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On the drainage density of tidal networks

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[1] The drainage density of a network is conventionally defined as (proportional to) the ratio of its total channelized length divided by the watershed area, and in practice, it is defined by the statistical distribution and correlation structure of the lengths of unchanneled pathways. In tidal networks this requires the definition of suitable drainage directions defined by hydrodynamic (as opposed to topographic) gradients. In this paper we refine theoretically and observationally previous analyses on the drainage density of tidal networks developed within tidal marshes. The issue is quite relevant for predictions of the morphological evolution of lagoons and coastal wetlands, especially if undergoing rapid changes owing, say, to combined effects of subsidence and sea level rise. We analyze 136 watersheds within 20 salt marshes from the northern lagoon of Venice using accurate aerial photographs and field surveys taken in different years in order to study both their space and time variability. Remarkably, the tidal landforms studied show quite different physical and ecological characteristics. We find a clear tendency to develop characteristic watersheds described by exponential decays of the probability distributions of unchanneled lengths, and thereby a pointed absence of scale-free distributions which instead usually characterize fluvial settings. We further find that total channel length relates well to watershed area rather than to tidal prism, a somewhat counterintuitive result on the basis of dynamical considerations. Finally, we show that in spite of the apparent site-specific features of morphological variability, conventional measures of drainage density appear to be quite constant in space and time, indicating a similarity of form. We show that such similarity is an artifact of the Hortonian measure. Indeed, important morphological differences, most notably in stream (or link) frequency reflecting the true extent of branching innervating the marshes and the sinuosity of tidal meandering, may only be captured by introducing measures of the extent of unchanneled flow paths based on hydrodynamics rather than topography and geometry. *INDEX TERMS:* 1824 Hydrology: Geomorphology (1625); 1890 Hydrology: Wetlands; 1848 Hydrology: Networks; 1815 Hydrology: Erosion and sedimentation; *KEYWORDS:* four tidal networks, geomorphology, drainage density

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1. Introduction

[2] Recently various tidal network properties have been explored through an extension of the treatment of digital terrain maps (DTMs) to cases where drainage directions are determined by local hydrodynamics rather than by topography [*Rinaldo et al.*, 1999a, 1999b; *Fagherazzi et al.*, 1999] and through the analysis of their planar geometry [*Marani et al.*, 2002]. DTM archives and accurate aerial surveys provide substantial data that have much refined our understanding from an existing large literature describing the morphology and dynamics of channel networks which develop across the tidal basin controlling the hydrodynamics and sediment exchanges between salt marshes and tidal flats [e.g., *Myrick and Leopold*, 1963; *Pestrong*, 1965; *Boon*, 1975; *Pethick*, 1980; *Boon and Byrne*, 1981; *Leopold et al.*, 1993; *Steel and Pye*, 1997; *Friedrichs and Perry*, 2001].

[3] In order to perform morphometric analyses of tidal networks one needs an objective procedure for delineating the drainage area to any link or to any cross section of a channel. A new method, based on flow hydrodynamics, for delineating drainage directions and contributing areas throughout the tidal network was proposed by *Rinaldo et al.* [1999a]. The method basically simplifies the (2D) shallow water equations to a Poisson boundary value problem solving for the field of free surface elevations and deduces drainage directions from the related gradients. The method, applied to three tidal environments and several of the embedded watersheds (quite different in their tidal, geologic, vegetational and hydrodynamic characteristics), revealed interesting geomorphic features [*Rinaldo et al.*, 1999a], including a comparison of scaling relationships in measures of tidal landforms with analogous ones found in the fluvial system [e.g., *Rodrìguez-Iturbe and Rinaldo*, 1997]. We notice that instead of finding scale invariance features of the type clearly prevailing in fluvial systems, a nearly complete lack of

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scaling features in all tidal systems analyzed was revealed. To investigate the generality of such a result, in this paper we first examine the structure and the validity of the assumptions built in the Poissonian hydrodynamic model, and relax them selectively (upon comparison with a fully equipped finite element model of the complete equations) to probe its limits owing to a fair assessment of possible artifacts of the schemes adopted.

[4] We then turn to the analysis of drainage density through proper definitions. According to *Horton*'s [1945] basic definition, drainage density is defined dimensionally as the inverse of a length, i.e., the ratio of the network total length to its watershed area: $D = \Sigma L/A$. On assuming uniformly distributed lengths of unchanneled paths and a simplified geometry of the basin (i.e., a rectangular basin with a single channel in the middle), then drainage density would be one fourth the inverse of the average length of unchanneled pathways. The Poissonian model discussed above and its modified versions, however, define locally drainage direction through free surface gradients in analogy to what happens in fluvial settings where topographic gradients drive the drainage. Thus unchanneled drainage lengths can be defined unambiguously for any marsh site, though in a steady state model characterizing only the average features of the tidal system. It has been recently proposed, in the context of the geomorphology of river basins [*Tucker et al.*, 2001], that the unchanneled length required to first access the drainage network is a random space function, thus characterized by its mean but also by its variance and progressive moments and, notably, by its spatial correlation structure. In this paper we study for the first time the distributions of unchanneled lengths in a tidal environment.

[5] The above results, taken as a whole, bear significant morphodynamic implications. In fact, coastal wetlands exist in a state resulting from the interaction of strong counteracting forces acting both in the horizontal and the vertical planes, leading either to their establishment and maintenance or to their rapid deterioration [e.g., *Day et al.*, 1999]. Chief landforming processes in the vertical plane are the combined actions of compaction, subsidence and sea level rise possibly compensated by accretion processes. The resulting balance is complex and affected by many factors of physical, chemical and biological nature. Accretion rates are possibly offset by the rates of sea level rise [*Day et al.*, 1999], but often self-tuned in nature to balance it and thus leading to the survival of the tidal landforms for long periods of time [*Redfield*, 1972; *Orson et al.*, 1987]. In the horizontal plane, the development of drainage patterns on tidal marshes controls the hydrodynamics and sediment exchanges between saltmarshes and tidal flats and, in general, within the entire coastal wetland [e.g., *Pestrong*, 1965; *Boon*, 1975; *Pethick*, 1980; *Boon and Byrne*, 1981; *Steel and Pye*, 1997; *Rinaldo et al.*, 1999a, 1999b]. The importance of the careful observation of drainage density, and thus of planar patterns of tidal wetlands and of the embedded landforms, objectively observed and manipulated, is thus hardly overestimated. Implications on the origin and long-term evolution of the complex of morphological structures which characterize tidal environments, such as lagoons, deltas or estuaries are noteworthy and justify a careful screening of the type proposed herein.

[6] The analysis of the planar structure of channel marsh and tidal flats has recently allowed an assessment of comparative analyses of tidal and fluvial network morphologies, including watershed delineation, scaling features (or lack of them thereof), and geomorphic relationships with landscape-forming flowrates [*Fagherazzi et al.*, 1999; *Rinaldo et al.*, 1999a, 1999b]. It became apparent, however, that several features of the tidal channels, chiefly the width and the curvature of the axis, show strong variations in space unusual (or unheard of) in fluvial morphology, even over length scales of hundreds to thousands of widths [*Marani et al.*, 2002]. Interestingly, the spatial scale of persistence of geomorphic features is often limited to a few tens of meters. In any real case of fluvial versus tidal patterns, differences are the norm rather than the exception once carefully examined.

[7] The observations of the geometry of tidal networks on which the present work is based are obtained from the digitalization of aerial photographs and regard tidal environments with different morphological and tidal characteristics. For in-depth descriptions of the environments considered and of the processing tools on aerial photographs and on digital terrain maps see *Fagherazzi et al.* [1999].

[8] This paper is organized as follows: an introductory section describes the study area, chiefly to clarify scopes through images. The two following sections then discuss the validity of the assumptions embedded in the Poissonian models by relaxing them progressively, up to a complete comparison with a finite element model of the complete equations within a much larger area to avoid assumptions on boundary conditions. Section 4 then uses the models introduced and their results for a detailed description of the drainage densities of a part of the northern lagoon of Venice (Italy), where large variability is detected. A set of conclusions closes the paper.

2. Study Area

[9] The lagoon of Venice (see Figure 1) has an area of roughly 550 km^2 and is characterized by a semidiurnal tidal regime with a range of about ±0.7 m. Two narrow land strips about 0.5 km wide separate the tidal basin from the sea, while communication and active exchange is granted by three inlets whose widths range from 400 m to 800 m. Great concerns remain on the fate of the residual landforms of the lagoon, which motivate the present morphological studies.

[10] Figure 2 shows aerial photographs of two salt marshes (among the 20 isolated within the Pagliaga and S. Felice sites shown in Figure 1) in the northern part of the Venice lagoon together with their channel networks. The extraction was performed on suitably processed and contrasted aerial photographs with a spatial resolution of about 0.8 *m* which constitute the basis for most of the analyses described below. Field surveys were extensively employed to verify remotely sensed data and topographic data, particularly salt marsh elevation data, complete the description of the tidal system.

[11] The study sites were chosen to sample systems with different characteristics. S. Felice salt marsh is very close to the Lido inlet and hosts exclusively halophytic vegetation,

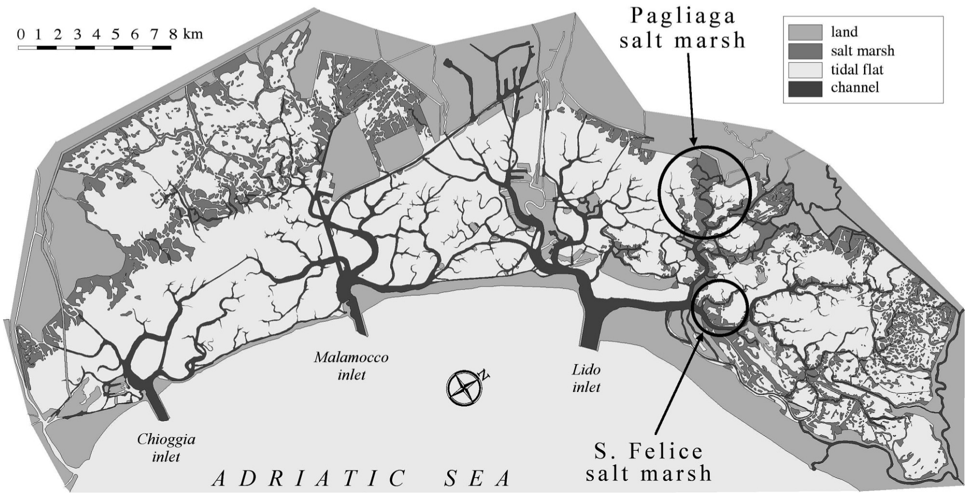

Figure 1. Map of the Lagoon of Venice. The circled areas indicate the locations of the study sites.

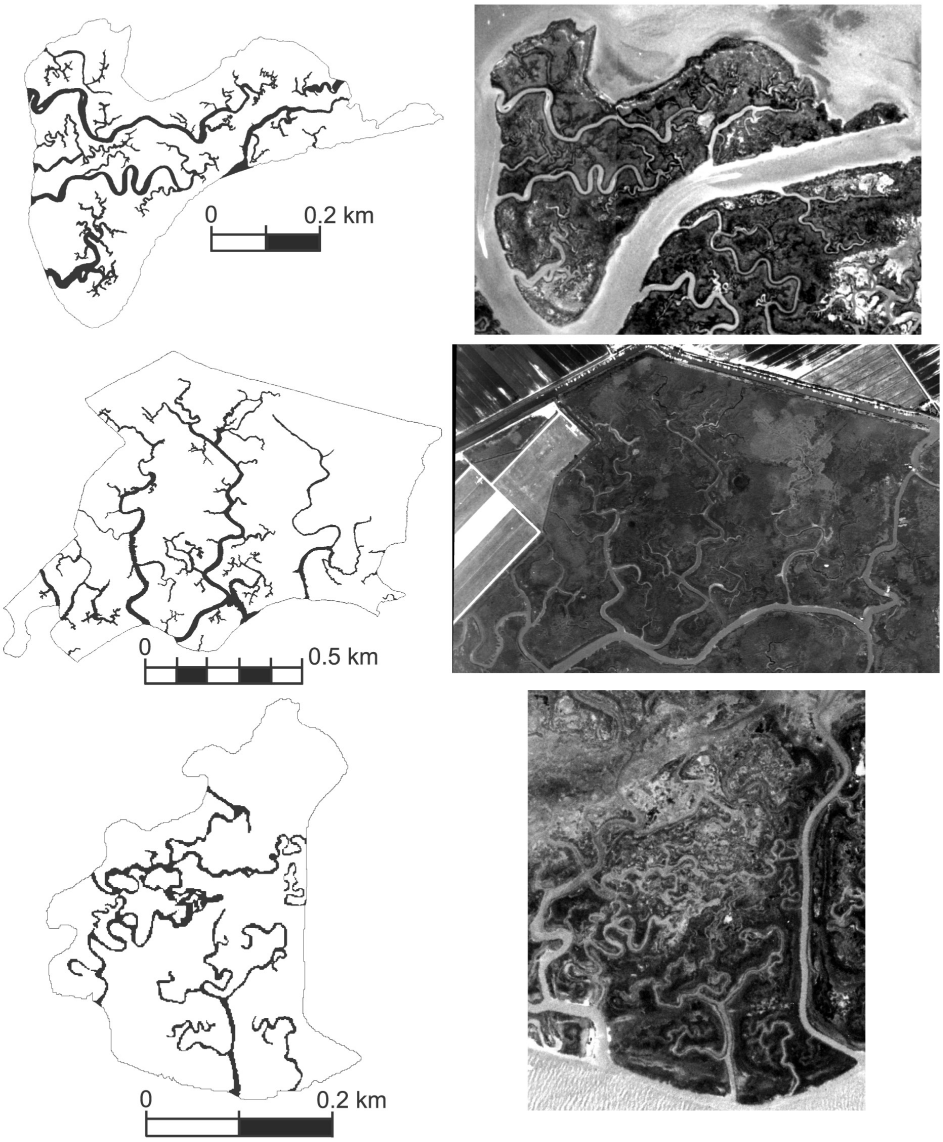

Figure 2. Three sample aerial photographs and channel network extractions from the salt marshes of the Venice lagoon considered. It should be noted that the total number of 20 marshes investigated allowed extraction of 136 tidal channel patterns.

mainly constituted by *Spartina maritima, Salicornia veneta* and *Sarcocornia fruticosa* [*Silvestri*, 2000]. Its elevation ranges from about 0.0 m a.m.s.l. to 0.34 m a.m.s.l. [*Belluco*, 2001] and its area slightly increased in the past 30 years (from 522,000 m^2 in 1968 to 546,000 m^2 in 1998 [*Belluco*, 2001]). Pagliaga salt marsh is located near the boundary of the tidal basin where flow resistance considerably reduces the amplitude of normal modes of tidal oscillation. Pagliaga hosts wide areas of *Fragmithes australis*, a glycophytic species, and the halophytic species *Juncus maritimum, Halimione portulacoides* and *Puccinellia maritima* [*Silvestri*, 2000]. Its elevation ranges from 0.10 m a.m.s.l. to 0.45 m a.m.s.l. [*Belluco*, 2001] and its total area has remained quite constant in the past 10 years, while the total length of its channel network has decreased (from 39500 m in 1987 to 32800 m in 1996 [*Belluco*, 2001]). Soil texture and mechanics varies considerably from one site to the other, also in view of the strong gradients of mean sediment size documented along the general direction from the outlet to the tidal boundary [*Barillari*, 1978].

[12] The images and the extracted data well exemplify the variability observed in salt marsh morphology. Network characteristics (Figure 2) seem in fact to vary not only from one salt marsh to another (e.g., from Pagliaga to S. Felice) but also within the same salt marsh and within distances of a few hundred meters. Some interesting geomorphological questions then arise. One important issue, which constitutes the main motivation of the paper, is the quantitative characterization of the degree of diversity of the observed landforms, and the related investigation of their variability, in order to establish whether this is to be ascribed to natural fluctuations around a general tendency or rather to the result of space-varying physical properties and geomorphic processes; or else to measuring artifacts. As it turns out, traditional measures fail to capture important differences and thus to these questions we try to provide an assessment in what follows.

[13] Regarding possible historical changes in the characters of the marshes studied, we have analyzed landforms in time (from 1968 to 1998, see section 4.) observing little variation. How can this fact, seemingly suggesting that the landforms are nearly equilibrated to forcing factors, be reconciled with the documented reduction of lagoonal marsh areas from 149 km^2 in 1912 [*Cucchini*, 1928] to 91 km^2 in 1939 [*Pancini*, 1939] to just 47 km^2 in 1997 [*Silvestri*, 1997]? First, it must be observed that the areal reduction has not been uniform within the lagoon - the marshes in the central and southern lagoon disappeared at a much faster rate owing to their exposure to stronger anthropic, wave and tidal current actions, facing an impoverished production of sediments largely due to huge freshwater diversions (fourteenth to eighteenth centuries). Indeed actual overall sediment volume budgets estimate a deficit of at least half a million cubic meters per year [e.g., *Silvestri*, 1997]. Second, in the northern lagoon (where our field sites are located), the assumption of treating observational landforms as point-samples equilibrated to forcing factors makes sense. In fact, tidal salt marshes have the potential of responding very rapidly to changes in forcing [*Allen*, 1997; *Friedrichs and Perry*, 2001] and this seems the case at hand [*Day et al.*, 1999]. Thus their form and function represent a short-term dynamic balance between relative sea level, sediment supply and vegetation growth. We thus assume that morphologically the tidal marshes and flats studied are generally near (or progressing toward) dynamic equilibrium (as somewhat improperly we term a near-steady state), rather than far out of equilibrium on a slow evolution toward geologic maturity [*Friedrichs and Perry*, 2001].

3. Watershed Delineation in Tidal Basins Revisited

[14] Watershed delineation in tidal basins is a difficult task, owing to the unsteady character of the flow field induced by tidal currents. Indeed drainage directions, defined by the steepest descent of the water surface topography, vary both in space and in time, thus in principle preventing a unique definition of the divides characterizing a tidal network. This problem has been bypassed by the procedure for the delineation of time-independent watershed areas in tidal environments proposed by *Rinaldo et al.* [1999b]. Time-independent watersheds are delineated on the basis of the water surface topography obtained by suitably simplifying the classic two-dimensional shallow water equations of momentum and continuity. In particular, by assuming that tidal propagation across the intertidal areas (i.e., tidal flats and/or salt marshes) flanking the tidal channels is frictionally dominated and that, at any instant t, the local water surface elevation, say $\eta_1(\mathbf{x}, t)$, above the instantaneous average tidal elevation $\eta_0(t)$ on the shallow flats is relatively small, *Rinaldo et al.* [1999b] used dimensional analysis to show that, for a nearly horizontal bottom topography, the free surface can be described by the following (dimensional, opposed to the corresponding dimensionless form employed by *Rinaldo et al.* [1999a]) Poisson boundary value problem:

$$\nabla^2 \eta_1 = \frac{\lambda}{(\eta_0 - z_b)^2} \frac{\partial \eta_0}{\partial t} \tag{1}$$

where z_b is the average bottom elevation of the intertidal regions, and

$$\lambda = \frac{8}{3\pi} \frac{U_0}{C^2} \tag{2}$$

with C is Chèzy's friction coefficient, and U_0 a characteristic value of the maximum tidal current, taken to be constant within the intertidal regions considered. Boundary conditions are null elevations on the propagating channels and no-flux conditions at the other boundaries.

[15] It is worthwhile recalling that equation (1) strictly holds provided that $\eta_1 \ll \eta_0$, that is, the water depth over the intertidal areas is large enough and the tidal embayment is relatively short so as to ensure a relatively fast propagation and a weak deformation of the tidal wave.

[16] In order to derive time-independent solutions, *Rinaldo et al.* [1999b] further simplified the problem by assuming that, at each instant, the water level in the tidal channel network bordering the intertidal areas is spatially independent and equal to $\eta_0(t)$, that is $\eta_1 = 0$. This assumption allows to assume a constant value of the forcing term on the right-hand side of equation (1) estimated using representative values of η_0 and $\partial\eta_0/\partial t$. As a consequence

the Poisson equation (1), subject to the no-flux condition $\partial\eta_1/\partial n = 0$ on the boundary with the mainland and to the condition $\eta_1 = 0$ on the creek network (which embodies the hypothesis that the propagation of the tidal wave is much faster through the channel network than on the salt marshes) allows the determination of a spatial distribution of representative water levels. On the basis of the distribution of water depths flow directions can be obtained at any location on the salt marsh, by determining the steepest-descent direction, and the divides related to any channel cross section may be identified.

[17] It should be noted that, given the hypotheses underlying the procedure, the divides tend to be equidistant from the channel axes, independently from channel width and depth. This result appears rather surprising since the tidal wave propagates faster through larger (and deeper) channels and they thus influence larger portions of the surrounding shallow flats than smaller channels do. We thus propose herein a stringent test of limits and validity of the approximations embedded in the model of *Rinaldo et al.* [1999a].

[18] In order to more closely describe the behavior of the system we relax in the following the hypothesis that the tidal wave instantaneously propagates within the channel network and assume that tidal elevation varies in space and in time according to the solution of one-dimensional shallow water equations provided by *Dronkers* [1964] under the hypotheses: (1) spatial and temporal gradients of channel width w are negligible in the momentum equation; (2) flow velocities are smaller than the mean celerity of propagation of the tidal wave; (3) tidal excursions are relatively small compared to channel depth; (4) the energy losses can be linearized in the manner proposed by Lorentz [*Lorentz*, 1926; *Zimmermann*, 1982]; (5) the tidal wave is not reflected at the inner end of a given channel where it dissipates completely. The resulting relationship is [*Rinaldo et al.*, 1999b]

$$\eta(x,t) = \sum_{i=1}^{m} a_i(\omega_i)\exp\left(-\frac{\omega_i\sigma_i x}{c_0}\right)\cos\omega_i\left(t - \frac{\beta_i}{c_0}x\right) \qquad (3)$$

$$\sigma_i = \sqrt{-\frac{1}{2}+\frac{1}{2}\sqrt{1+\frac{\Lambda^2}{\omega_i^2}}}, \qquad \beta_i = \sqrt{\frac{1}{2}+\frac{1}{2}\sqrt{1+\frac{\Lambda^2}{\omega_i^2}}} \qquad (4)$$

where x is the intrinsic coordinate along channel axis; ω_i ($=2\pi/T_i$) and a_i are, respectively, the frequency and the amplitude of the ith component of the tide; $\Lambda = \lambda g/D_0$, D_0 is the mean channel depth, and g the gravitational constant; σ_i and β_i are dimensionless coefficients which account for the damping and the phase lag experienced by the ith component of the tidal wave as it propagates along the channels, and c_0/β_i is the mean frictionless celerity of propagation of the tidal wave corrected to account for the storage effect associated to intertidal regions. In particular, $c_0 = \sqrt{(gD_0)w/B}$, where B is the total width of the main channel and of the lateral flats computed with reference to the channel axis. Note that the friction coefficient λ, though formally equivalent to the one appearing on the right-hand side of equation (1), is numerically different, owing to the different values typically attained by C and U_0 in the channels.

[19] Mathematically the new problem reduces to the solution, at a given instant t of the tidal cycle, of equation (1) by imposing $\partial\eta_1/\partial t = 0$ on impermeable boundaries and $\eta_1 = \eta - \eta_0$ along the channels. Here η is given by equation (3), while $\eta_0 = \langle\eta\rangle$ denotes its average value over the tidal embayment considered. Such a problem must be solved iteratively since, on one hand, tidal propagation within the channels is influenced, through c_0, by the storage of water in the intertidal regions (that is by watershed extension), on the other hand the term on the right-hand side of equation (1) depends on the value attained by η_0 and by its temporal derivative $\partial\eta_0/\partial t$. In particular, the first iteration can be easily carried out by evaluating the distribution of B in the channels, and hence of c_0 and η, on the basis of the divide delineation obtained by assuming an instantaneous tide propagation in the channel network. The watershed distribution estimated by solving the Poisson problem is then used to obtain an improved distribution of η within the channel network to be used as boundary condition in the second iteration. This procedure is repeated until the changes in watershed areas do not exceed a given tolerance. It is thus possible to evaluate watershed extent at various instants during a tidal cycle, provided they are close enough to high water so that the hypothesis that $\eta_1 \ll \eta_0$ is satisfied.

[20] The results of the application of the model to the case of a channel network located in the northern part of the lagoon of Venice are shown in Figures 3, 4, and 5. The values of the friction coefficient λ adopted in the simulation have been estimated by setting $C = 55\ m^{1/2}/s$, $U_0 = 0.7\ m/s$ in the channels, $C = 20\ m^{1/2}/s$, $U_0 = 0.05$ m/s in the intertidal regions. Moreover, D_0 has been evaluated on the basis of the spatial distribution of bottom elevations. A forcing tide with period, amplitude and phase lag typical of spring conditions [see *Rinaldo et al.*, 1999b] has been imposed at the outlet of the tidal embayment analyzed (Lido outlet in Figure 1).

[21] The temporal evolution of the forcing tide elevation in a neighborhood of high water is plotted in Figure 3, where the instants at which watersheds have been calculated are indicated. Figure 4 displays divides and watersheds for a sample of subbasins at the instant $t/T = 0.21$ during ebb. It appears that, in general, the divides do not coincide with the lines equidistant from channel axes, and that they migrate during the tidal cycle thus inducing a time variability of the watersheds. This behavior is clearly shown in Figure 5, which shows the temporal evolution of watershed areas of the tidal subbasins specified in Figure 4, and is consistent with observations and with results from a finite element model [*Defina*, 2000] (which is appropriately described below). The deviations from the values obtained by assuming an instantaneous propagation of the tidal wave in the channel network, represented by straight horizontal lines, do not follow any particular trend, their extent depending on the subbasin considered. Nevertheless, it is important to note that both in the rising and in the falling phases of the tide, when the water level is slightly above the average elevation of the flats, the values of watershed area tend invariably to the solution given by the model of *Rinaldo et al.* [1999b]. This indicates that tidal propagation within the shallow storage zone adjacent to the channels is in this phase essentially governed by the planimetric configuration of the channel network, which

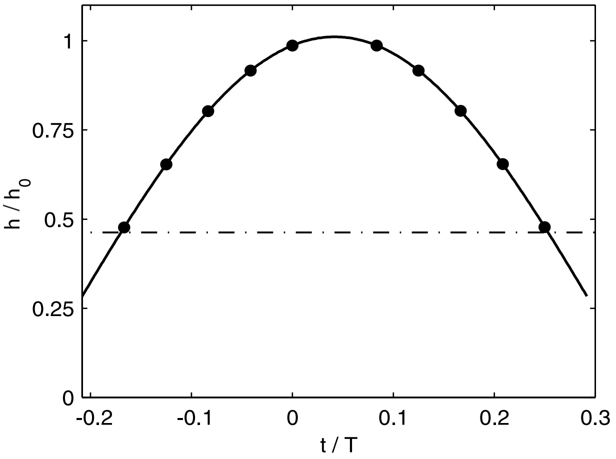

Figure 3. Characteristics of the forcing tide at the outlet section of a tidal embayment in the northern part of the lagoon of Venice (Lido outlet in Figure 1). The water elevation η, scaled with the maximum tidal amplitude a_{max}, is plotted versus time t, scaled by the tidal period T, in a neighborhood of high water.

alone determines the configuration of the watersheds in the infinite-celerity scheme. This is important from a morphological point of view since the maximum flood and ebb discharges occur when levels exceed or are just below the channel bank-full elevation, respectively [*Bayliss-Smith et al.*, 1978; *Healey et al.*, 1981; *French and Stoddart*, 1992]. The above results therefore suggest that the time-invariant watershed delineation proposed by *Rinaldo et al.* [1999a] is indeed suitable to predict peak discharges, which have been shown to be related to watershed and cross-sectional areas [*Rinaldo et al.*, 1999b]. It is also worthwhile to note that, according to the present model, the tendency toward a time-constant value of the watershed areas is enhanced as the flow resistance over the intertidal regions increases, a circumstance which is quite common in the actual system, e.g., due to the presence of dense vegetation.

[22] In order to further test the robustness of our results we have also compared them to those obtained from a full-fledged semi-implicit, Galerkin finite element model [*Defina*, 2000] discretizing the complete shallow water equations over the whole lagoon of Venice and including a refined description of wetting/drying processes. It should be emphasized here that our interest toward a simplified model is justified by the fact that a finite element model could not conceivably be used for the mathematical description of the evolution of a tidal environment over morphologically-meaningful periods of time as, due to the numerical burden involved, the duration of the simulation would basically be the same as the time interval being simulated. Besides, differences with the results of simplified approaches, even in the worst cases, are minor.

[23] Figure 6 shows the comparison between the values of the maximum discharge computed through the time-dependent Poisson model described above and the finite element model for some selected locations in the channel network of the northern lagoon of Venice. It is seen how the two sets of values compare quite favorably with discrepancies of the order of 15%. This leads to the conclusion that maximum discharges obtained through the Poisson models introduced (and it was seen above that the infinite-celerity and finite-celerity Poisson models yield very similar results as far as maximum discharge is concerned) are consistent with those determined through a complete hydrodynamic simulation. This has definite relevance for tidal morphodynamics because it has been shown that maximum discharge, tidal prism and channel area (and width) can be empirically related [e.g., *Rinaldo et al.*, 1999a, 1999b].

4. Tidal Drainage Density

[24] *Tucker et al.* [2001] argued that the proper definition of drainage density, as a measure of the degree of channelization of a given watershed, may be mapped using two scalar fields defining respectively the local hillslope length from any unchanneled site to the channel network and the local hillslope length to the valley network. It is interesting, in this framework, to note that conventional (Hortonian) characteristic path length, i.e., the inverse of drainage density, $\ell_H = D^{-1} = A/\Sigma L$, is exactly four times the inverse of the unchanneled mean path length ℓ in the case of an ideal, rectangular basin with a single straight channel, i.e., $\ell_H = 4\ell$. In more complex, real-world, catchments this one-to-one relationship between drainage density and unchanneled mean path length does not exist as it becomes dependent on the shape of the basin and on the features of the channel network (i.e., its branching and meandering characteristics). We note here that the Hortonian length ℓ_H is a measure of how the catchment is dissected by the channel network, whereas ℓ indicates how efficiently the network "serves" (i.e., drains or feeds in ebb and flood) its catchment determining the mean flow distance from a point on the marsh to the nearest channel.

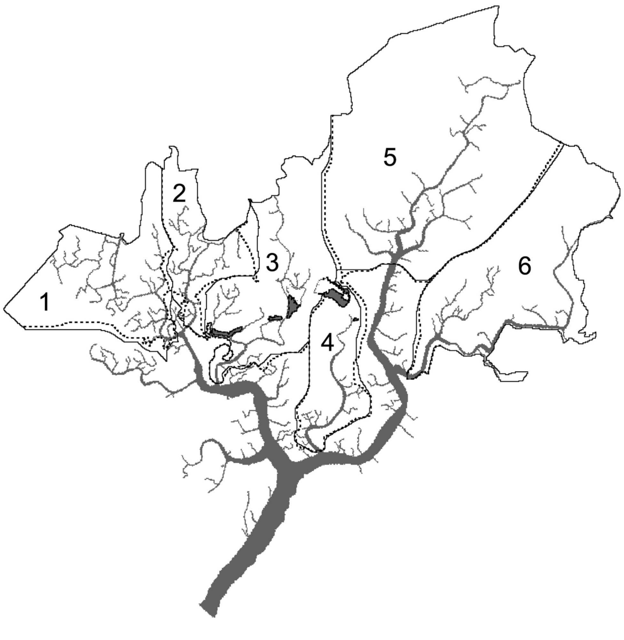

Figure 4. Watershed delineation for a sample of subbasins located in the northern part of the lagoon of Venice obtained for t/T = 0.21 during ebb by assuming instantaneous propagation along the channels (solid line) and by computing a finite celerity value (dotted line).

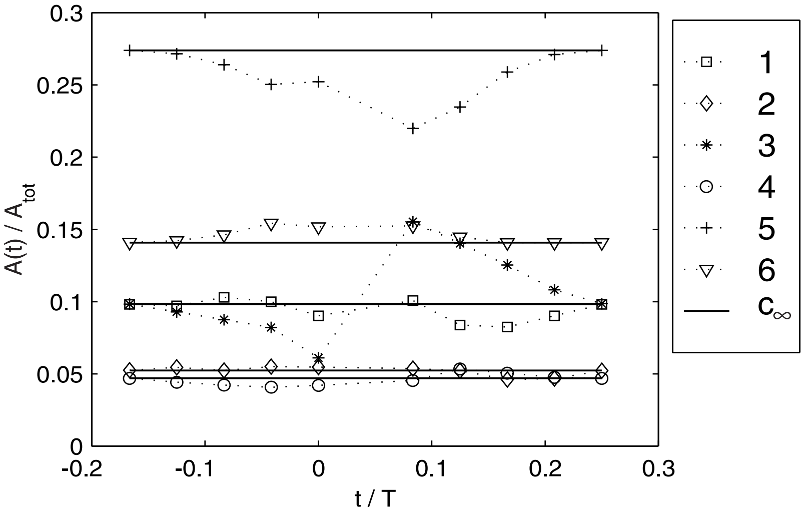

Figure 5. Watershed area $A(t)$, scaled by the total area of the tidal embayment A_{tot}, is plotted versus time for the six tidal sub basins of Figure 4. The straight horizontal lines represent the time invariant watershed areas obtained through *Rinaldo et al.*'s [1999b] model, i.e., assuming that tide propagates instantaneously within the channel network.

[25] "Overmarsh" paths for the salt marshes monitored within the lagoon of Venice are studied via flow directions derived from relevant free-surface gradients (i.e., via the Poissonian hydrodynamic model applied to the study areas described in section 3). Thus for any unchanneled site defined within a tidal landscape we determine objectively the flow path to the nearest tidal channel and compute its length, thereby defining a random space function. Figures 7 and 8 show the semilog plot of the probability distributions of overmarsh pathways in different areas of the S. Felice and Pagliaga salt marshes. We observe that the approximately linear trends suggest exponential probability distributions of the type observed in fluvial environments by *Tucker et al.* [2001]. The slope of the semi-log plot is the

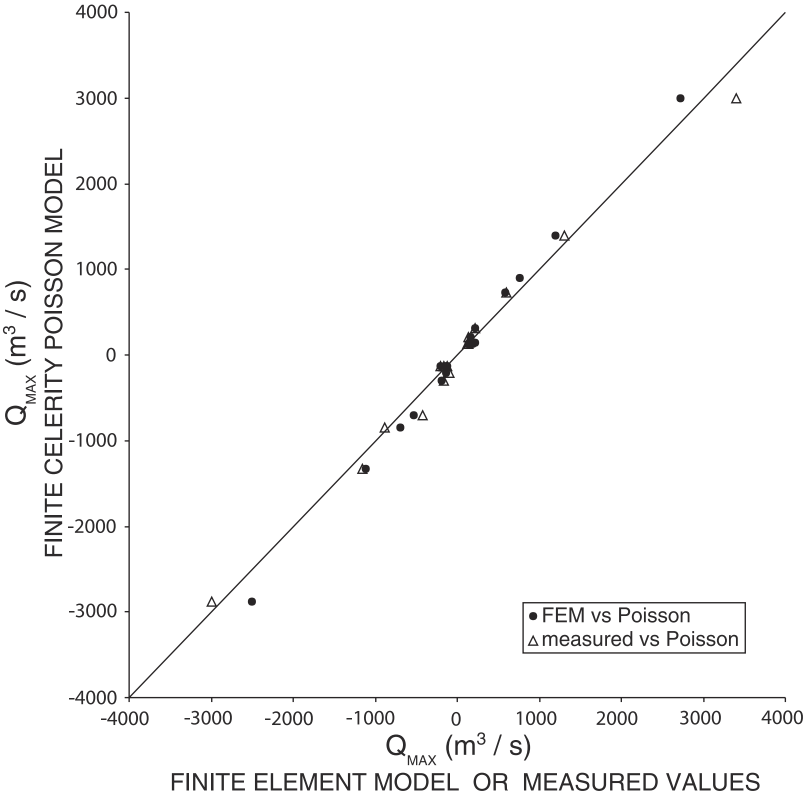

Figure 6. The values of maximum discharge obtained at different sections in the northern lagoon of Venice by use of the Poissonian model presented above are compared to direct observations and to the results from a full-fledged finite element model.

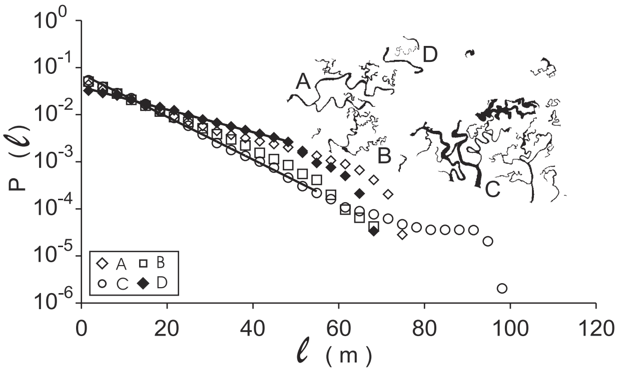

Figure 7. Probability density function of overmarsh path length ℓ evaluated for several watersheds within the S. Felice salt marsh. Note that an approximately straight observational trend on the semilog plot suggests an exponential distribution.

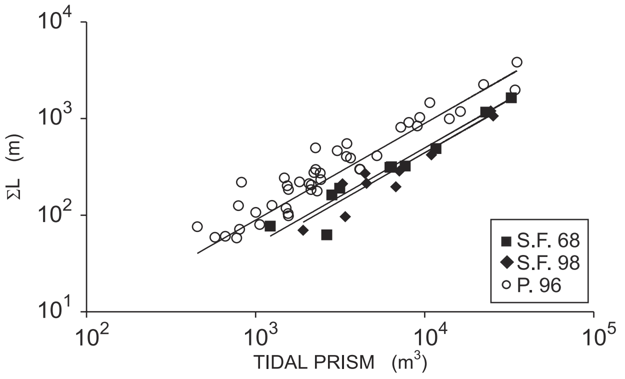

Figure 9. Total network length versus tidal prism for several subbasins in S. Felice and Pagliaga salt marsh. The approximately linear trend differs from one marsh to the other but is quite constant over time.

mean of the exponential distribution, and thus the mean overmarsh path length, which appears to fluctuate considerably in space even in adjacent sites (Figures 7 and 8). It is thus relevant to assess whether these are to be considered natural fluctuations around a mean behavior or rather the symptoms of space-dependent processes influencing network development.

[26] In this view it is of practical and theoretical importance to study the dependence of total network length on other physical characteristics of the salt marshes. Figure 9 shows the relationship between total channel length of the tidal network and the tidal prism for watersheds selected within the salt marshes described above. The tidal prism is defined as the total volume of water which is exchanged through the outlet of the channel network between low water slack and the following high water slack, i.e., during flood. In the absence of any significant fresh water flow into the tidal basin, an equal volume of water is exchanged during ebb. In the following the tidal prism is computed (neglecting propagation effects) as $P = \int_A [h_{max}(\mathbf{x}) - max(z(\mathbf{x}), h_{min}(\mathbf{x}))] d\mathbf{x}$, where $h_{max,min}(\mathbf{x})$ are, respectively, the maximum and the minimum tidal level reached in spring tide and $max(z, h_{min})$ is the maximum between local topographic elevation, $z(\mathbf{x})$, and $h_{min}(\mathbf{x})$. The tidal prism depends not only on the area of the salt marsh, but also on: its topography; the geometry of the channels cutting through the marsh (the volume of water contained in the network is also included in the computation); and the maximum elevation locally attained by the tide. The computation of the tidal prism P yields an approximately linear relationship, as shown in Figure 9, in general agreement with *Allen* [1997] who reported a positive correlation (though not necessarily linear) between total channel length and tidal prism. The observational data of Figure 9 show clear evidence of a local linear relationship between total network length and tidal prism, although the intercepts of the curves differ for the two areas considered in the Venice lagoon. One thus wonders whether this is the result of differences in the processes at work or rather just a sign that total channel length does not adjust to tidal prism but to other physical quantities. It would be desirable, in fact, to relate total channel length to a feature of the salt marsh which would make the relationship independent from location. To this end, Figure 10 plots total channel length versus subbasin area A. The experimental points from the different sites considered reasonably fall onto the same line, suggesting that total network length responds to the total area served regardless of tidal amplitude. The data, fitted to a power law, yield roughly unit values of the exponents for both salt marshes and for all years of observation (details on the computations and statistics are reported in the caption). The linear relationship in Figure 10 agrees qualitatively with *Steel and Pye* [1997], who obtained a positive correlation (albeit apparently not a linear one) between total length and watershed area from a survey of 13 British salt marshes. However, their work was based on a manual definition of divides rather than on the dynamically based procedure presented here and yielded considerably more scatter than found in the study sites within the Venice lagoon. The relation in Figure 10 suggests a rather spatially constant mechanism of network development and a constant Hortonian drainage density, the slope of the relationship $\Sigma L \propto A$. With respect to differing mean overmarsh path lengths ℓ, one wonders whether there is a common morphodynamics of tidal networks leading to structures

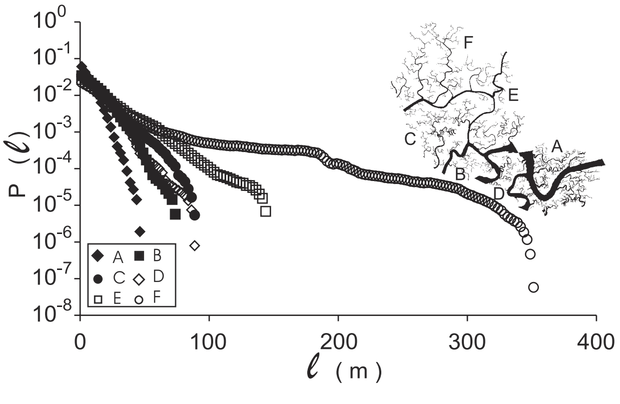

Figure 8. Probability density function of overmarsh path length ℓ evaluated for several watersheds within the Pagliaga salt marsh. Note that an approximately straight observational trend on the semilog plot suggests an exponential distribution.

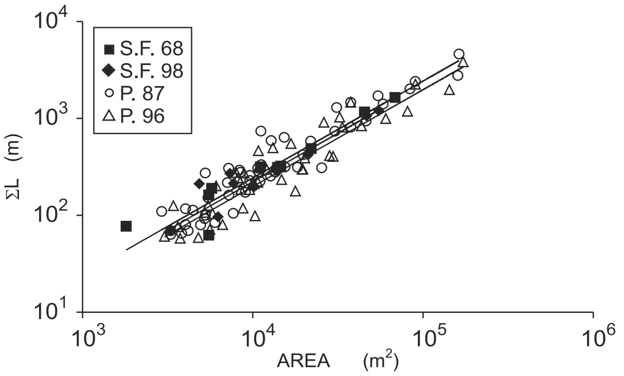

Figure 10. Relationship between total network length and basin area for several subbasins in S. Felice and Pagliaga salt marshes showing a common linear trend. The data have been fitted to a power law with unit exponent ($\Sigma\ L \simeq aA^{1\pm0.05}$). The best estimate are $a = 0.024$ m^{-1} for S. Felice 1968 ($r^2 = 0.991$); $a = 0.022$ m^{-1} for S. Felice 1998 ($r^2 = 0.978$); $a = 0.024$ m^{-1} for Pagliaga 1987 ($r^2 = 0.911$); and $a = 0.020$ m^{-1} for Pagliaga 1996 ($r^2 = 0.885$). Notice that $a = \ell_H^{-1}$ is equal to the Hortonian drainage density.

nearly homogenous in space or else the Hortonian measure may not be distinctive.

[27] To substantiate this observation, the relationship between Hortonian characteristic length ℓ_H and the mean overmarsh path length ℓ is studied. In fact, the existence of such a relationship would confirm that the geometry of the network, including branching and meandering characteristics, is similar from place to place. To this end we computed ℓ for numerous watersheds in Pagliaga and S. Felice salt marshes. The result is seen in Figure 11 which indicates that mean overmarsh path length exhibits a larger scatter than experienced by total length (Figure 10), and no clear trend over the interval of areas spanned by the data is evident. The experimental relationship between ℓ_H and ℓ is given in Figure 12 and reinforces the previous observation. While a positive correlation may be inferred, important fluctuations emerge. These are due to rather different subbasin shapes, branching and meandering characteristics of the tidal networks cutting through the salt marshes. The results of Figures 10, 11, and 12 indeed indicate that, since Hortonian drainage density remains relatively constant and mean overmarsh path length reflects instead different network features (though ideally they should be one-to-one related), there is not a similarity of forms from one location to another in the network structure and in the way the network dissects the salt marsh. Moreover, the Hortonian measure of drainage density is not particularly distinctive, as it happens [*Kirchner*, 1993; *Rodrìguez-Iturbe and Rinaldo*, 1997; *Rinaldo et al.* 1999a; *Dodds and Rothman*, 2000] to topological measures (in particular, Horton's bifurcation and length ratios or Tokunaga's cyclicity) for network comparison.

[28] A conclusive test is illustrated in Figure 13, where the ratio ℓ_H/ℓ is plotted against link frequency [*Horton*, 1945], defined as the ratio of the number of channel links to the watershed area A. The ratio ℓ_H/ℓ is a measure of the efficiency with which, for a certain Hortonian drainage density (i.e., a given total channel length per unit area), the salt marsh is dissected by the network: high values of ℓ_H/ℓ for a given ℓ_H correspond to small values of ℓ, i.e., to a spatial arrangement of channel links which efficiently reduces the mean overmarsh path length. Figure 13 shows the data from our field sites (Figure 13a) jointly with the data from simple geometrical settings (Figure 13b). Cases 1, 2, 3, 4 and 6 share the same values of total network length and basin area and thus the same Hortonian length ℓ_H. These cases show how, for a fixed ℓ_H, different branching structures and meandering characteristics yield different values of the efficiency ℓ_H/ℓ. Cases 5 and 7 have a larger

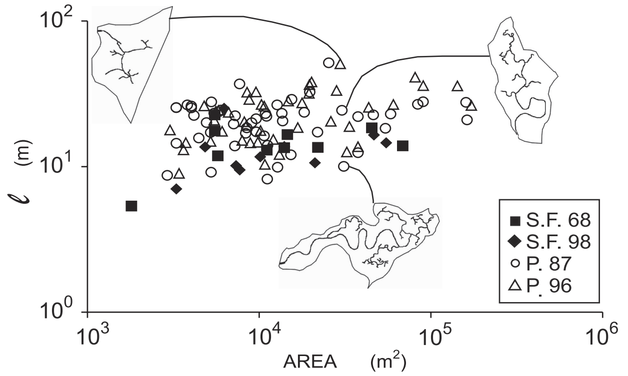

Figure 11. Relationship between mean overmarsh path length and basin area for several subbasins in S. Felice and Pagliaga salt marshes. The relationship does not indicate any clear trend. In particular, we have estimated the best relationship $\ell \simeq bA^c$ with the following results: S. Felice 1968 $b = 2.92$, $c = 0.17$ ($r^2 = 0.22$); S. Felice 1998 $b = 3.92$, $c = 0.12$ ($r^2 = 0.11$); Pagliaga 1987 $b = 10.69$, $c = 0.06$ ($r^2 = 0.03$); Pagliaga 1996 $b = 3.63$, $c = 0.19$ ($r^2 = 0.22$). The insets show the planforms of three watersheds characterized by approximately the same area but vastly different structure of the channeled and unchanneled pathways, including quite different tidal meandering. Thus area alone simply cannot properly distinguish the correct value of ℓ.

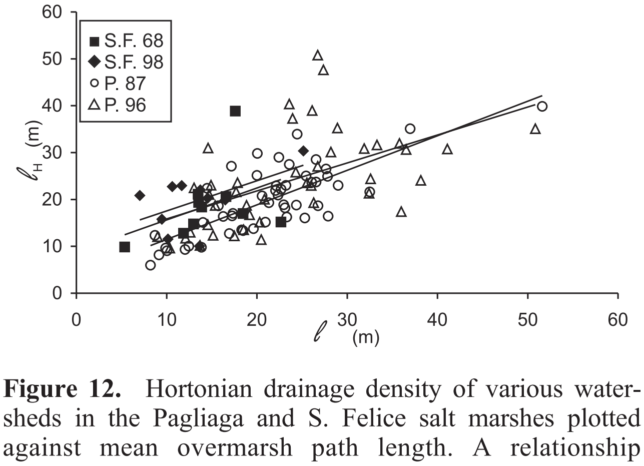

Figure 12. Hortonian drainage density of various watersheds in the Pagliaga and S. Felice salt marshes plotted against mean overmarsh path length. A relationship common to all the areas may be seen even though the data are quite scattered. Here we show the best realtionship of the type $\ell_H \simeq d\ell + e$: S. Felice 1968 $d = 0.68$, $e = 8.80$ ($r^2 = 0.16$); S. Felice 1998 $d = 0.64$,$e = 11.13$ ($r^2 = 0.29$); Pagliaga 1987 $d = 0.74$, $e = 4.11$ ($r^2 = 0.59$); Pagliaga 1996 $d = 0.60$, $e = 9.89$ ($r^2 = 0.30$).

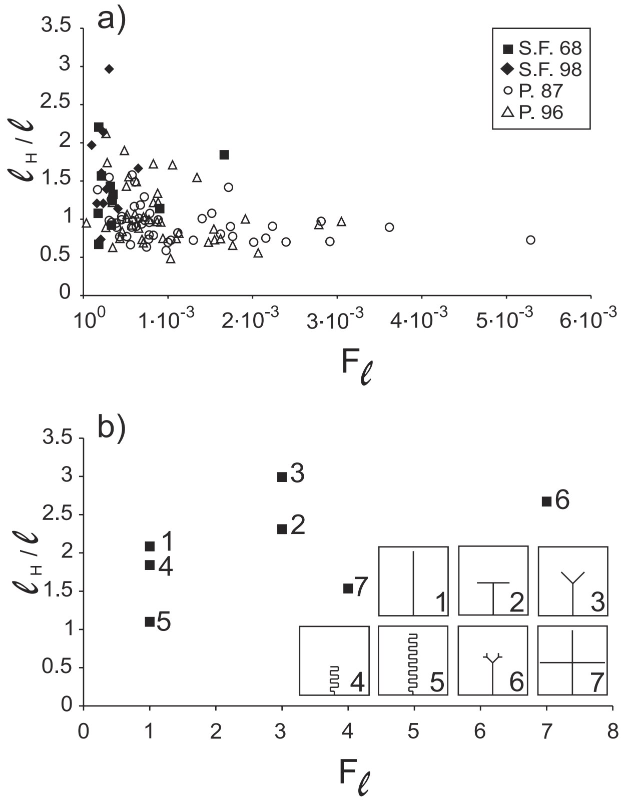

Figure 13. Ratio of Hortonian and true mean unchanneled lengths versus link frequency for (a) various watersheds in the Pagliaga and S. Felice salt marshes and (b) for schematic test settings.

total network length and thus smaller values of ℓ_H than the previous ones. Again a wide variability in the efficiency ℓ_H/ℓ is observed as a function of meandering and branching characteristics. The test cases illustrated explain the wide variability observed in Figure 13a, in spite of the constancy of ℓ_H in Figure 10. We thus conclude that the traditional Hortonian morphological description does not provide a complete picture of the geometry of a tidal network and of its relationship with the salt marsh which it dissects.

[29] Our results seem also to support the known concept of inheritance of the major features of channelized patterns from sand- or mud-flat to a salt marsh [e.g., *Allen*, 2000; *Friedrichs and Perry*, 2001]. In fact, the constant value of the Hortonian drainage density ℓ_H suggests that the total length of the channel network is uniquely defined by salt marsh area rather than by its tidal prism. Thus when the tidal landscape reaches an elevation that allows the colonization by alophytic vegetation, this freezes the configuration of the network which can, from then on, only undergo minor changes immaterial to its basic structure. This complies with the notion that tidal channels in marshes are remarkably stable landscape features [e.g., *Goldthwait*, 1937; *Pestrong*, 1965; *Redfield*, 1972; *Leopold et al.*, 1993] and several conceptual models of (1) nearly imperceptible lateral migrations of highly meandering saltmarsh channels [*Gabet*, 1998] and (2) youthful salt marshes [*Yapp et al.*, 1916, 1917; *Yapp*, 1922; *Beeftink*, 1966; *Beeftink and Rozema*, 1988; *French and Stoddart*, 1992; *French*, 1993; *Pethick*, 1980; *Steel and Pye*, 1997; *Allen*, 2000].

[30] The impact of the above results on the general morphodynamic model of the lagoon of Venice, on which research is actively progressing, remains to be seen. In particular, forthcoming research will correlate link frequencies with ratios of tidal channel width to depth, as a general proxy for sediment and vegetational characteristics of a salt marsh.

5. Conclusions

[31] The analyses of the tidal environments within the lagoon of Venice described above allow a number of conclusions regarding the morphological description of tidal networks and salt marshes which may be relevant to the general case: (1) the distributions of the flow lengths of unchanneled pathways in salt marshes within observational tidal networks, analyzed and discussed in detail in the paper, show interesting features. Our introduction of suitable drainage directions, defined by hydrodynamic gradients, is based on a Poissonian model which proves robust and reliable upon comparison with complete models in a large spectrum of cases of practical interest. This bears important consequences for the prediction of the morphological evolution of lagoons and coastal wetlands. (2) Drainage densities, i.e., the extent of tidal channelization, of various salt marshes have been observed experimentally and analyzed. We find a clear tendency to develop watersheds described by exponential decays of the probability distributions of unchanneled lengths, and thereby a pointed absence of scale-free distributions. (3) The total length of the channel network is found to be uniquely defined by salt marsh area rather than by its tidal prism. We suggest that this supports the concept of inheritance and thus salt marsh area might be a proxy of the dynamic forcing responsible for the formation of the network during its history. This implies that when the tidal landscape reaches an elevation that allows the colonization by alophytic vegetation, the configuration of the network freezes and can, from then on, only undergo minor changes not altering its basic structure. (4) Similarity of forms developing at different sites is not observed, although Hortonian measures indicate a robust relationship between total network length and marsh area. Such relationship is artificially independent from important factors such as marsh elevation and vegetation types, which indeed affect the relevant geomorphology. Mean unchanneled lengths, computed appropriately, resolve the lack of distinctiveness of Horton's drainage density.

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