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Sea level rise, hydrologic runoff, and the flooding of Venice

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[1] This paper deals with hydrologic studies relevant to the works engineered for the protection of the city of Venice (Italy) from major flooding under significant climate change scenarios. Such works foresee the temporary closure of the lagoon surrounding the city to tidal exchanges with the Adriatic Sea in times of sea storm surges via the operation of a set of mobile gates. A general hydrologic model of the $\sim$2000 km^2 mainland contributing runoff to the lagoon of Venice is coupled in time and space with a 2-D finite element model of the relevant tidal hydrodynamics to forecast maximum lagoonal surges in times of closure. We also study the impacts of run-through discharges bypassing the mobile gates and wind setups at time scales comparable to the foreseen closures (from a few to tens of hours). Climate change scenarios are recapitulated by up to +50 cm relative sea level rises by 2100 (the projected lifetime of the current protection works). Possible flooding of the city due to residual fluxes entering the lagoon during prolonged closures is examined. A probabilistic framework is also proposed for computing the statistics of maximum lagoon rises and stage-rise durations. Our studies suggest the adequacy of the design of temporary closures with respect to flooding and provide methods for general exercises in assessing the impact of regional climate change scenarios.

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1. Introduction

[2] The description of freshwater runoff to the lagoon of Venice has long been the subject of extensive studies owing to particularly complex interrelations between natural and built environments, in particular in view of the major human interventions on freshwater pathways occurred over several centuries [e.g., *Cucchini*, 1928; *Dorigo*, 1983; *Zonta et al.*, 2005; *Collavini et al.*, 2005; *Zuliani et al.*, 2005]. The relevance of estimates of freshwater discharges stems from the societal importance of hydraulic protection works adapting to ever-changing models of social and economic development [e.g., *Dorigo*, 1983], and for the ecological and morphodynamic implications of freshwater mixing within the Venice lagoon, whose ecological and cultural services are particularly important (see, e.g., *D'Alpaos* [2004] and *D'Alpaos et al.* [2007, and references therein]; for long-term evolution of the ecosystem see, e.g., *Fagherazzi et al.* [2006] and *Marani et al.* [2007]). In recent times, accurate estimates of freshwater inflows gained importance to evaluate their impact on lagoonal water levels during the planned temporary closure of the lagoon to tidal exchanges with the Adriatic Sea through the operation of mobile gates (the MOSE system) in times of sea storm surges.

[3] The present study focuses on the application of a coupled hydrologic-hydrodynamic model of the lagoon system. The hydrologic model relies on a detailed description of the geomorphological setting, runoff production and evapotranspiration processes [e.g., *Marani et al.*, 2006; *Rinaldo et al.*, 2006a, 2006b; *Botter et al.*, 2008]. The hydrodynamic component is a general 2-D finite element tidal model reproducing in great detail the morphology of the lagoon of Venice that proved its reliability through extensive testing [*Defina*, 2000; *Carniello et al.*, 2005; *D'Alpaos and Defina*, 2007; *Defina et al.*, 2007]. An important factor in our assessment is the availability of long records from a large meteorological and hydrological database (see, e.g., Figure 1), in which the temporal resolution of the observations, say $\Delta t = 1$ h, is smaller than the characteristic time of the hydrologic response of the basins that make up the watershed (in the range 6–32 h). Comparative validation of modeling results with extensive collections of high-frequency, spatially distributed field data proved fundamental for predictive purposes.

[4] The aim of our exercise is the prediction of runoff volumes discharged in times of lagoon's sealing to sea storm surges. Surges are foreseen to increase substantially under projected sea level rise, thought of as recapitulating

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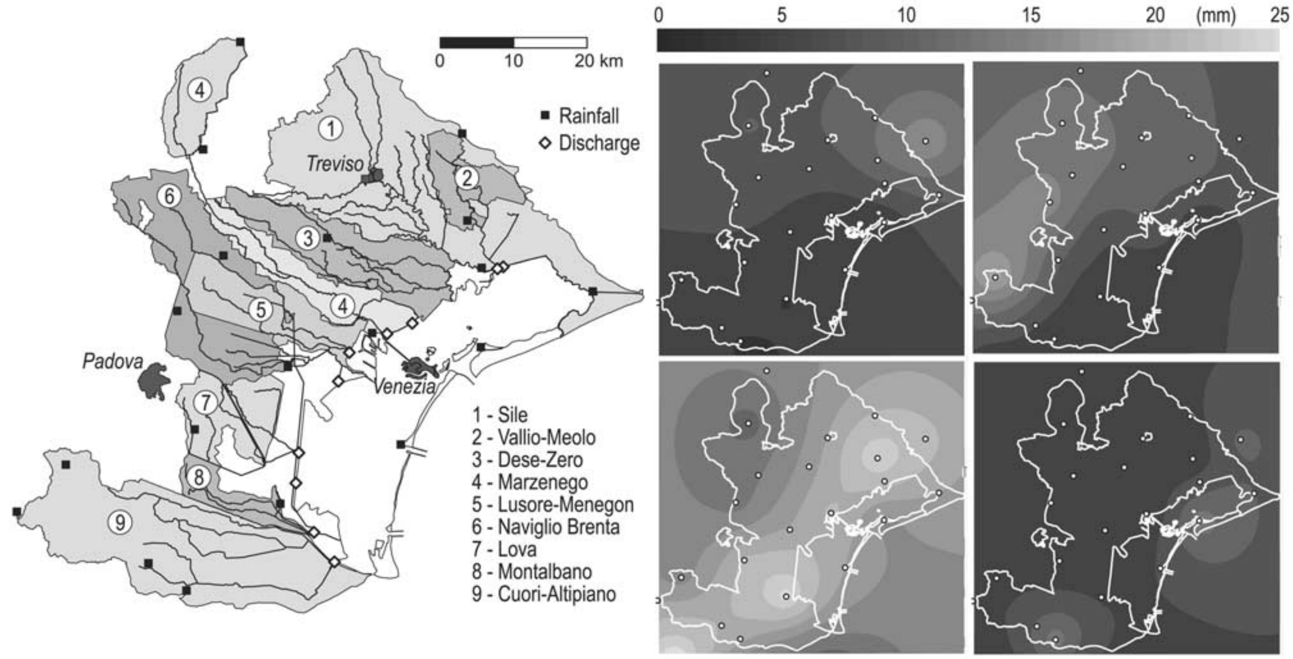

Figure 1. The Venice lagoon system. (left) Sketch of the overall (~2000 km^2) watershed, showing all major subbasins, their outlets, and the position of the currently operating meteorological and hydrologic gauging stations (geographic extensions of the map are 11°41′30″–12°54′50″ latitude and 45°09′06″–46°01′50″ longitude). (right) Four snapshots of kriged rainfall intensities, emphasizing spatial gradients that may impair evaluations of rainfall volumes based on point measures.

climate change effects in the area [e.g., *Pirazzoli*, 2002]. Though regional estimates of relative sea level (RSL) changes are still rather uncertain [*Bindoff et al.*, 2007; *Intergovernmental Panel on Climate Change*, 2007], it is safe to assume that RSL scenarios are likely to increase significantly the times of closure within the lifetime of the currently designed barriers. Because RSL directly impacts operations of the closures and the Venice protection goals, a noteworthy importance derives for the prediction of runoff volumes under different closure scenarios. Added interest in the exercise stems also from claims that no such closure would be sustainable owing to the combined effects of excessive runoff from the mainland and run-through discharge bypassing the closure system [*Pirazzoli*, 2002; *Pirazzoli and Umgiesser*, 2003, 2006]. Should, in fact, the combined effects of external runoff postulate the obsolescence of the system under construction, a radical revision of the planned works would be in order.

[5] Closures are planned to limit the maximum water level within the lagoon at +110 cm above mean sea level (amsl), the threshold for significant flooding of the city [e.g., *Consorzio Venezia Nuova*, 1997; *Carbognin et al.*, 2004], and mean sea level rise is projected up to a +50 cm RSL scenario by 2100 [*Pirazzoli*, 2002]. This provides a projection compatible both with climate change scenarios [*Bindoff et al.*, 2007] and with the expected lifetime of the planned protection works [e.g., *Bras et al.*, 2001].

[6] The paper is organized as follows. Section 2 reports about materials (the database) and methods (the mathematical models). Section 3 discusses the results of the application of the mathematical model, and proposes an approach for estimating the probabilistic structure of duration curves for elevations above a given threshold in times of closure. Section 4 closes the paper with a set of conclusions.

2. Materials and Methods

[7] The drainage basin in the lagoon of Venice is identified as the flat region whose channel network permanently drains into the lagoon of Venice (see Figure 1). We neglect contributing areas that contribute runoff only via controlled operations at hydraulic structures owing to their limited magnitude [*Marani et al.*, 2004a]. Gravity as well as mechanical drainage is operating, at times in an alternating mode. Major freshwater tributaries (Dese, Zero, Marzenego, Lusore and Naviglio Brenta; see Figure 1) exhibit variable lengths of their estuaries where tidal effects are strong, often leading to flow reversal. The flat nature of the catchment and the nearly completely engineered drainage system (no digital terrain model approach for determining drainage directions is meaningful in this context) call for a subtle catchment delineation based on detailed information on channel network and contributing area structure. Additional complexity stems from the many hydraulic devices (spillways, diversions, manually operated sluice gates for irrigation purposes, interconnections) that contribute to the regulation of discharges across the entire watershed. Meteorological stations and discharge gauging stations are suitably distributed within the watershed (Figure 1), as correlation scales of observed rainfall patterns prove consistently smaller than the mean distance among stations and the gauged outlets include most significant sources of runoff to the lagoon [*Marani et al.*, 2004b].

[8] The drainage basin covers an area of about 1850 km^2 (Figure 1), delimited by the Gorzone river (south), the

Euganean Hills (west) and the Sile river (north, where a flood spillway created by an old levee breach contributes freshwater somewhat unrelated to local meteorological events [*Marani et al.*, 2004a]). Hydraulic connections between the channels composing the drainage basin and the neighboring river catchments exist (e.g., within the Sile, Brenta and Bacchiglione river basins), through which transient discharge tradeoffs occur. Significant base flows occur only in a few drainage basins (Marzenego, Dese, Zero) that originate from groundwater feeding the powerful natural spring lines lying between Cittadella and Castelfranco Veneto (Figure 1). Freshwater runoff into the lagoon of Venice is distributed among 27 outlets along the lagoon border. Land uses relevant to runoff production were determined in a spatially distributed manner by means of remote sensing and GIS tools [*Marani et al.*, 2004a, 2004b, 2006]. Information gathered from ad hoc studies to define the detailed hydraulic-hydrologic functioning of the system are reported elsewhere [*Marani et al.*, 2004a, 2004b, 2006; *Rinaldo et al.*, 2006a, 2006b] (see also auxiliary material).[1]

[9] The mathematical machinery of the hydrologic model is based on the geomorphologic theory of the hydrologic response employing the formulation of transport by residence-time and lifetime distributions [e.g., *Rinaldo and Rodriguez-Iturbe*, 1996; *Rinaldo et al.*, 2006a, 2006b]. Nested travel times allow a complete description of all geomorphic transitions (from unchanneled to channeled states, and within channeled pathways through the network hierarchy) including the complex description of drainage densities in a nearly completely engineered drainage context. Evapotranspiration fluxes are computed and updated, through the monitored data, via the FAO-Penman-Montieth method [*Allen et al.*, 1998; *Settin et al.*, 2007]. Four different models of runoff generation yield comparable results [*Botter et al.*, 2006] and in this context we use a Green-Ampt scheme for physically based descriptions of both infiltration excess and saturation excess runoff generation processes.

[10] The availability of data about rainfall patterns in space and time allows a fully distributed character in the processing of the forcings and of the related path probabilities. Here we employ a 100 m × 100 m grid through ordinary Kriging of rain gauge observations using experimental variograms [*Marani et al.*, 2004b]. Water routing of the surface and subsurface components is performed by means of suitably defined travel, residence and lifetime distributions [*Botter et al.*, 2006, 2008]. Note that at the time scales of interest here and for low, flat and mostly reclaimed catchments, groundwater contributions can be addressed by adding a base flow obtained from field data for gravity drained outlets ($\sim$45% of total drained area) [*Rinaldo et al.*, 2006b; *Marani et al.*, 2006]. Groundwater seepage is neglected for reclaimed catchments subject to continuous or alternate mechanical drainage.

[11] To characterize travel times for channeled states, we employ inverse Gaussian distributions (see auxiliary material) which are exactly derived from the parabolic approximation to the 1-D momentum balance equation [e.g., *Brutsaert*, 2005]. This is assumed to be appropriate owing to the small flow velocities and Froude numbers at hand [e.g., *Rinaldo et al.*, 1991; *Brutsaert*, 2005]. For unchanneled pathways, exponential distributions are employed whose mean (the inverse of the mean residence time) is given in view of local drainage density, topography and field experiments with Lithium tracers and nonpoint source nitrates [*Settin et al.*, 2007; *Botter et al.*, 2006, 2008].

[12] Hydraulic computations within rivers and waterways are also necessary because of the nature of drainage to pumped outlets or, in gravity-driven flows, of the marked tidal effects, in particular the sizable flow reversal often induced in the flat terminal reaches by the microtidal regime typical of the Venice lagoon [e.g., *Marani et al.*, 2006] (see also data in Figure 2). Tidal reaches are clearly delimited, usually by a drop in elevation used by mills in the past, and the induced transition through critical conditions ensures the independence of upstream reaches from tidal effects. We assume, in a consolidated scheme [*Marani et al.*, 2004a, 2004b], that a 1-D unsteady hydrodynamic model collects decoupled hydrologic flows at the relevant nodes, and computes, by a standard implicit numerical solution of De Saint Venant and continuity equations, water levels and flow rates. Here we may safely assume $Fr \ll 1$ (where Fr is Froude's ratio of inertia and gravity for the 1-D flow) and the implementation adopted is tailored to low-flow situations (and dry bed emergence typical of tidal computations) by means of an adequate definition for flow velocity as the water level approaches zero [e.g., *Defina*, 2000; *Marani et al.*, 2006]. Boundary conditions require some reasoning. While, in fact, in reproducing measured flow rates we assign the observed tidal water elevation in time as downstream boundary condition (and assign hydrologic flow rates as upstream boundary conditions for all inflow nodes), further assumptions are needed for a predictive use of the models. To evaluate runoff during closure times, we have chosen to maintain the boundary condition at the freshwater outlets as the initial closure elevation rather than iterating the calculation as the lagoonal level would be affected by the outflowing runoff. The limited rise produced (at most of the order of a few tens of centimeters) and the slight overestimation induced in the resulting runoff estimates support this position that sharply curtails the computational burden.

[13] Each of the 27 outlets (and their catchments and drainage network) has been examined individually. A large set of field measurements of hydrological, meteorological or hydraulic parameters at each outlet and distributed over the tributary areas has been implemented for an elaborate validation of the model in a fully predictive mode [*Marani et al.*, 2006; *Rinaldo et al.*, 2006a]. The model has thus been applied separately to all the catchments (gravity drained or otherwise) composing the watershed of the lagoon of Venice. The validation curves shown in Figure 2 illustrate a sample of the robust predictive capabilities shown by the model. The Nash-Sutcliffe indices for hourly sequences of several simulated months are shown in Table 1. Total errors for simulated runoff volumes in relatively long (i.e., 1 year at hourly time steps) continuous runs turn out to be in the surprisingly narrow range 3–15% (see Figure 2) [*Marani et al.*, 2006]. The performance of the model is significantly worse, though still largely acceptable, for the single outlet collecting runoff from the $\sim$600 km^2 southern mainland

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2008WR007195.

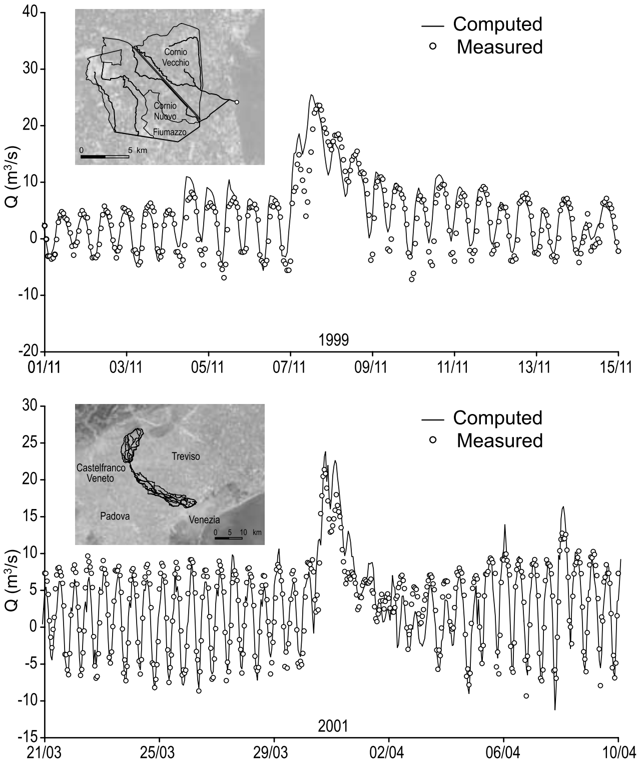

Figure 2. Computed and observed discharges, here shown from a partial hourly record at two sample outlets of the 27 simulated ones. Model validation is shown here for (top) the Lova catchment (events occurred in April 1999) and (bottom) the catchment of the River Marzenego (events of March 2001). Note the oscillations of flow rates and the flow reversal induced by the microtidal regimes, overcome only by strong hydrologic contributions. Tidal fluctuations are forced by the oscillation of the downstream boundary condition (BC) imposed by the measured tidal elevation at the outlet, whereas hydrologic BCs are produced as time-varying inputs to selected nodes of the discretized 1-D tidal reach of the delivering waterway [*Rinaldo et al.*, 2006b]. The extent of the tidal reach is determined by a physical control, usually a drop in elevation creating permanent critical conditions. Extensive validations for all 27 outlets (and whereabouts on the pertinent watersheds and hydrology) are reported elsewhere [*Marani et al.*, 2006] (see also auxiliary material).

(Bacino Sud in Table 1 and Figure 1) which is particularly complex from the hydraulic viewpoint (for instance, large reclaimed areas therein undergo double, and small catchments even triple, pumping at different locations to reach the lagoon). The capabilities of the theoretical tools to reproduce the complex observational signal in a continuous mode are deemed noteworthy. It should be noted that models of this type are usually termed continuous, though discretized at hourly time steps, because they do not require initial conditions and are continuously supplied the relevant meteorological and hydrological boundary conditions. Further details on the hydrologic models are provided in the auxiliary material.

[14] The hydrologic model is applied to the evaluation of runoff volumes discharged into the lagoon in times of prolonged closures under RSL change scenarios. We shall assume a constant lagoon elevation during closure times, thus directly translating runoff volumes into mean lagoon elevations (the static assumption). We have tested the general viability of this assumption by running the coupled hydrologic and hydrodynamic models for selected events and computing the actual wind and wave setups. The distributed nature of the freshwater outlets, and the much smaller hydrodynamic time scales of redistribution of surface gradients with respect to the closure times, warrant that free surface gradients dissipate rapidly unless sustained by strong and persistent winds. Significant local setups may be generated in such cases. Complete numerical simulations of the relevant hydrodynamics prove the viability of the static assumption [*D'Alpaos*, 2004; *Carniello et al.*, 2005; *Bajo et al.*, 2007]. Note that the events selected are considered for the strength of the observed winds and the induced setups. This is deemed reasonable, on one side because one does not want to cloud the main issue centered on flooding of Venice in relation to the planned gates' operating rules, and on the other because maximum setups are generated in the southern lagoon for strong Bora (northern) winds, whereas Venice lies in a region relatively setup-free. Numerical simulations show that the largest instantaneous setups in Venice with respect to no-wind conditions never exceed 20 cm [*Carniello et al.*, 2005]. Figure 3 illustrates the main features and selected calibrations for the hydrodynamic model of the lagoon whose numerical code embeds about 51,000 nodes and 100,000 finite elements [*Carniello et al.*, 2005; *D'Alpaos and Defina*, 2007]. In particular, testing dealt with comparisons of measured and computed water levels, wind shear stresses at the free surface, wave heights, computed water discharges at the three outlets neglecting and considering the wind shear stress at the free surface [*Carniello et al.*, 2005; *D'Alpaos and Defina*, 2007]. Details on the hydrodynamic model are provided in the auxiliary material.

[15] The MOSE system consists of an integrated system of 79 mobile barriers designed to temporarily isolate Venice lagoon from the sea for high storm-induced meteorological

Table 1. Sample Assessment of the Predictive Capabilities of the Hydrologic Model for the Largest Five Freshwater Outlets Draining 72% of Total Watershed Area[a]

Catchment	Dese-Zero	Marzenego	Lusore-Menegon	Vallio-Meolo	Bacino Sud
Average measured discharge (m^3/s)	9.88	3.62	4.16	4.54	2.73
Observed variance ($(m^3/s)^2$)	388.83	31.75	33.36	53.73	23.22
Nash-Sutcliffe index	0.89	0.80	0.77	0.82	0.72

[a] Shown are mean and average measured discharge and the Nash-Sutcliffe index computed over a 1-year series simulated at hourly time steps. There are 27 total freshwater outlets.

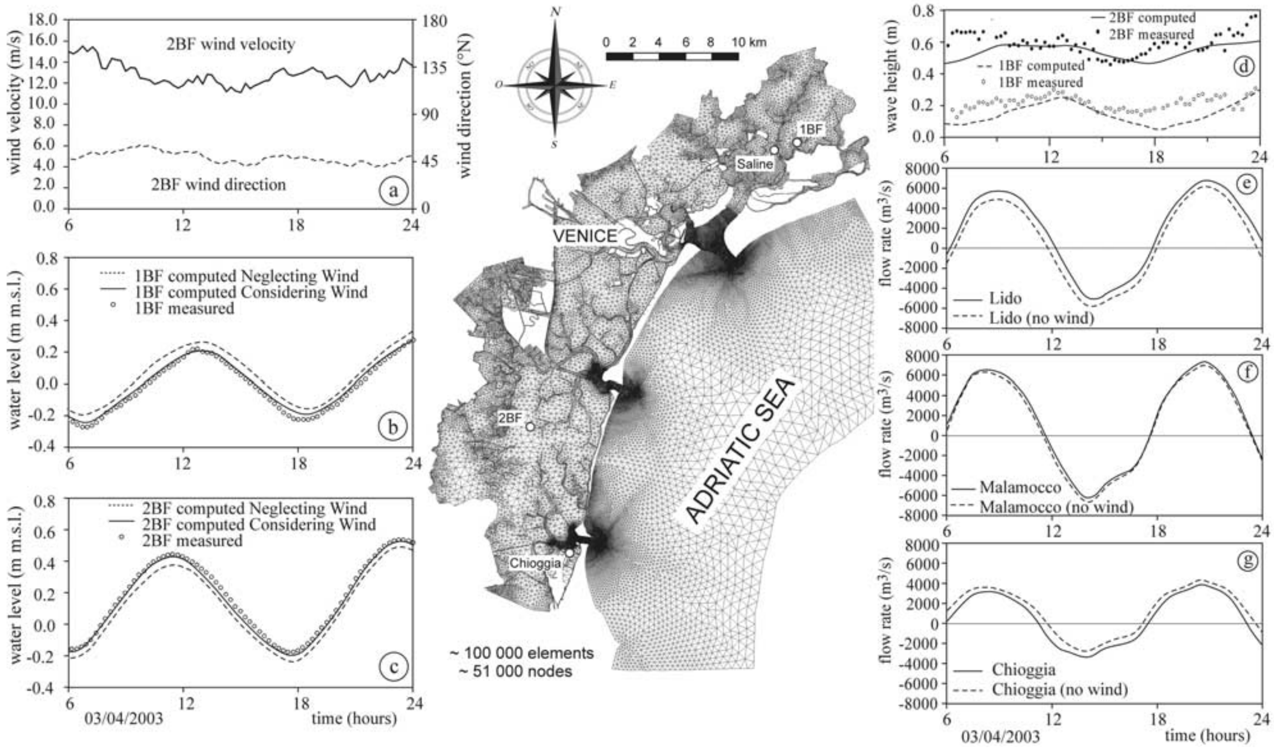

Figure 3. The general computational mesh reproducing the hydrodynamics of the lagoon of Venice (~51,000 nodes and ~100,000 elements) on 3 April 2003. (a) Measured wind velocity (solid line) and direction (dashed line) above the Venice lagoon and comparison of measured (circles) and computed water levels at the gauging stations (b) 1BF and (c) 2BF. We show comparative results obtained by neglecting (dashed lines) and accounting for (solid lines) wind shear stress at the free surface. Comparison of (d) measured (circles) and computed (solid and dashed lines) wave height at 1BF and 2BF gauging stations and computed water discharges at the three inlets: (e) Lido, (f) Malamocco, and (g) Chioggia, neglecting (dashed lines) and considering (solid lines) the wind shear stress at the free surface.

tides yielding water levels higher than +110 cm amsl inside the lagoon. The design protection has been established with reference to a predefined frequency of flooding with reference to the historic Punta della Salute marigraph. This implies certain time constraints due to engineering operations at the gates, and also suitable forecasts of sea surges resulting in extended closure times [e.g., *Consorzio Venezia Nuova*, 2005; *Eprim et al.*, 2005]. The choice of regulation, and thus the distribution of closures, reflects a balance of costs and benefits reasoning on the actual and future topography of the city.

[16] During closures, only two external regimes are assumed to produce significant increments of the lagoonal surface: (1) runoff from freshwater tributaries, producing an average rise, the ratio between discharged volumes and mean lagoonal surface, computed by integration of instantaneous total runoff fluxes in time over the individual closure times; and (2) run-through discharge allowed into the lagoon because of intrabarrier filtration due to the gates design. We neglect other contributions. In fact, direct groundwater seepage to the lagoon from the first aquifer overlying a deep and articulate layered aquifers system [*Gambolati et al.*, 1974; *Gatto and Carbognin*, 1981] is neglected because of current evidence on its magnitude and on saltwater intrusion into the first aquifer system [e.g., *Di Sipio et al.*, 2006]. Evaporation from lagoonal surface over closure time scales is likewise neglected. Note also the contrasting effects of the neglected fluxes.

[17] As per regime 1, of particular concern here are the hydrological arguments suggesting the purportedly obsolete MOSE design [*Pirazzoli*, 2002; *Pirazzoli and Umgiesser*, 2003, 2006]. In these studies storm surge events observed over the last decades, driven by anomalous meteorological conditions, were analyzed by adding a RSL scenario up to +50 cm. This corresponds to the high end of the latest IPCC scenarios [*Bindoff et al.*, 2007] as well as of local predictions in the Adriatic for the year 2100, considered a reasonable lifetime of the planned protection works [*Bourdeau et al.*, 1998]. Such RSL estimate is consistent with predictions of local subsidence of the Venice area [e.g., *Carbognin et al.*, 2004]. Freshwater runoff contributing to lagoon level rise during prolonged closures was estimated by *Pirazzoli* [2002] and *Pirazzoli and Umgiesser* [2003, 2006] as equivalent to the rainfall volume directly falling on lagoon surface (hence the hydrological rise was taken as twice the mean rainfall height).

[18] As per regime 2, design throughflows account for the technical room allowed to moving gate elements and, in particular, for possible asynchronous oscillations generated by hydrodynamic instabilities that may arise for certain incoming sea waves [*Blondeaux et al.*, 1993; *Mei et al.*, 1994; *Vittori et al.*, 1996; *Sammarco et al.*, 2000; *Panizzo*

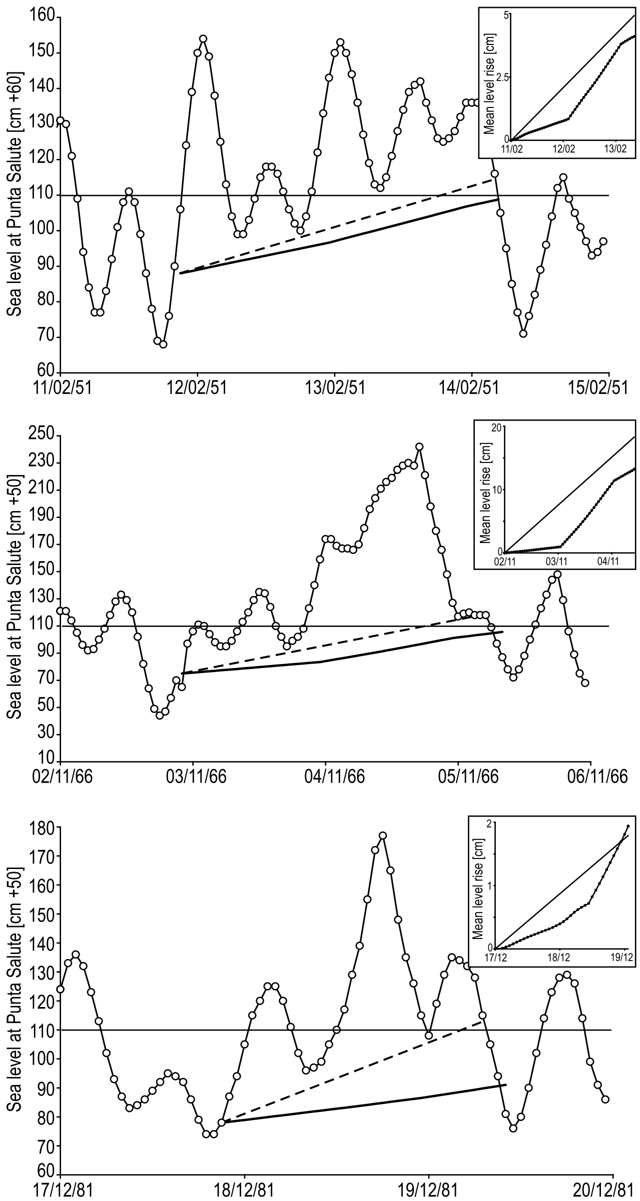

Figure 4. Simulation of overall surges due to mobile gate operation for three historic events (February 1951, November 1966, and December 1981). For each event the mean lagoonal level is calculated by using the complete hydrological models including run-through discharges and plotted jointly with the lagoonal level measured at Punta della Salute (circles). The level rises estimated by *Pirazzoli and Umgiesser* [2003] are plotted as dashed lines and are compared with the elevations estimated by the present hydrological model (solid lines). Insets show freshwater contribution to lagoonal rise for the three events. For each, the mean rise is calculated by using the hydrologic model (circles) and by assuming runoff from mainland equal to precipitation directly falling onto the lagoon surface during closure time (solid lines).

et al., 2006]. Previous analyses of run-through fluxes bypassing the mobile gates have assumed rise rates ranging, depending on operational conditions, from 0.27 cm/h without gate oscillations, to 0.45 cm/h under a 10° oscillation, up to 2.1 cm/h for 15° oscillations [*Pirazzoli*, 2002]. Experiments carried out on a physical model (in a notably large scale, 1:10), however, yielded accurate evaluations of the intragates filtration [*Consorzio Venezia Nuova*, 2003, 2006]. Throughflow in time depends on the instantaneous difference of sea and lagoon elevations, the wetted cross section, a function of seaward head, the angle of feasible oscillations of the hinged gates, and a discharge coefficient. The mean lagoon rise Δh can be given as a function of the duration, say d, of the closure event by the relation

$$\Delta h \sim 0.0042\, d^2 + 0.1955\, d \qquad (1)$$

where Δh is expressed in cm and d in h, from which all calculations follow directly. Note that the values assumed by *Pirazzoli and Umgiesser* [2003] and *Umgiesser and Matticchio* [2006] are significantly higher than the ones suggested by the 1:10 scale model. The maximum rate of lagoonal level rise is suggested to be $\sim 0.5 < 2.09$ cm/h. Note also that the rather large 1:10 model prevents significant scale effects for the physical model results [*Consorzio Venezia Nuova*, 2006]. We do not assume a dependence of the rate of change of water level rise within the lagoon on local wind speed [e.g., *Umgiesser and Matticchio*, 2006, Figure 3].

[19] It was inferred by *Pirazzoli and Umgiesser* [2003, 2006] that, under the described scenario, the city of Venice would be variably flooded despite the protection of MOSE gates because of the prolonged closures induced by the mean sea level rise. Clearly this raises concerns because attaining frequent lagoon levels beyond the critical threshold (+110 cm) would definitely make a case for the obsolescence of the ongoing project.

3. Results

[20] Mean lagoonal level rises, R_{tot}, have been estimated as $R_{tot} = v_Q + v_P + v_L$, where: v_Q and v_P express the specific discharge and precipitation respectively. Given the time scales involved, the rise is usually computed assuming instantaneous redistribution across the lagoonal surface (i.e., v_Q is the ratio between total incoming volume and lagoonal surface); v_L accounts instead for the rise rate due to intergates throughflow. Five surge events observed during the past 60 years have been studied in detail (February 1951, November 1966, October 1976 and 1980 and December 1981). Corresponding rainfall observations (and, where available, wind speed, air temperature, solar radiation and relative humidity) have been collected to represent the proper meteorological forcings. A large set of significant events within the 1999–2007 database, whose complete tidal, meteorological and pluviometric records were available, have also been analyzed. Tidal forcings have all been accounted for according to the hypothesis of sea level rise adopted by *Pirazzoli and Umgiesser* [2003] (i.e., +50 cm added directly to the sea elevations for the historical records).

[21] Computed discharges allow for a detailed description of inflow with realistic delays, in particular accounting for the role of tidal propagation along fluvial reaches and unsteady pumped outlets. Figure 4 shows a sample of the results obtained for the studied events. The observational lagoonal level is plotted jointly with the increase in water

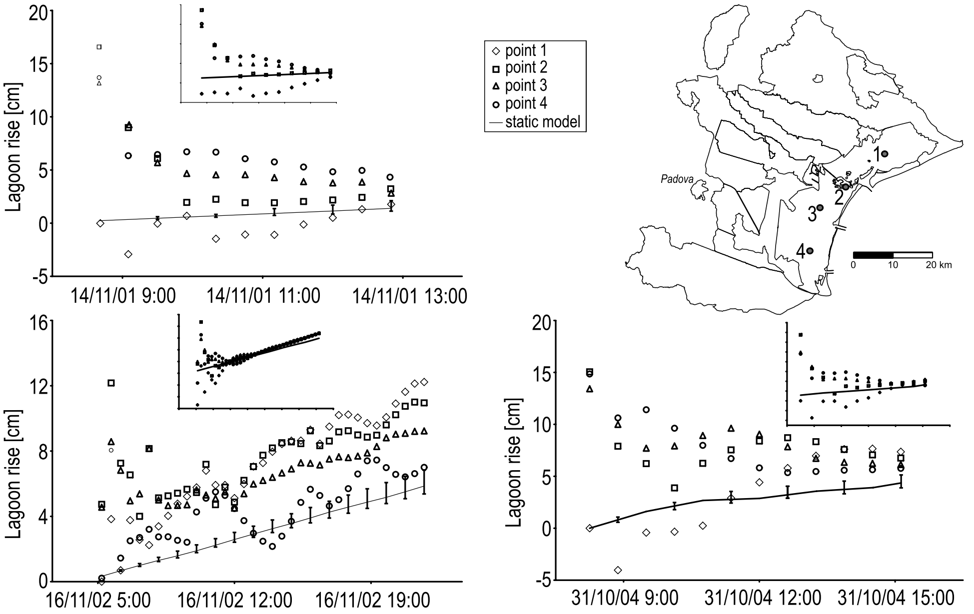

Figure 5. Numerical simulation through the complete hydrologic-hydrodynamic model. Three observed events are simulated (14 November 2001, 16 November 2002, and 31 October 2004) under +50 cm RSL rise. Wind speed and duration are those observed in the field. Note that one event (16 November 2002, bottom left) is characterized by persistent strong winds. Local rise at different locations within the lagoon (see legend) are shown. Note that if the wind effects are removed from the model (insets), all local setups collapse onto the static rise within a few hours.

level according to *Pirazzoli and Umgiesser* [2003, 2006] (dashed line) and the results of our simulations (solid line). In each case the closure of the mobile barriers corresponds to the minimum tidal level preceding the critical event as assumed by *Pirazzoli and Umgiesser* [2003]. For the February 1951 event (Figure 4, top) mean sea level is increased by 60 rather than 50 cm, as in the work by *Pirazzoli* [2002], to account for the relevant subsidence rates. During the 58-h closure period, an overall rise rate of ~0.5 cm/h has been estimated. It should be noted that hydrological contributions to lagoonal rise are smaller than those due to the run-through discharge bypassing the mobile gates. The extreme high tide of November 1966 (Figure 4, middle) represents the worst recorded flood occurred in Venice, with an estimated return period larger than 100 years. In the worst-case scenario a closure of about 60 h would be needed. According to *Pirazzoli and Umgiesser* [2003], a lagoon rise of 18 cm would follow while accounting for detailed space-time rainfall distributions and runoff production a total contribution of ~13 cm is obtained. The notable performance of the rough hydrologic model, in this case overestimating only by a factor of 2 the value resulting from detailed simulation, is due to the much larger resulting closure time than the hydrologic lead time for most subcatchments. This is not the case in general. Figure 4 (bottom) shows the event of December 1981 where the high tide was induced by the superposition of wind waves from the southeast (scirocco) and northeast (bora). The overall effect, estimated at 1 cm/h by *Pirazzoli and Umgiesser* [2003], is confined by the mathematical model to a mere 0.05 *cm*/*h* freshwater discharge rate. Suffice here to notice that recent significant interventions have changed appreciably the hydrology of the contributing mainland with respect to the conditions of the recorded events (e.g., the hydrological contribution from the Sile river was increased by the construction of a floodway in Trezze, and a major system of diversions has been since completed to improve hydraulic protection of the city of Mestre), and this further complicates reliance on first-order models that ignore mainland hydrology.

[22] Our evaluations suggest that none of the selected events would actually have flooded the city. Local setups at different lagoonal locations for selected events may be significant (Figure 5), but not in the neighborhood of the city for long enough time spans. Especially if the closure event is characterized by short durations and is sustained by strong winds, the order of magnitude of the local setups in unfavored locations may be comparable with (or exceed) the average rise. If strong winds persist (and the closure time is particularly short) local wave setups at northern or southern boundaries may exceed persistently the static rise (e.g., Figure 5, bottom left). It is significant to note, however, that if one removes the wind from the numerical calculation, all three examples in Figure 5 (see insets therein) would produce the alignment of the rise anywhere on the static rise within few hours at most. Note also that the geographic location of the city of Venice within its lagoon prevents exposure to extreme wind setups. Thus the assumption of building a statistics of mean hydrologic rises unaffected by wind setup makes sense.

[23] We have extended our analysis by simulating a complete 6 year period (1999–2005) under the +50 cm RSL rise scenario with the foreseen MOSE operations. The meteorological time series identifies about one hundred events exceeding the critical level threshold (+110 cm above Punta della Salute). The closure periods vary in the

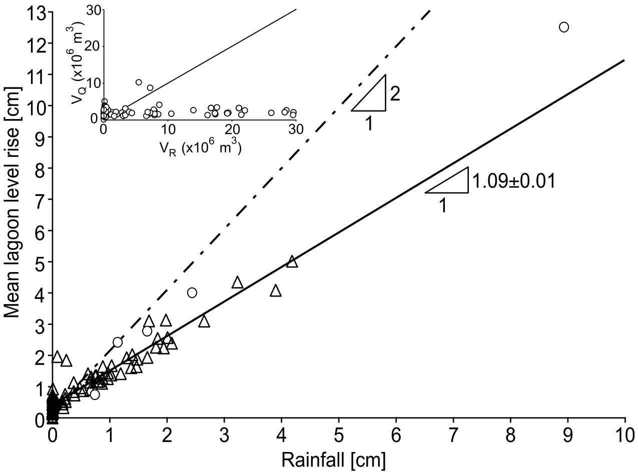

Figure 6. Experimental relation between mean precipitation directly falling above the lagoon and mean lagoonal level rise. Solid line interpolates experimental points relative to the observation period (2000–2005). Dash-dotted line reproduces the model results of *Pirazzoli and Umgiesser* [2003]. Circles indicate the historic events studied by Pirazzoli and Umgiesser and in the present paper. Triangles indicate closure events simulated during 2000–2006 subject to +50 cm RSL rise.

range 12–45 h. The hypothesis that the mean lagoonal rise due to freshwater income doubles precipitation falling directly above lagoonal surface [*Pirazzoli and Umgiesser*, 2003] can thus be tested on a larger database. Figure 6 shows that a linear relation approximates modeling results, whose slope is roughly half of that assumed by *Pirazzoli and Umgiesser* [2003, 2006]. Note that the linear character is granted chiefly by the run-through fluxes which normally exceed runoff. The inset shows the unreliability of the general correlation of total runoff volumes and rainfall within the lagoon integrated over the closure time. For low flows, moreover, base flow of the drainage network plays a major role and the proposed correlation loses any meaning (Figure 6). Our results suggest that the design of closure systems does not prove obsolete because of hydrologic reasons under the constraining scenario of +50 cm of RLS rise proposed up to the year 2100.

[24] One is also interested in the probability distribution of the duration of flooding events at different elevations, which would allow quantitative risk and damage analyses. A few further assumptions are in order to model more realistically gate operations. We shall assume that at the beginning of the closure period the inner levels correspond to those at the mouth of Lido where observations allow the alarm to be issued. This clearly leads to overestimates of the computed rates of water level rise, as alarms are issued in ascending phases and inner levels are inevitably lower. One further needs to define the rules adopted for gate operations [e.g., *Eprim et al.*, 2005]. Actual closure criteria foresee different rules depending on the intensity of the predicted surge, rainfall and wind speed, all generated from meteorological forecast and empirical correlations from nowcasting [*Consorzio Venezia Nuova*, 2005; see also *Vieira et al.*, 1993; *Eprim et al.*, 2005; *Massalin et al.*, 2007], and these, and their errors, are of no concern here. Events are classified into two classes. Class 2 events are the most intense, referring to storm surge elevations in excess of +150 cm amsl or projected closures longer than 11 h (corresponding, in current conditions, to return periods T_r larger than 10 years). For class 2 events closure starts at +65 cm amsl, which is then taken as the initial condition for the model. Class 1 events are less extreme, and are subdivided into class 1A (closure shorter than 11 h, negligible forecasts for rainfall, wind smaller than 10 m/s lead to closure at +100 cm amsl) and class 1B (closure shorter than 11 h, negligible wind velocity, intensity >1 mm/h of direct rainfall forecasts and sizable recorded rainfall over the mainland during the day preceding closure, leading to closure at +90 cm amsl). These operational rules can be summarized as: class 1 events (surge events <150 cm amsl, closure at +90 cm amsl shorter than 11 h) and class 2 events (surge events ≥150 cm amsl, closure at +65 cm amsl longer than 11 h).

[25] Intense rainfall events occurring over the mainland and storm surges in the Adriatic are not uncorrelated [e.g., *Pirazzoli and Tomasin*, 2002]. Correlated conditions prevent the use of unconditional distributions. Thus one cannot simply establish the probability of runoff volumes integrated for arbitrary times, say by analyzing arbitrarily long (generated or observed) time series of hydrologic runoff. Probability of closure times would then directly yield the comparative value for the probability of maximum inner elevation and duration of the relative levels. To bypass this problem, we have chosen to use directly hydrologic data sets related to recorded events, and summarized by projected RSL rises. Gate closures are thus operated on the basis of observed tidal levels rather than on predicted ones. This is tantamount to assuming "perfect" tidal level forecasts in actual operations so that the possible effects of forecasting errors are not considered. These effects have been studied elsewhere [e.g., *Cecconi et al.*, 1998] leading to error bounds on the closure periods and on statistics of false alarms that helped shape the actual operational rules.

[26] The entire time series of sea levels (at the Lido inlet) and inner lagoon elevations (at Punta della Salute), consists of hourly values in the period (1924–2007) (properly corrected for relative sea level changes and subsidence [e.g., *Cecconi et al.*, 1998]). For a subset of 8 years (2000–2007), detailed precipitation records within 21 stations over the mainland and runoff measurements at 18 stations were available (Figure 1). We assume that the frequency of 8 years of recorded events subject to a +50 cm RSL rise is sufficient to broadly characterize the population of possible closure events.

[27] Climate change scenarios are assumed to be recapitulated by a RSL change. Indeed it seems that projecting over the lifetime of civil and mechanical engineering works (of the order of 100 years) hardly justifies further assumptions on the nature of rainfall changes in this area [e.g., *Giorgi et al.*, 2001]. Thus 2100 scenarios, with their baggage of uncertainty [*Pal et al.*, 2004; *Piani et al.*, 2007], are assumed to be tackled by a range of +30 and +50 cm of relative sea level (RSL) rise, to be compared with current (+0) conditions. Thus simply adding the RSL change to the sea level time series is assumed to provide significant climate change scenarios. Figure 7 shows the

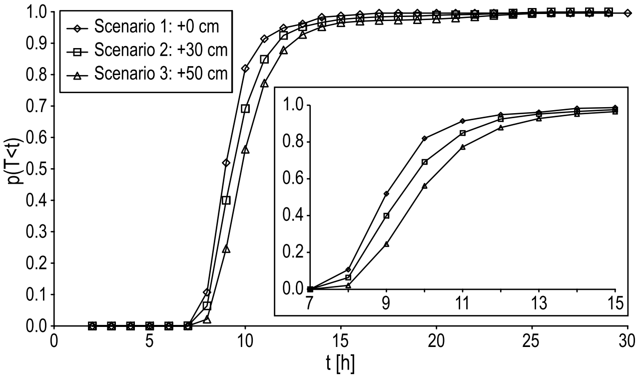

Figure 7. Cumulative distribution function of closure durations directly derived from the given operational rules and the 1924–2007 hourly tidal level database. RSL scenarios considered are (1) current (+0), (2) +30 cm amsl, and (3) +50 cm amsl. Inset shows the enlargement of the range 7–15 h, which suggests that the RSL increase does not appreciably affect closures of duration larger than 12–13 hours but rather modifies the distribution of closures in the range 8–11 h.

cumulative distributions of the duration of all closures resulting from the analysis of the Lido and Punta della Salute tidal levels under the above closure rules for +0, +30 and +50 RSL rise scenarios. One notes, in particular, the longer tails for the distributions leading to nonnull frequencies of durations of the order of 20 h for the +50 scenarios. Though statistical figures may slightly change through refined sampling intervals for water levels (that is, smaller than 1 h), it is significant that the mean closure time would not radically change in the face of +50 cm sea level rise although the number of closures would increase almost exponentially. This is due to the oscillatory nature of the sea surges. Because the aim of this work is confined to provide statistical estimates of lagoonal rises in times of closure (and not, say, of constraints in the usage of navigation locks or the ecological effects of the induced closures), our assumptions seem justified.

[28] We are thus in the condition to simulate the lagoon rise in times of closure for the period 2000–2007 for which all meteorological and hydrologic boundary conditions are available for running the hydrologic model and for evaluating properly the direct rainfall contribution over the lagoonal surface. The results of our simulations are shown in Figures 8 and 9.

[29] Figure 8 illustrates the frequencies of the maximum elevations reached within the lagoon in times of closure (expressed in cm amsl) computed for the given rules under three different RSL scenarios (current, +30 and +50). The resulting distributions are rather complex owing to the strong nonlinear character of the operating rules for closure. A counterintuitive result is the fact that in some cases class 2 events (closing at +65) lead to small rises, and only for increased RSL. Thus the RSL rise-induced distributions of peak elevations are broader than in current conditions. The bulk of the distributions is centered for events of class 1 (i.e., in the range 90–95 cm amsl). A significant result is that even in the +50 cm RSL change no event would reach elevations larger than +105 cm amsl This is a result of practical importance because the threshold of +110 cm amsl is perceived as a vital goal of local defences through reclamation and local damming.

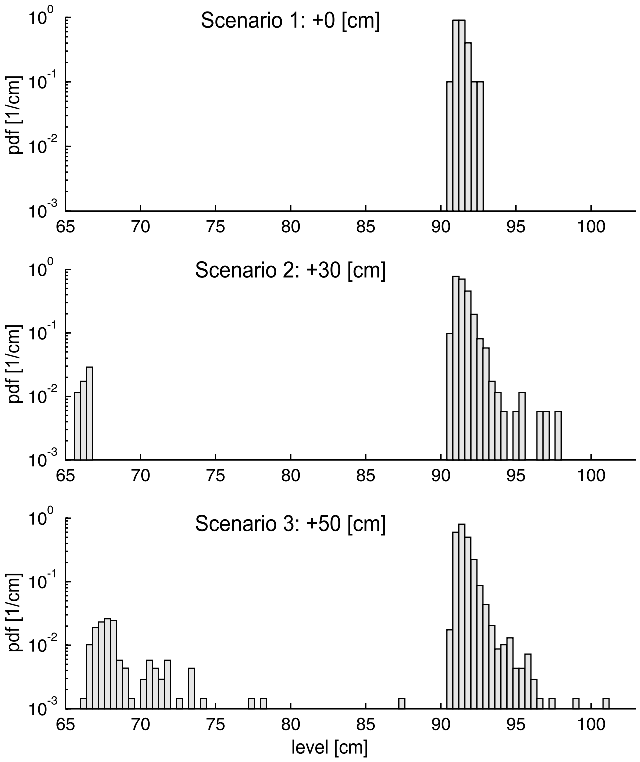

Figure 8. Frequencies (pdf) of the maximum levels reached within the lagoon in times of gate closure for the meteorological and hydrological conditions observed in the period 2000–2007 under three different RSL rise scenarios (+0, +30, and +50 cm).

[30] Figure 9 shows (deliberately in dimensional units, rather than normalized) the computed number of hours per year for which, in times of closure, the lagoon lies at elevations $\geq h$ for the simulated period (2000–2007). The graph approximates the probability of crossovers for the

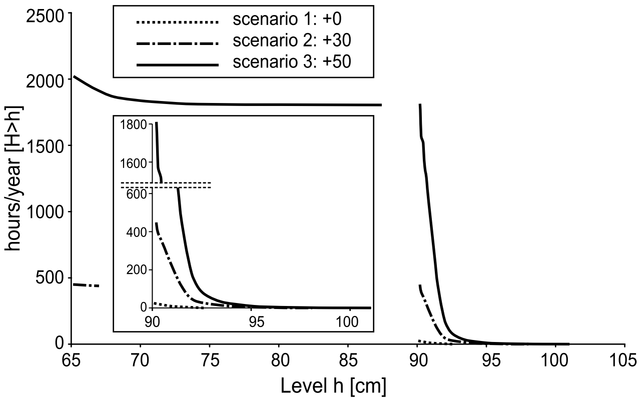

Figure 9. Number of hours per year of closure in which the lagoonal elevation remains at values larger or equal than h (cm amsl) for the period 2000–2007. The graph, normalized by the total number of closure hours per year, approximates the distribution function for crossovers at the threshold h.

threshold elevation *h*. The tail of the distributions suggests that under gate operations elevations larger than +105 cm amsl would never be reached even under +50 cm RSL changes. It is remarkable, however, that no class 2 event would have occurred in current (+0) conditions. Also remarkable is the fact that the +50 cm projection of the 2000–2007 time series would never yield elevations larger than +105 cm amsl (i.e., 0 h above it in Figure 9). The threshold character of the operational rules for closure is responsible for the complexity of the plot. Because class 2 operations, closing at +65 cm amsl, produce maximal rises until +87 cm (that is, no +65cm closure reaches +89 cm amsl) and +90 closures are responsible for the right tail of the plot, the discontinuity in the lines simply suggests that roughly from +75 to +90 cm amsl we have approximately the same number of hours of exceeded elevations per year.

4. Conclusions

[31] The following main conclusions are worth emphasizing.

[32] 1. Detailed hydrologic and hydrodynamic models of the tributary watershed and the Venice lagoon has been set up and validated through large hydrologic, hydrodynamic and meteorological observational databases. The hydrologic model predicts overall freshwater runoff in general conditions with global errors well below common standards, and lends itself to applications for predicting runoff volumes in times of lagoon closures. Such closures, designed to protect the city of Venice from flooding by interrupting temporarily sea-lagoon exchanges in times of sea storm surges, are operated under a certain class of rules that foresees closure at +65 or +90 cm amsl depending on forecasted intensity and duration of the surges.

[33] 2. By using the available observational database of tidal and meteorological observations (2000–2007), we have simulated gate operations in current conditions, and through a +30 and +50 cm RSL rises. Actual freshwater runoff volumes have been evaluated by accounting for actual closure times and for the individual hydrologic response of each outlet tributary to the lagoon. Rainfall patterns in space and time, whether directly falling onto the lagoon surface or on the mainland, have been suitably interpolated through 21 rain gauges scattered within the domain. Frequencies of maximum elevations in times of closure, and number of hours of closure in which lagoonal elevations remained at (or above) a given elevation have been computed. We suggest that in case of prolonged closures, or in the absence of significant winds, the static rise due to external waters is adequate to characterize the system anywhere, whereas it is always accurate to reproduce the average conditions in Venice whose geographic location prevents major persisting wind setups.

[34] 3. The hypothesis of exchanging precipitation volumes falling directly on the lagoonal surface with net mainland runoff (in times of closure) does not describe properly the behavior of the system. Neglecting the effects of variable lead times of the hydrologic response may yield reasonable (though conceptually inconsistent) results only if closure times were invariably much larger than the lead time of runoff. The ratio of the lagoonal to the watershed surfaces would then act simply as some average runoff coefficient. This does not hold in current conditions where typical lead times are in the range 10–30 h whereas closures would typically last 11 h plus operational times. Moreover, the size, elongated shape and climatic features of the Venice lagoon prevent total rainfall volumes from being correctly estimated unless proper geostatistical tools are employed (see Figure 1 and *Marani et al.* [2004b]).

[35] 4. Claims of obsolescence of the planned system for flooding protection from freshwater runoff and throughflows for selected observed events, under +50 cm RSL rise, are not confirmed. The scope of the storm barrier, to protect the city of Venice from flooding, would be met should the gates operate as planned.

[36] 5. Probability distributions of the duration of flooding events at different elevations, speculated to be of interest for risk and damage analysis, have been derived and discussed. The frequencies of the maximum elevation reached within the lagoon in times of closure have also been computed. Of particular interest is the result that, under gate operations, lagoon levels larger than +105 cm amsl are never reached for the hourly simulation of the period 2000–2007 subject to a +50 cm RSL rise.

[37] Overall, our exercise suggests the suitability of the general operating rules of a storm barrier for the lagoon of Venice with respect to hydrologic flooding, even for projected RSL rises on time scales comparable with the lifetime of the closure works under construction.

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