finds the best configuration in terms of number of neurons in the hidden layer. Several tests were carried out to calibrate the ANNs and find the optimal number of neurons in the hidden layer.

Fresh Water Inputs—Water Budget Estimation

Comprehensive water mass balance analysis was used to assess the magnitude of fresh water inputs to the lagoon. The water budget was determined by the following equation:

$$Q_{ss} + Q_{sg} + (P - E) \times A + R + GW = \Delta V/\Delta t \qquad (1)$$

where Q_{ss} and Q_{sg} are respectively the surface and groundwater water exchange between the lagoon and the sea (in cubic metres per day), P is the precipitation rate (in metres per day), E is the evaporation rate (in metres per day), A is the surface area of the lagoon (in square metres), R is the total surface fresh water input (in cubic metres per day) and GW is the total groundwater fresh water input (in cubic metres per day). The balance between inputs and losses must equal the rate of change in volume ($\Delta V/\Delta t$) of the basin, with V as the volume of the lagoon (in metres) and Δt the time interval considered (day).

The net daily surface fluxes through the seaward channels (Q_{ss}) were calculated by averaging the hourly values obtained by the neural network prediction over a 1 day period (see section "Water Fluxes Through the Seaward Channels—Neural Network Prediction").

Table 1 Measuring surveys and number of flux measurements performed in Acquarotta and Schiapparo channels

Survey	Period	Number of flux measurements	
		Acquarotta	Schiapparo
S1	29/06 - 02/07/2010	39	92
S2	20-25/08/2010	83	80
S3	8-9/02/2011	–	25
S4	12-14/06/2011	–	85
S5	23-24/08/2011	57	12
Total		179	294

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Since the lagoon is separated from the Adriatic Sea by a sandy barrier, it is reasonable to assume the existence of a groundwater flux through the permeable barrier (Santos et al. 2008; Rapaglia et al. 2010; Schmidt et al. 2011). The daily groundwater flux through the sandy barrier (Q_{sg}) was calculated by applying Darcy's law:

$$Q_{sg} = A_b K \frac{\Delta h}{L} \tag{2}$$

where A_b is the cross-sectional area of the aquifer (in square metres), K is the hydraulic conductivity (in metres per day), $\Delta h = h_{lag} - h_{sea}$ is the hydraulic head difference between the lagoon and the sea (in metres) with h_{lag} and h_{sea} as the mean daily water levels in the lagoon and the sea respectively, and L as the average width of the sandy barrier (800 m). The mean daily water level of the lagoon was calculated as the average of the levels at stations TG1 and TG2. The cross-sectional area A_b was calculated from the length of the sandy barrier (20,000 m) times its approximate depth (5 m) (Ricci Lucchi et al. 2006). The hydraulic conductivity (K) of the sandy barrier was set to 1 mday^{-1}, which is a typical value for marine poorly sorted sandy sediments (Prof. Spilotro G., personal communication).

Daily rainfall over the surface of the lagoon was calculated using data from the meteorological station at Lesina. The daily evaporation rate from the lagoon was determined by the bulk aerodynamic transfer method (Ham 1999) using measurements of air temperature, relative humidity, wind speed and air pressure at the meteorological station and water temperature at site TG1. The rate of change in volume was calculated using the daily mean water level of the lagoon (h_{lag}) and assuming the surface area of the lagoon (A) is 5×10^7 m^2 which is assumed not to change significantly over time.

The sum of surface (R) and sub-surface (GW) fresh water inflows represents the water budget closure term in equation 1. In order to quantify the temporal variation of this term, the water budget of Lesina Lagoon was estimated on a daily basis for the whole period of investigation (May 2010 to August 2011).

The accuracy of the calculation of the daily water balance depends on the accuracy of calculation of each member of equation 1. The error of the water budget closure term is therefore calculated as the sum of the absolute errors of the water balance components.

Hydrodynamic Model Description

A framework of numerical models (SHYFEM, www.ismar.cnr.it/shyfem) was applied to the surface domain of Lesina Lagoon and its adjacent shore. The hydrodynamic model uses finite element spatial discretisation to resolve the vertically integrated shallow water equations (Umgiesser and Bergamasco 1995; Umgiesser et al. 2004). Because of the shallow depth of the domain, the wind effect leads to a mixing of the water column and we therefore selected a 2-D model approach. The computational grid consists of almost 12,000 triangular elements with a resolution that varies from a few kilometres in the open sea to 350 m in the lagoon's shallow flats and a few metres in the seaward channels (Fig. 1).

The model is especially well suited to very shallow areas and has been successfully applied to several shallow water coastal systems (Umgiesser et al. 2004; Ferrarin and Umgiesser 2005; Ferrarin et al. 2008, 2010; De Pascalis et al. 2011). The finite element modelling system consists of a hydrodynamic model, a transport and diffusion model, and a radiational transfer model for heat exchange between the atmosphere and the sea water.

The model uses a semi-implicit algorithm for integration over time, which has the advantage of being unconditionally stable with respect to gravity waves, bottom friction and Coriolis terms, and allows transport variables to be solved explicitly (Umgiesser et al. 2004). The terms treated semi-implicitly are the Coriolis term and pressure gradient in the momentum equation, and the divergence terms in the continuity equation. Bottom friction, computed following the Strickler formulation, is treated fully implicitly for stability reasons due to the shallow nature of the lagoon, while the remaining terms (advective and horizontal diffusion terms in the momentum equation) are treated explicitly (Umgiesser et al. 2004; Umgiesser and Bergamasco 1995). The maximum allowable time step in the simulation was set to 100 s, and the model adopts automatic sub-stepping over time to enforce numerical stability with respect to advection and diffusion.

The water transport time scale has been used as a fundamental parameter for understanding chemical and ecological dynamics in lagoon environments (Rodhe 1992; Gong et al. 2008). There are several studies describing and comparing different transport time scales (Takeoka 1984; Monsen et al. 2002; Jouon et al. 2006; Liu et al. 2008; de Brye et al. 2012). In this study, the local water renewal time (WRT) was computed by simulating the transport and diffusion of a Eulerian conservative tracer released uniformly throughout the entire lagoon with a concentration corresponding to 1, while a concentration of zero was imposed on the seaward and fresh water boundaries. The local WRT is considered as the time required in each water parcel for the tracer concentration to fall to 0. To compute it, we refer to the mathematical expression given by (Takeoka 1984) known as the remnant function. The water renewal

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time could then be computed for each point of the domain as (Cucco and Umgiesser 2006):

$$W\tilde{R}T(x, y) = \int_{t=0}^{\infty} r(t, x, y)dt \tag{3}$$

where $r(t, x, y) = C(t, x, y)/C(0, x, y)$ is the local remnant function, with $C(t, x, y)$ the local concentration of a conservative tracer at time t (s) and $C(0, x, y)$ its initial value. The integral in the above equation is numerically approximated in accordance with the simulation time step. To account for the residual tracer mass at the end of the simulation, local water renewal time values are subsequently corrected, assuming exponential decay of the tracer, as:

$$WRT(x, y) = \frac{W\tilde{R}T(x, y)}{1 - r(T, x, y)} \tag{4}$$

where $r(T, x, y)$ is the local remnant function at the end of the simulation ($t = T$).

Such a transport time scale can be associated with the renewal time concept and is an adequate indicator related to environmental health of the aquatic system (Abdelrhman 2005; Plus et al. 2009; Ouillon et al. 2010; Hartnett et al. 2012).

The model solves the advection and diffusion equation to compute the dispersal and fate of the conservative tracer using a first-order explicit scheme based on the total variational diminishing method (Cucco et al. 2009). The horizontal turbulent diffusivity was calculated using the model proposed by (Smagorinsky 1963), with a Smagorinsky parameter of 0.3. The volume-weighted average of local renewal times equals the overall water renewal time of the basin computed as the time integral of the total concentration over the model domain, divided by the initial amount of material in the water body.

The principal forcings of the lagoon are sea level, wind, fresh water input, rain and heat flux through the water surface. All simulations were forced by observed wind, solar radiation, precipitation, cloud cover, air temperature and relative humidity. At the seaward open boundary, water levels measured hourly at Vieste were prescribed. In this way, the velocities and fluxes are free to adjust. Major tributaries were treated as inflow boundaries, assuming that they drained all the surface and sub-surface fresh water coming from their catchment basins. The discrete inflow of each individual tributary was computed using the daily fresh water fluxes estimated by neural network prediction and the distribution coefficients given in (Francavilla 2007). At the closed land–water boundaries, the normal velocity was set to zero and the tangential velocity was considered a free parameter.

Results and Discussion

Water Level Variation in the Lesina Lagoon

Figure 3 shows the daily lagoon water level (as average of data acquired at stations TG1 and TG2) and in the open sea (Vieste) for the study period. Daily precipitation data, shown in the bottom panel of Fig. 3, highlight the presence of a wet season from September to March and a relatively dry season from May to August. The water level in the lagoon was generally higher than sea level during the wet season. Fig. 3 shows that during heavy precipitation events, fresh water coming from the drainage basin raises the water level of the lagoon by up to 20 cm. The time-lag for this to occur is on the order of a few days, but could not be estimated exactly because rainfall from the meteorological station may not precisely reflect rainfall over the catchment area. Due to the small cross-sectional area of the seaward channels and the presence of grilles at the lagoon end of the channels, the water level takes several days to return to its initial stage. The water level in the lagoon is also occasionally influenced by the sea (during storm surge events) with a delay of about 4 days (correlation coefficient of the daily value equal to 0.6).

The results of the tidal spectral analysis shown in Fig. 4 clearly indicate that short-period tidal waves (diurnal (D) and semi-diurnal (SD) constituents) are damped out in the lagoon due to the small cross-sectional area of the connecting channels and the presence of grilles at the lagoon end of the channels. The tide in the open sea in front of the lagoon has a typical daily oscillation of about 30 cm, while tidal oscillation in the lagoon is significantly lower (about 2 cm). The long-period tidal oscillations (frequency $<$0.01 cph) propagate into the lagoon where they constitute the dominant tidal fluctuation (Fig. 4).

Meteorological records show that the predominant winds in this region are from the north-east and south-west. Figure 5 shows the hourly water level variation observed inside the lagoon at stations TG1 and TG2 and the wind speed. The water level time series show that the lagoon responds to the wind by oscillating along its main axis. Fluctuations on the order of a few centimeters are probably associated with sea breezes. The east–west water level difference can be up to 50 cm during intense storm events (Fig. 5). However, due to the very shallow depth of the basin, when the wind stops blowing these oscillations are rapidly damped by bottom friction.

Surface Fluxes Through the Seaward Channels

Instantaneous surface flux measurements show average ebb discharges of 1.8 and 4.4 $m^3\ s^{-1}$ and average flood discharges of 1.3 and 3.7 $m^3\ s^{-1}$ in the Acquarotta and

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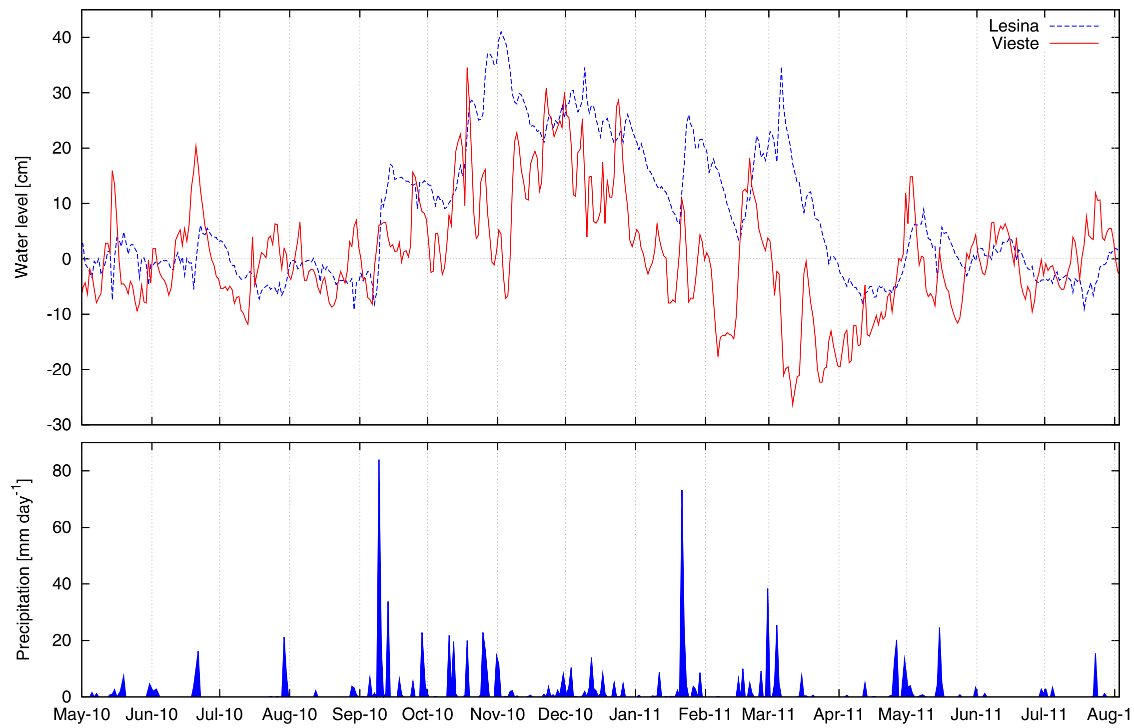

Fig. 3 Seasonal variation of daily water level in Lesina Lagoon (*blue dashed line*) and open sea, Vieste (*red continuous line*). Precipitation measured close to Lesina Lagoon is shown in *bottom panel*

Schiapparo channels, respectively. The maximum measured ebb discharges were 3.2 $m^3\ s^{-1}$ in the Acquarotta channel and 11.8 $m^3\ s^{-1}$ in the Schiapparo channel. The average error in the flux measurements was estimated from replicates to be 0.8 $m^3\ s^{-1}$.

The long-term variability of surface water fluxes between the sea and the lagoon was reproduced using the neural network approach described in section "Water Fluxes Through the Seaward Channels–Neural Network Prediction." The final ANNs use one hidden layer with seven neurons.

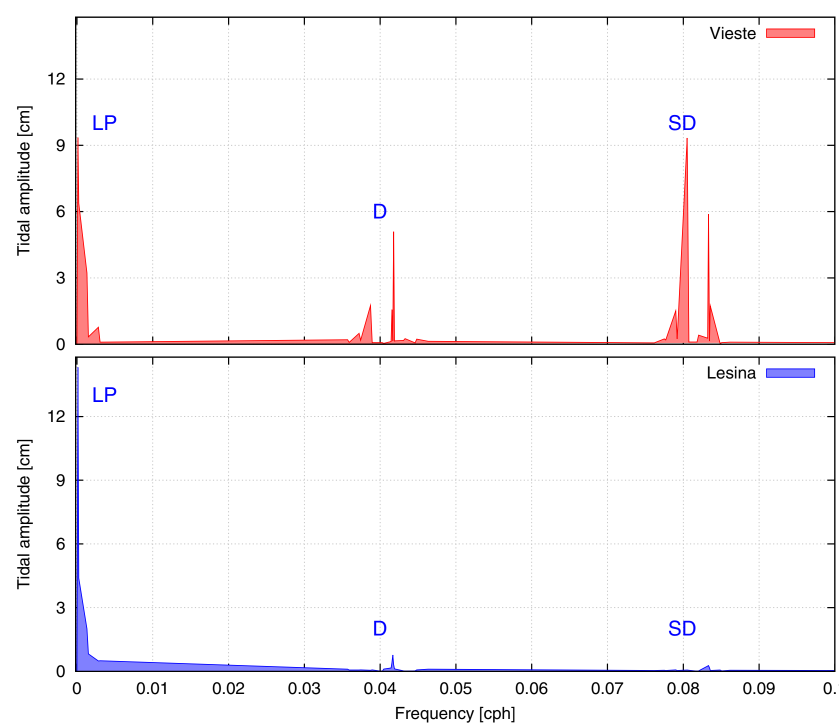

Fig. 4 Tidal spectral analysis of water level time series at Vieste (*top*) and Lesina (*bottom*). *LP* = long period, *D* = diurnal, *SD* = semi-diurnal

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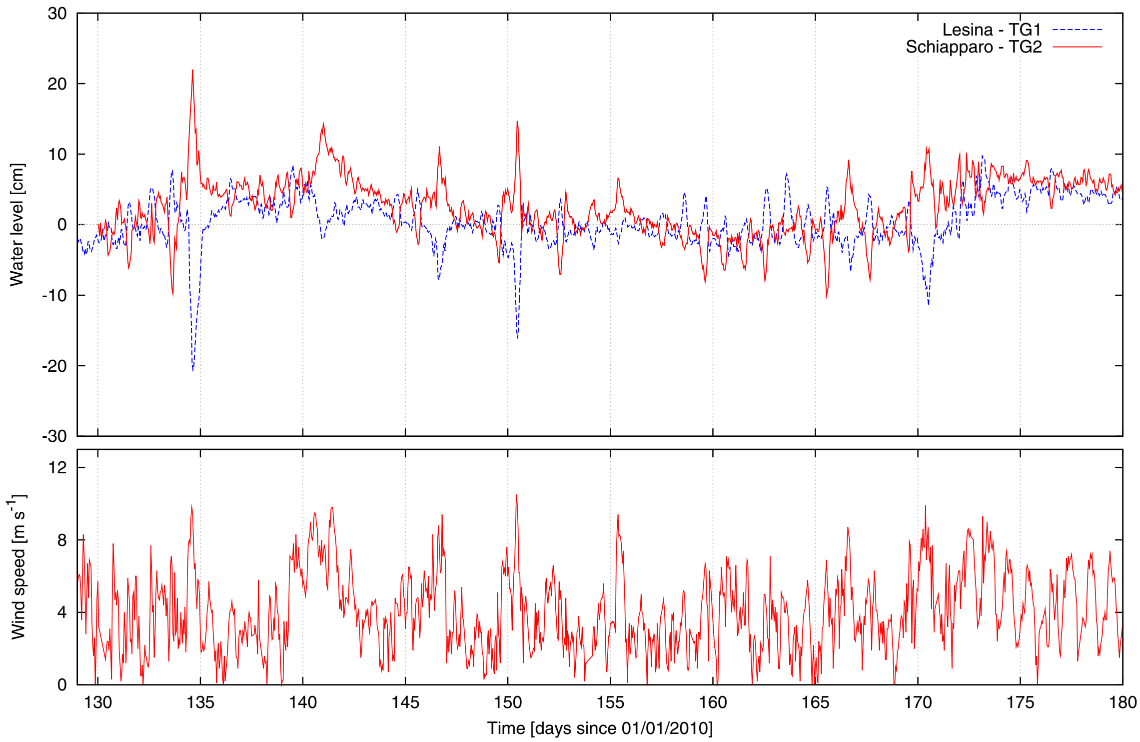

Fig. 5 Short-period fluctuations of water level inside Lesina Lagoon. *Blue dashed line* and *red continuous line* refer to tide gauges TG1 (close to Lesina city) and TG2 (Schiapparo), respectively. Wind speed measured close to Lesina Lagoon is shown in *bottom panel*

Figure 6 shows that the calibrated artificial neural networks well reproduce the surface water exchange between the lagoon and the sea through the Acquarotta and the Schiapparo channels. The root mean square error of the neural networks in the testing phase is 0.6 and 1.0 $m^3\ s^{-1}$ for the Acquarotta and Schiapparo channels, respectively.

Exchange through the channels is determined by the hydraulic head difference between the lagoon and the sea. Although the short-period tidal oscillations are damped out by the narrow seaward channels, the instantaneous surface water fluxes between lagoon and sea are modulated by the tide in the Adriatic. During intense wind events, and when the mean water levels in the lagoon and sea are similar, the difference in water levels inside the lagoon (due to the wind set-up) may induce the water in the two seaward channels to flow in opposite directions. Hence, during these specific events, one end of the lagoon (the up-wind area) receives seawater whereas the other discharges.

The calculated daily net fluxes through the channels and the daily hydraulic head difference between the lagoon and the sea are shown in Fig. 7. Since the water level in the lagoon is generally higher than sea level, net water transport is generally seaward. However, during the dry season, net transport from the sea to the lagoon is observed. The average net surface water fluxes through the seaward channels computed by the neural networks are -1.2 and -3.1 $m^3\ s^{-1}$ for the Acquarotta and Schiapparo channels, respectively.

Water Budget

Field observations and neural network-derived water fluxes enabled the lagoon's daily water mass balance to be analysed for the full period of investigation (May 2010 to August 2011). The analysis allowed the quantification of the time-varying total fresh water input to the Lesina Lagoon. The time series of the water budget closure term, which consists of both surface and sub-surface fresh water inputs, is plotted in Fig. 8. There is strong temporal variability of the closure term, which can exceed 15 $m^3\ s^{-1}$. The results indicate that the peak values of the water budget closure term coincide with heavy precipitation events (upper part of Fig. 8). The water budget closure term has an average value of 4.5 $m^3\ s^{-1}$ with a standard deviation of 6.6 $m^3\ s^{-1}$.

It was not possible to quantify the individual contributions of surface and sub-surface fresh water inflows in the budget closure term, but on the basis of these results, several considerations can be made:

– The sum of surface and sub-surface fresh water inflows calculated in this study (4.5 $m^3\ s^{-1}$) is 36 % higher than the tributaries discharge estimated by (Francavilla 2007) using point discharge measurements carried out in 2006 and 2007 (3.3 $m^3\ s^{-1}$). This means that three quarters of the fresh water is discharged into the lagoon through the major tributaries and only one

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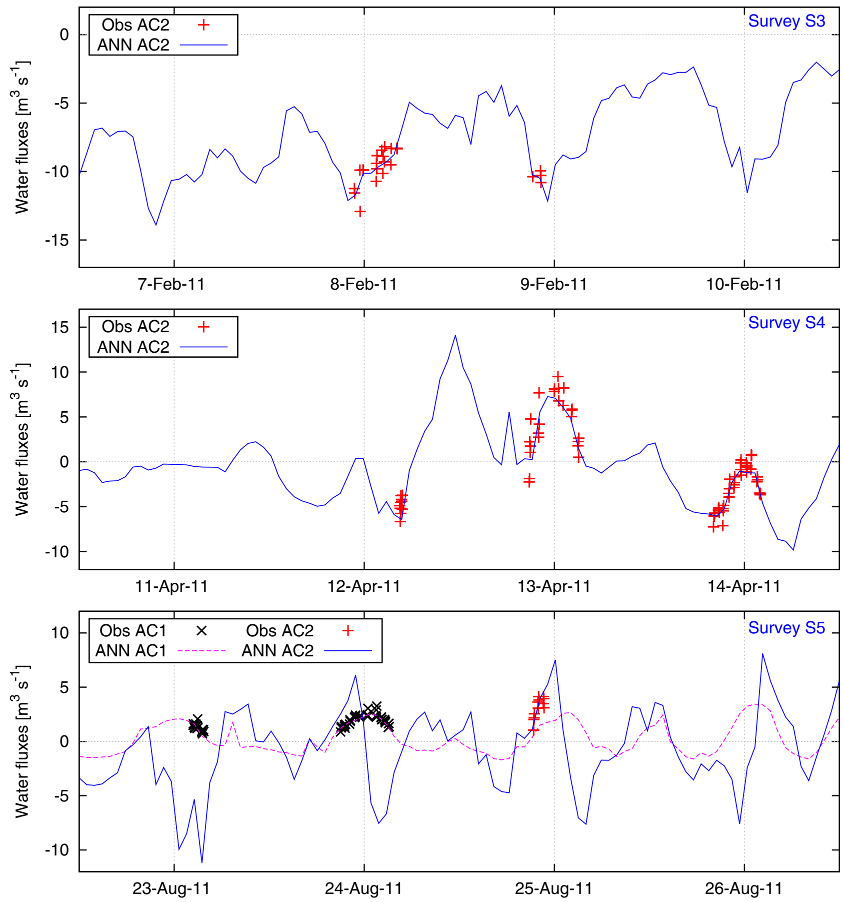

Fig. 6 Time series of measured (*black stars* for station AC1 and *red crosses* for station AC2) and computed by the ANN (*blue continuous line* for station AC2 and *magenta dotted line* for station AC1) surface water fluxes between the lagoon and the sea

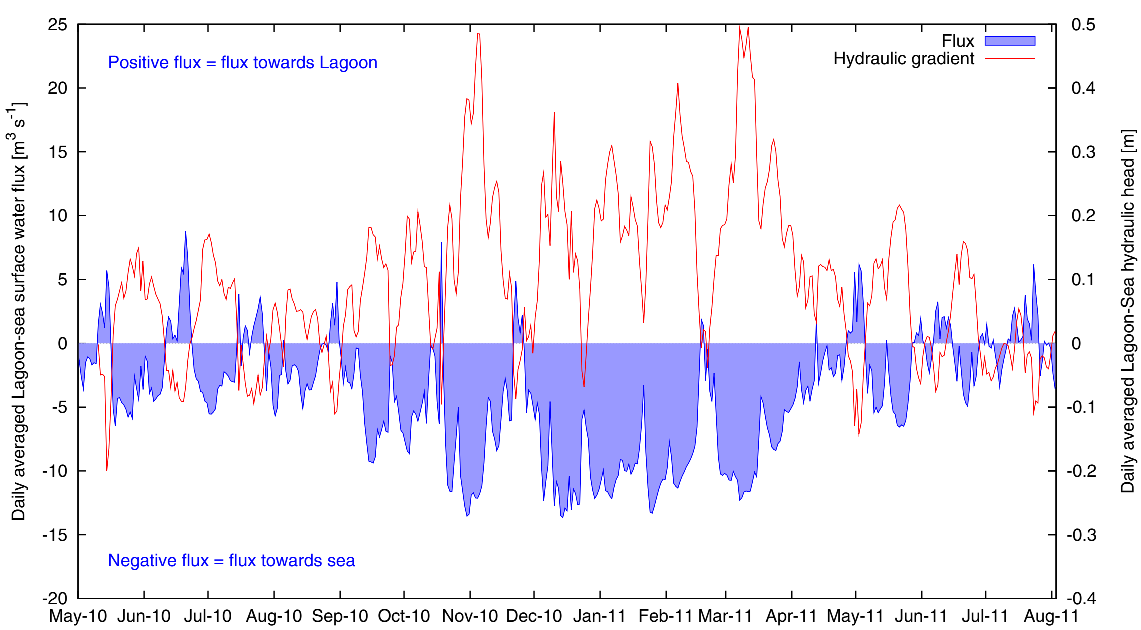

Fig. 7 Daily averaged flux rate of surface water through seaward channels (*blue band*), as estimated by the neural network prediction, and daily averaged hydraulic head difference between lagoon and sea (*red line*). Negative value indicates flux seawards and positive value indicates flux towards lagoon

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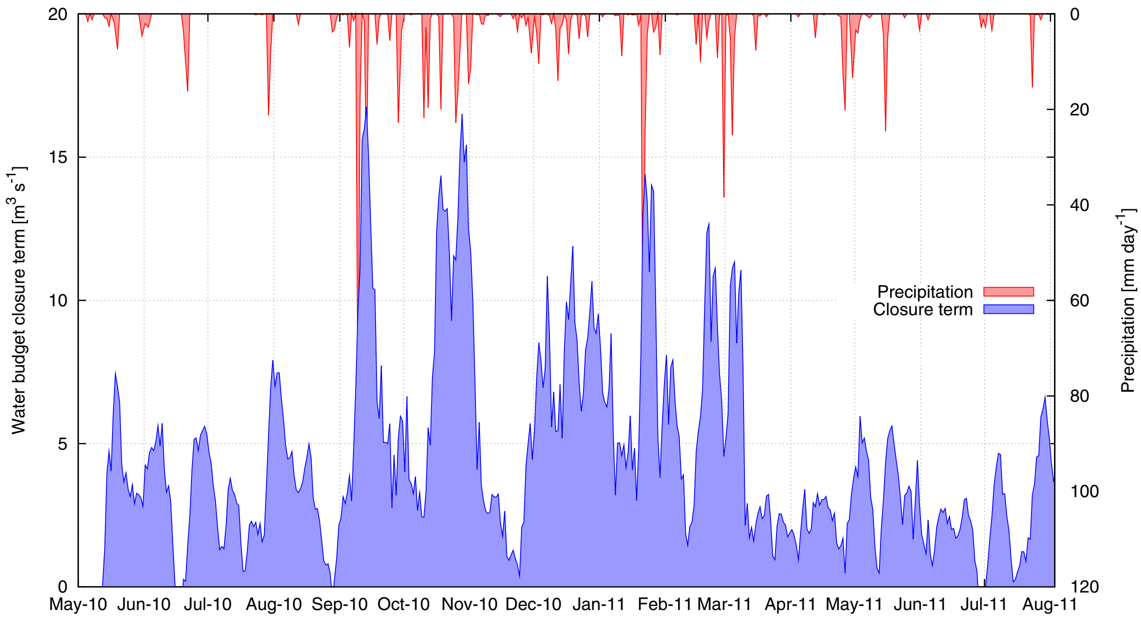

Fig. 8 Variation of water budget closure term, consisting of both surface and groundwater fresh water inflows, from May 2010 to August 2011. Accumulated daily precipitation is shown at *top* of figure

quarter results from groundwater discharge and surface runoff.

– Using a radium isotope (^{224}Ra) mass balance, (Rapaglia et al. 2012) found the total groundwater contribution (which accounts also for the spring water discharged into the lagoon by the tributaries) to the Lagoon of Lesina to be about 11 m^3 s^{-1}. The radium measurements were performed in February 2010, so the estimated discharge is in the range of the water budget closure term calculated in this study for the wet season.
– The computed groundwater flux through the sandy barrier was estimated using the methods described in section "Fresh Water Inputs—Water Budget Estimation." According to Darcy's Law, a sea–lagoon hydraulic head of 0.5 m (maximum measured value, Fig. 7) would lead to a discharge of about 1×10^{-3} m^3 s^{-1}. The groundwater flux between the lagoon and the sea is thus three orders of magnitude less than the surface fluxes through the seaward channels. Therefore, this seaward groundwater flux appears to be a negligible component of the water balance of the Lesina Lagoon. It should be noted that hydraulic conductivity in sands varies over four to five orders of magnitude and often varies over several orders of magnitude within a single aquifer (Burnett et al. 2006), so the uncertainty of this term is very high. Moreover, the average hydraulic conductivity could be higher due to the presence in the barrier of five buried ancient seaward channels (De Pippo et al. 2001; Fidelibus et al. 2011), which may act as preferential conduits for the flow.
– The water budget closure term contains urban waste waters and agricultural runoff discharged into the lagoon. The importance of this contribution is greater during the winter rainy period (Roselli et al. 2009).

There is uncertainty arising from measurement errors and the complex spatial heterogeneity that characterises hydrological processes. Due to the small dimensions of the Lesina Lagoon, we could reasonably assume that the errors for the precipitation, the evaporation and the change in volume terms are about one order of magnitude smaller than the error of the fresh water fluxes between the lagoon and the sea computed by the ANNs. The groundwater flux between the lagoon and the sea and the error in its estimation resulted to be negligible. Accordingly, the total error of the water budget closure term was estimated to be 1.6 m^3 s^{-1}.

Hydrodynamics and Renewal Capacity

The estimated water budget closure term was used as fresh water input in the numerical simulations. Since it was not possible to quantify the discrete contributions of surface and sub-surface fresh water inflows, we assume in model simulations that all fresh water flowed into the lagoon through the major tributaries indicated in Fig. 1.

Several simulations were carried out to calibrate and validate the model against available observational data on water level and water flux through the seaward channels. The most important parameter to be set for the hydrodynamic

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model is the value of the bottom friction coefficient. Calibration was carried out by varying the Strickler bottom friction coefficient in the computational domain and comparing the computed results with the observed data. In this study, the bottom friction coefficient was assumed to vary depending on the physical features of different areas of the study site. Distinctions were made between the lagoon, the sea, the reed bed area and the Acquarotta and Schiapparo seaward channels. Inside these channels, a further distinction was made between the channel itself and the area of the grilles at the lagoon end. Strickler coefficient values of between 17 and 40 $m^{1/3}\ s^{-1}$ have been used in the hydrodynamic modelling of other coastal systems having sub-areas with similar morphodynamic characteristics to those of the study site (Umgiesser et al. 2004; Ferrarin and Umgiesser 2005; Ferrarin et al. 2008, 2010; De Pascalis et al. 2011).

Measured data from the S1 and S2 surveys were used in the calibration process. The calibrated bottom friction coefficients were: 32 $m^{1/3}\ s^{-1}$ for the sea, 30 $m^{1/3}\ s^{-1}$ for the lagoon, 15 $m^{1/3}\ s^{-1}$ for the reed bed and 28 $m^{1/3}\ s^{-1}$ for the channels. A friction coefficient of 1.6 $m^{1/3}\ s^{-1}$ was imposed for the grilles to reproduce their damping effect on channel flow.

The model was validated by running one more simulation and comparing the model's prediction with other independent data sets of water flux (surveys S3, S4 and S5) and water level measured in 2011. The results were found to be generally in good agreement with the available data. The comparison between measured and computed water levels at stations TG1 and TG2 is shown in Fig. 9. The statistical analyses of simulated water levels and water fluxes are summarised in Table 2. The correlation coefficient between model results and observations is greater than 0.8 for both water level and water fluxes. The root mean square error is about 3 cm for the water level in the lagoon and about 1.8 $m^3\ s^{-1}$ for the discharge through the seaward channels.

The calibrated model was used to simulate the evolution of a conservative tracer and to estimate the water renewal time distribution. Two yearly simulations were carried out in order to investigate the seasonal variation of WRT: simulation SL1 started in June 2010 and simulation SL2 started in September 2010. One month (May and August in the simulations SL1 and SL2, respectively) was used as start-up period to reach an initial flow condition for the advection and diffusion calculation. Even if the transport time scale is integrated over the whole simulation duration, the initial time of the computation influences its estimation. The decay of the tracer concentration was faster in the fall–winter period when fresh water inputs are higher and the wind, and its mixing action, is generally stronger. Consequently, the WRTs of the simulation started in September (Fig. 10b) were generally lower than the ones computed by the simulation started in June (Fig. 10a). The basin-wide average water renewal time of Lesina Lagoon is 192 and 142 days for simulations SL1 and SL2, respectively.

The computed WRT distribution in the lagoon for both simulations shows a clear east–west gradient, with the lowest local water renewal times in the eastern part, into which most of the tributaries flow, while the western part of the lagoon had the highest values due to the limited water exchange (Fig. 10). The simulation started at the beginning of the summer produced WRTs of more than 250 days in the western side of the lagoon (Fig. 10a).

As show in Fig. 2, the application of the hydrodynamic model is the final step of the integrated model chain. The uncertainties at preceding points in the chain (ANNs, water

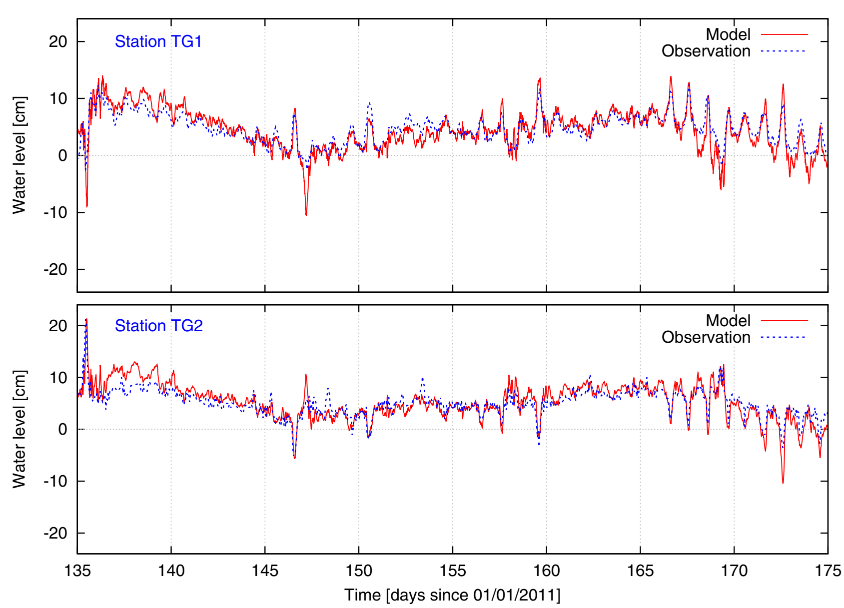

Fig. 9 Time series of computed (*red continuous line*) and measured (*blue dotted line*) water levels at stations TG1 and TG2

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Table 2 Statistical analysis of simulated water levels in the lagoon (TG1 and TG2) and water fluxes through seaward channels (AC1 and AC2) for the year 2011

Station	Variable	RMSE	BIAS	*R*
TG1	Water level	4.6 cm	0.0 cm	0.93
TG2	Water level	2.6 cm	-0.3 cm	0.84
AC1	Water flux	1.2 m^3 s^{-1}	-0.2 m^3 s^{-1}	0.88
AC2	Water flux	2.5 m^3 s^{-1}	-0.6 m^3 s^{-1}	0.83

Results are given as RMSE (root mean square error), BIAS (difference between mean of observations and simulations) and R (correlation coefficient between model results and observations)

budget) accumulate and influence the hydrodynamic model results. In order to assess the level of uncertainty on the computed WRT, four additional simulations, two for case SL1 and two for case SL2, were carried out in which the total fresh water input was increased and decreased by the error estimated in the water balance (1.6 m^3 s^{-1}, see section "Water Budget"). The results of this sensitivity study showed a basin-wide average WRT of 164 and 208 days for case SL1 and of 125 and 152 days for case SL2. Therefore, an error of about 35 % in the total fresh water input produces an average and a maximum uncertainty of 10 and 15 %, respectively, in the WRT estimation. It has to be noted that the maximum uncertainty (28 days) is lower than the seasonal variability of WRT (50 days).

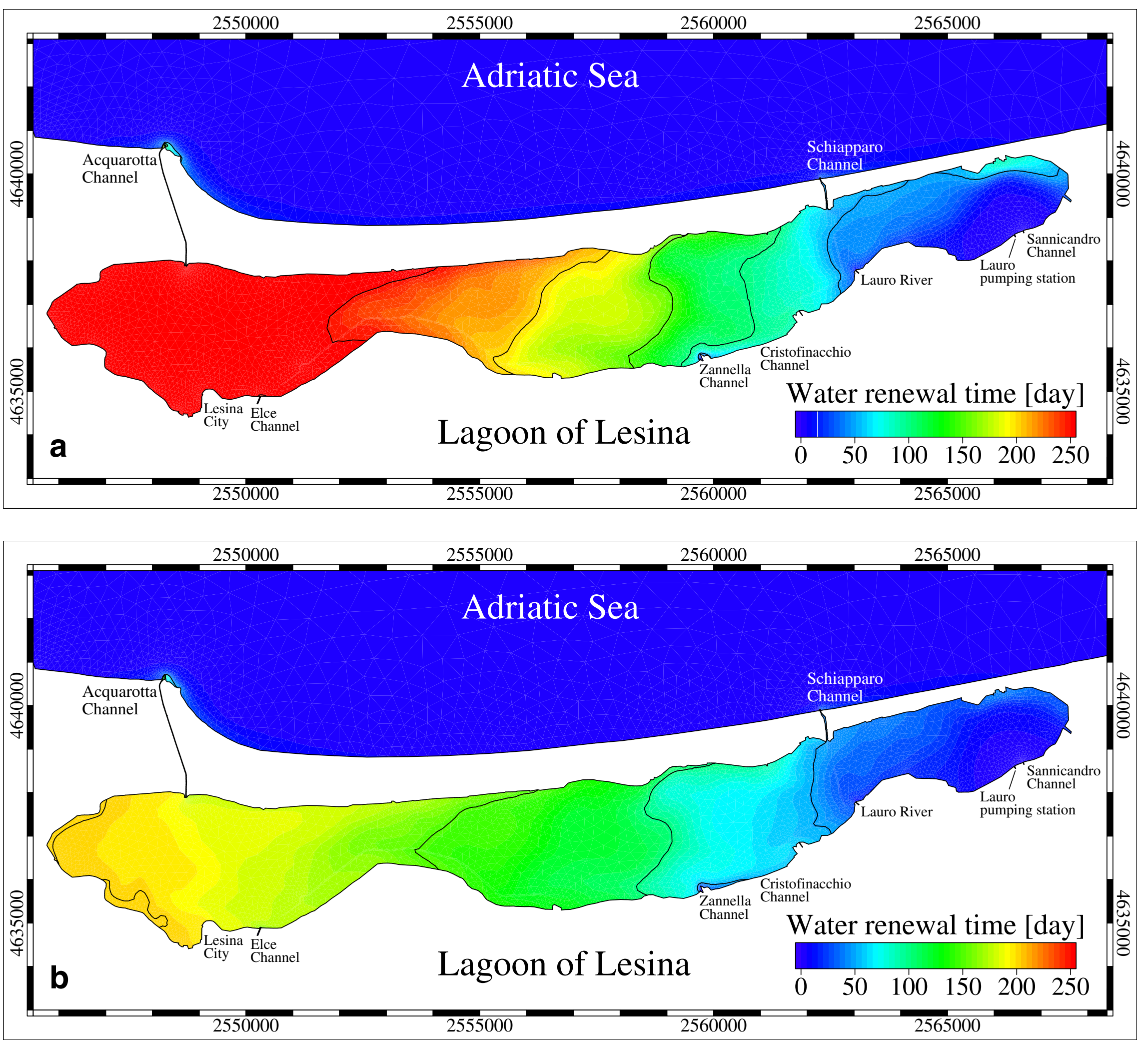

Fig. 10 Modelled spatial distribution of water renewal time for Lesina Lagoon for yearly simulation started in June (**a**) and September (**b**)

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The spatial distribution of WRT can be used to improve our understanding of the links between physics, hydrology and ecosystem conditions. In the eastern part of the lagoon, from the east boundary to the Schiapparo channel, the fresh water inputs and sea–lagoon exchange ensure the removal of the dissolved substance in less than 50 days. Indeed, high renewal capacity corresponds to the area characterised by low salinity, coarser sediments and reed beds (Roselli et al. 2009). The western part of the lagoon is instead dominated by a water re-circulation system and is only slightly involved in the exchange with the open sea. The resulting water renewal times are thereby higher than 250 days. This relatively confined area is characterised by muddy sediments, high concentrations of nutrients and organic matter at the sediment interface, and high oxygen depletion (Manini et al. 2003; Roselli et al. 2009; Specchiulli et al. 2010). Thus, in the Lesina Lagoon, areas with longer renewal times would exhibit a higher degree of eutrophication and saprobity than those with shorter times. Consequently, renewal has a strong effect on the structure of benthic communities and biodiversity, influencing the number of species, the density of individuals and the amount of biomass (Guelorget and Perthuisot 1992; Tagliapietra et al. 2012). The computed transport time scale pattern may help to explain the highly heterogeneous spatial distributions of benthic assemblages and trace elements found in the Lesina Lagoon (Fabbrocini et al. 2005; Specchiulli et al. 2010; Frontalini et al. 2010).

Conclusions

A multidisciplinary approach consisting of a set of mutually consistent models (artificial neural networks, water balance analyses and hydrodynamic modelling) was used in this study to investigate the seasonality of the hydrological regime and renewal capacity of the micro-tidal Lesina Lagoon. The accuracy of the different points in the model chain was evaluated as well as the level of uncertainty on the end product, the water renewal time.

The results obtained with this integrated approach provide important insight into the general hydrological conditions of the lagoon, which are characterised by large spatial and seasonal variations. The total fresh water input is strongly influenced by meteorological conditions, with peaks after heavy rain events, while the groundwater flux between the lagoon and the sea was found to be a minor component of the water balance of the Lesina Lagoon.

The numerical simulations showed that the renewal capacity of the lagoon depends on the beginning of the simulation and is changing seasonally. The water renewal behaviour of the system was higher in the wet season when fresh water inputs are higher and the action of the wind is more effective in mixing the lagoon's waters. The basin-wide average water renewal time for Lesina Lagoon is 192 and 142 days for yearly simulations started in June and September, respectively. The average uncertainty in the WRT, estimated through a sensitivity study, is about 10 %.

The computed water renewal time is a very important parameter for Lesina Lagoon that helps explaining the highly heterogeneous spatial distributions of many biogeochemical variables. All numerical simulations show a clear east–west gradient for water renewal time, with lower values in the eastern part of the lagoon where the main fresh water inputs are located. The WRT distribution reflects the peculiar ecological structure of Lesina Lagoon, which is characterised by progressive changes (east–west gradients) in the main environmental variables. These environmental gradients influence directly the structure of biological assemblages selecting sensitive species.

The developed 2-D approach, which describes the spatial heterogeneity of the renewal behaviour of coastal transitional waters that cannot be illustrated by a zero-dimensional homogeneous approach, is a powerful tool for the management of these important ecosystems.

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