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C. Camporeale,[1] E. Perucca,[1] and L. Ridolfi[1]

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[1] The occurrence of cutoff events, although sporadic, is a key component in the complex dynamics of meandering rivers. In the present work, we show that cutoff has a twofold role: (1) It removes older meanders, limiting the planform geometrical complexity (geometrical role), and (2) it generates an intermittent noise that is able to influence the spatiotemporal dynamics of the whole river (dynamical role). The geometrical role limits the spatial evolution of the meanders, sporadically eliminating portions of the river planimetry. In this way it stabilizes the mean river geometry around a statistically steady state. The dynamical role is due to the propagation of a noise wave that is triggered by cutoff events. Because of the spatial memory component which is present in the meandering dynamics, such waves propagate all along the river, thus affecting its meandering dynamics.

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1. Introduction

[2] The intrinsic dynamics of meander evolution are driven by several linear and nonlinear processes which, along with external forcing (e.g., soil properties, streamflow fluctuations, and riparian vegetation), lead to the formation of typical planimetric patterns [e.g., *Parker et al.*, 1983, *Howard*, 1992, *Perucca et al.*, 2005, *Seminara*, 2006]. The planimetric evolution of meandering rivers is also a key process in many engineering problems. For example, the evaluation of river bank erosion and the consequent sediment transport are fundamental data for fluvial management, navigation, river restoration, and oil research [e.g., *Sun et al.*, 1996]. Moreover, from the environmental point of view, the importance of mutual interactions between the riparian ecosystem and the meandering river dynamics is well known [e.g., *Salo et al.*, 1986; *Bradley and Smith*, 1986; *Hughes et al.*, 2001].

[3] The evolution of a meandering planform is characterized by three basic processes: (1) the continuous elongation of the river axis, with single or compound lobe formation, (2) the downstream (sometimes upstream) migration of the meander loops, and (3) the occurrence of cutoff events. In the present work, we emphasize the role played by the latter process and its interaction with the former two.

[4] Cutoff is the bypass of a meander loop in favor of a shorter path with the subsequent formation of an abandoned reach, called an oxbow lake. If a cutoff takes place to avoid the self-intersection of two reaches that come into contact, it is called a "neck" cutoff; otherwise the cutoff is known as a "chute" [*Allen*, 1965; *Gagliano and Howard*, 1984]. Since cutoff events are sporadic and are recognized to induce "important processes of geomorphic change" [*Mosley*, 1975], it is convenient to use its occurrence to distinguish two different timescales that characterize the meandering dynamics: a short timescale, that refers to the evolution of single meanders before the cutoff, and a long timescale, that includes the intermittent occurrence of more cutoffs [see also *Camporeale et al.*, 2005].

[5] The study of the role of cutoff occurrence in long-term river dynamics has been carried out according to two different, but interconnected, approaches: the descriptive and the numerical approach. The former one is typical in classical geomorphological studies, where the cutoff is implicitly taken into account when the planform characteristics of real rivers are analyzed with the aim of deriving some empirical laws that relate the hydraulics to some geomorphological parameters [e.g., *Leopold and Wolman*, 1960; *Carlston*, 1965, *Hansen*, 1967]. Although these valuable hydromorphological relationships are irreplaceable predictive tools which are still widely adopted, these approaches have seldom investigated how cutoff events are able to influence river dynamics. In fact, only a few observations really concerning cutoff events, oxbow lake formation and channel adjustment following the cutoff have been carried out [e.g., *Johnson and Paynter*, 1967; *Hooke*, 1995, *Gay et al.*, 1998, *Stølum*, 1998].

[6] The numerical approach has been the only alternative to the descriptive one. In fact, unlike the short-term dynamics, the mathematical difficulties of cutoff modeling preclude the analytical study of the long-term dynamics. Models describing the short-term meandering dynamics [e.g., *Ikeda et al.*, 1981; *Smith and McLean*, 1984; *Zolezzi and Seminara*, 2001] and the cutoff occurrence have therefore been used to simulate the long-term planimetric evolution of a meandering river [e.g., *Howard*, 1984; *Sun et al.*, 1996; *Stølum*, 1996]. In this way, some important aspects related to cutoffs have emerged: the interactions between river migration and sedimentation processes [e.g., *Howard*,

[1]Dipartimento di Idraulica and Water and Environment Research Center, Politecnico di Torino, Turin, Italy.

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1984], some clues of self organized criticality [*Stølum*, 1996] and the self-confinement of the meander belt, evidence of the attainment of a statistical steady state of some geometrical characteristics of the river planimetry [e.g., *Howard*, 1984], and recognition of the important phenomenon of "secondary lobe" formation (double heading) [*Brice*, 1974; *Ferguson*, 1984; *Lancaster and Bras*, 2002]. Finally, in a recent work [*Camporeale et al.*, 2005], we have shown that such steady state results are mainly governed by two typical spatial and temporal scales, and only some of the hydrodynamic mechanisms regulating the short-term dynamics seem to play a significant role in the long-term dynamics.

[7] Prompted by the intriguing results obtained in previous studies, in this paper we attempt to elucidate the dynamical mechanisms by which cutoff events are able to influence the long-term river evolution. In particular, we recognize here that the cutoff plays two fundamental actions: (1) it removes older meanders, limiting the geometrical complexity driven by the fluid dynamic processes, and (2) cutoff acts as a shot noise able to influence the spatiotemporal dynamics of the whole river planimetry through the spatial memory component which is present in the meandering short-term dynamics. Though these two roles are closely linked, for the sake of clarity they will be described separately in the following. Moreover, the effect of external forcing will not be taken into account in order to isolate the role of cutoff.

2. Fundamental Mechanisms of River Meandering Dynamics

2.1. Short-Term Dynamics: Modeling Aspects

[8] The planimetric evolution of a meander is driven by the action of a helicoidal curvature-driven secondary flow, which is responsible for both the outward erosion and the along-stream migration of the river. In fact, secondary flow activates an inward lateral sediment flux on the bed [*Kalkwijk and De Vriend*, 1980], leading to the formation of a transversal slope of the bed (point bars). The consequence is (1) a second type of secondary flow, which is driven by topographic asymmetry [*Seminara and Solari*, 1998] and (2) topographic steering of the main flow toward the concave bank [*Dietrich and Smith*, 1983; *Dietrich and Whiting*, 1989], which induces outward erosion of the river. The interaction between the longitudinal convective transport of momentum and the shear stresses causes a phase lag between the curvature and the response in the bank erosion induced by the flow field. As a consequence, the system feels a spatial memory in the downstream (upstream) direction, and a downstream (or upstream) migration of the meanders is activated [*Howard*, 1984; *Parker and Andrews*, 1986; *Zolezzi and Seminara*, 2001]. From the above picture, it emerges that the planimetric evolution of meandering rivers is characterized by a continuous enlargement of the loops associated with downstream or upstream migration, until a cutoff event takes place.

[9] A usual framework for studying the meandering dynamics focuses on the evolution of the river centerline axis, supported by the geomorphological evidence that the erosion of the concave bank dynamically balances the deposits on the opposite point bar, allowing the width to remain constant during its migration [e.g., *Leopold and Maddock*, 1953; *Ikeda et al.*, 1981]. In this way the planimetric evolution can be interpreted as a plane curve which evolves in time and space [e.g., *Zolezzi and Seminara*, 2001; *Edwards and Smith*, 2002], and the formalism of differential geometry can be applied. The equation of motion for a curve parameterized by the vector $\mathbf{r}(s, t)$, with respect a cartesian reference, is

$$\frac{d\mathbf{r}}{dt} = \mathbf{n}V - \frac{\partial \mathbf{r}}{\partial s}\int_0^s CVds', \tag{1}$$

where t is time, s is the curvilinear coordinate, $\mathbf{n}$ is the normal unit vector, and C is the curvature. Two different but equivalent demonstrations of equation (1) were obtained by *Nakayama et al.* [1992] and *Seminara et al.* [2001]. We recall that the integrodifferential term on the right hand side represents a geometry-induced memory effect which derives from the time-dependent parameterization of the curvilinear abscissa and it is related to the deformation process. The local normal velocity V is usually modeled as a linear relation between the normal rate of erosion and the water velocity very near the bank line, u_b, i.e.,

$$V = E \cdot u_b, \tag{2}$$

where E is an erodibility coefficient that depends on the geotechnical characteristics of the bank [*Micheli and Kirchner*, 2002; *Wallick et al.*, 2006]. This hypothesis was confirmed by field investigations [*Pizzuto and Meckelnburg*, 1989] and has commonly been used in numerical simulations [*Howard*, 1984; *Sun et al.*, 2001a].

[10] To obtain the quantity $u_b(s)$, different linear meandering models have been proposed in the past depending on the different levels of approximation of the considered morphodynamic processes [see, e.g., *Ikeda et al.*, 1981; *Struiksma et al.*, 1985; *Odgaard*, 1986; *Crosato*, 1987; *Johannesson and Parker*, 1989; *Zolezzi and Seminara*, 2001]. In this paper, we use a slightly modified version of the first one (henceforth referred to as the IPS model), which is also the most simplified physically based meandering model, and the latter one (the ZS model), namely the most complete linear theory for morphodynamics of meandering rivers. Thus the role of cutoff is here investigated by using both the earliest and the latest fluid dynamic linear formulations proposed in literature.

[11] The ZS model takes into account the coupling between hydrodynamics and sediment dynamics and between curvature-driven secondary currents and topography-driven secondary flow. Moreover, it considers the spatial variation in the friction factor and in the bed load transport as well as the vertical variation of the eddy viscosity. *Zolezzi and Seminara* [2001] provided a linear solution to the problem in terms of the lateral Fourier decomposition of the longitudinal flow field perturbation, $u_b(s, n) = \sum_{m=0}^{\infty} u_m(s)\sin Mn$ (with $M = \frac{1}{2}(2m + 1)\pi$)), where the generic m mode of the Fourier decomposition reads

$$u_m(s) = A_m \sum_{j=1}^{N}\left[g_{j0}\int_{-\infty}^{s} e^{\lambda_{mj}(s-t)}C(t)dt \;+\; \sum_{k=1}^{N} g_{jk}\frac{\partial^{(k-1)}C(s)}{\partial s^{(k-1)}}\right], \tag{3}$$

where N = 4, $A_m = 2(-1)^m/M^2$, and the terms g_{jk} and λ_{mj} depend on (1) the aspect ratio, β, between the half width, b, and the water depth, H, (2) the dimensionless roughness, $d_s = d_m/H$ (d_m is the mean grain size), and (3) the Shields stress, τ*. One of the four eigenvalues λ_{mj} is always positive, giving rise to the dependance of the flow field on both the upstream and the downstream river geometry. Upstream dependence is the most common feature in natural meandering rivers, while downstream dependance is dominant in the so-called superresonant conditions (i.e., if β is greater than a critical value [*Seminara et al.*, 2001]). We consider only subresonant rivers in this paper.

[12] Unlike the ZS model, the IPS model neglects the full coupling between the sediment dynamics and the fluid dynamics, which is only partially accounted for through the use of a linear relationship between the bed elevation and the curvature, according to $\eta = -ACn$ (where A is the transversal bed slope). Also, the Euler equation is taken for the transversal momentum balance, and no spatial change in friction factor and bed load transport are considered. Finally, for the computation of the term A, the eddy viscosity is implicitly assumed uniform. These assumptions simplify the governing equations and lead the dynamics to be described by a single first-order ODE with the solution

$$u_b = -bUC + \frac{UbC_f}{H}\left[F^2 + A + 1\right]\int_{-\infty}^{s} e^{-\frac{2C_f}{H}(s-z)}C(z)dz, \quad (4)$$

which is formally similar to equation (3) with N = 1, where U, C_f and F are the cross averaged velocity, friction factor and Froude number, respectively. The IPS model [*Ikeda et al.*, 1981], despite its simplicity, captures the main features of meandering dynamics, and it has been used in several works [e.g., *Parker et al.*, 1983; *Beck et al.*, 1984; *Parker and Andrews*, 1986]. It should be noticed that the upstream geometry of the river is also taken into account in this model through the exponential term of the convolution integral, which is responsible, for example, for the upstream skewness of meanders and their downstream migration. On the other hand, the IPS model is not able to reproduce downstream skewness or upstream migration of the meander loops.

2.2. Long-Term Dynamics: Occurrence of the Cutoff

[13] Long-term dynamics are characterized by the irregular occurrence of cutoffs. Neck cutoff occurs when a meander becomes very tortuous and the water crosses the thin neck of the loop, giving rise to the formation of oxbow lakes. Chute cutoff, instead, occurs during heavy floods, when the overflow scours a new reach in the floodplain that bypasses a large loop, sometimes occupying the swales of newly deposited and unvegetated scroll bars.

[14] As mentioned in the Introduction, numerical simulations have been fundamental to understand some aspects of the long-term dynamics. For example, in work by *Howard* [1992, 1996] sedimentation patterns in the floodplain were highlighted and the location of the zones of depression in the floodplain were realistically reproduced. The influence of the variation of oxbow lake erodibility on river geometry was evaluated by *Sun et al.* [1996] while, in a subsequent work, *Sun et al.* [2001b] extended the analysis for the modeling of sediment sorting in bends. They were able to reproduce both the deposition of coarse material in the upstream arms of the point bar and the deposition of fine material in the downstream part.

[15] Another valuable contribution was made by *Stølum* [1996, 1997]. He suggested that the intermittent occurrence of cutoff events leads to dynamic proof of self organized criticality (SOC), i.e., a process which does not depend on the initial conditions and where the fluctuations (e.g., in the sinuosity) are driven by clustered events in space and time (the cutoffs). This process can also give rise to a fractal geometry of the river planform [*Nikora et al.*, 1993].

[16] Most of these numerical simulations have been carried out only modeling the neck cutoff, as it is an important shortening mechanism in freely meandering rivers with moderate (or small) range of flood variability [*Stølum*, 1998]. In contrast, the simulation of the chute cutoff would require a thorough description of sedimentation on point bars in unsteady conditions and the knowledge of the dynamics of floodplain topography and riparian vegetation. The mutual interactions between such processes are not fully understood yet, so the prediction of a chute cutoff still remains an open issue. To our knowledge, the problem was only addressed through a probabilistic approach by *Howard* [1996], with the introduction of an ad hoc probability of occurrence, and through a stochastic approach by *Liverpool and Edwards* [1995] that proposed a stochastic differential equation where oxbow lake formation was simulated by a dynamical noise term.

[17] Recently, we analyzed the temporal series of sinuosity, tortuosity, mean wavelength, mean curvilinear wavelength, and curvatures of simulated meandering rivers [*Camporeale et al.*, 2005]. Sinuosity is usually defined as the ratio between the length of the river and the length of the broken line joining the inflection points, while tortuosity is defined as the ratio of the river length to the linear distance between its endpoints. The wavelength is assumed equal to twice the linear distance between the inflection points, while the curvilinear wavelength refers to the distance along the river. We showed that these geometrical features of the river planform are mainly governed by spatial and temporal scales which permit the system to achieve a universal dimensionless behavior. The spatial scale D_0 is defined as the ratio $H_0/(2C_f)$, while the temporal scale is $T_0 = D_0^2/(bEU_0)$, in which the subscript 0 refers to the values of the straightened river [e.g., *Camporeale et al.*, 2005]. It is interesting to observe that the universal behavior obtained with the scale D_0 is in accordance with some empirical geomorphological laws [*Camporeale et al.*, 2005]. Finally, we demonstrated that a statistically steady state, substantially independent of the fluid dynamic detail of the model used in the simulations, is reached. As no external forcing, such as geology, pedological processes, riparian vegetation, were considered, we argued that the reason for this long-term collapse lies in the interplay with the cutoff dynamics.

[18] In this paper, the role of the cutoff is investigated by means of numerical simulations, in which, for the sake of simplicity, only the occurrence of neck cutoffs is modeled. Chute cutoff can be considered as a bypass process with a lower threshold condition than neck cutoff, which induces the same geometrical and dynamical consequences on the long-term qualitative behavior of the curve. It is, however, possible that the stochastic nature of chute cutoffs may

Table 1. Morphodynamic Parameters Used in the Simulations[a]

Runs	S1	S2	S3	S4
ds	0.01	0.004	0.01	0.01
τ^*	0.1	0.25	0.2	0.2
β	15.1	13.2	15.8	13.3
D_0, m	123	250	450	500
T_0, years	400	1000	600	750

[a]Here $d_s = d_m/H_0$ is the relative roughness, d_m is the mean sediment diameter, H_0 is the water depth, τ^* is Shield stress, $\beta = b/H_0$ is the aspect ratio, b is the half width, D_0 is the spatial scale, and T_0 is the temporal scale. The erodibility coefficient E has been assumed to be equal to 3×10^{-7} in all the simulations.

introduce a new component into the system dynamics, especially when the statistics that govern the occurrence of cutoffs are strongly correlated to the environment (e.g., riparian vegetation) where rivers meander (T. Sun, personal communication, 2007).

3. Role of the Cutoff

[19] In this section, we propose a new interpretation of the role of the cutoff on the long-term river dynamics. We think that the cutoff plays a twofold role: it is (1) a geometrical constraint, that entails a limitation of the enlargement and the age of meanders, and (2) a dynamical process, since it behaves as a noise generator that disturbs the deterministic meandering spatiotemporal dynamics. Our interpretation is here sustained by the outcomes of some long-term simulations whose morphodynamic parameters are shown in Table 1. The initial condition of each simulation is a straight line with small random perturbations, discretized as a sequence of points with constant spacing Δs and interpolated by a cubic spline. An iterative algorithm simulates the meander evolution. The excess bank longitudinal velocity u_b is evaluated for the IPS model by means of a fourth-order Runge-Kutta scheme, while for the ZS model, we used the analytical solution reported by *Zolezzi and Seminara* [2001] which requires four convolution integrals to be numerically solved (see *Camporeale et al.* [2005, Appendix B] for numerical details). Once the value of u_b is computed, the points are shifted normal to the centerline axis curve (Hickin orthogonal mapping [*Hickin*, 1975, 1984]). Finally, we adopted an ad hoc algorithm, which minimizes the computational time to find the occurrence of potential neck cutoff events. Further numerical details can be found in work by *Camporeale et al.* [2005].

3.1. Geometric Role: Cutoff as a Limitation to the Meander Evolution

[20] Cutoff limits and contains the spatial evolution of meanders whenever a single or multilobed loop has grown so much that a self-intersection is going to take place. A well known picture of the temporal evolution of a meander up to the cutoff event, is plotted in Figure 1: The small random oscillations of the initial condition have been smoothed through the elongation mechanism, and a characteristic wavelength has been selected. Such a process continues until a cutoff event occurs; it removes a reach of river and avoids a self-intersection. Therefore a first action by cutoff is to eliminate portions of river planimetry from the active channel sporadically. In this sense, we call this effect produced by cutoffs a geometric role. Although this role could appear quite trivial, a careful analysis shows the important consequences it has on the long-term dynamics.

[21] The main overall effect of the geometric role can be highlighted through the temporal analysis of some important planimetric characteristics. The time series of the mean curvature, C, and the mean curvilinear wavelength, λ_s, are reported in Figure 2, comparing the normal river evolution (i.e., with cutoff) with the artificial case where the cutoff mechanism has been disabled. In the latter case, unreal planforms with self-intersections appear and the tortuosity continues to increase while the river slope decreases.

[22] The two most important consequences of the geometric role emerge in Figure 2. The first one concerns the attainment of a stationary state. Comparing the two types of simulation (i.e., with and without cutoff), it can be seen that only in the simulations in which cutoff is allowed to interplay with the meandering dynamics do the mean curvature C and the mean curvilinear wavelength λ_s attain a statistical steady state. In contrast, where cutoff occurrence is inhibited, C will continue to decrease, and λ_s to increase. Similar behavior has also been obtained for the other geometrical quantities analyzed. Consequently, cutoff is the key mechanism by which long-term river dynamics stabilize around a stable mean geometry.

[23] The second effect of the geometrical role emerges again in Figure 2, which compares the results of the IPS and ZS models. In the early part of the runs, before the occurrence of the first cutoff, the two fluid dynamic models produce significant differences in the planform, as is testified by the different evolutions of C and λ_s. This confirms that the morphodynamic processes and their correct modeling are fundamental aspects in the short-term evolution of meandering rivers, and the most complete models have to

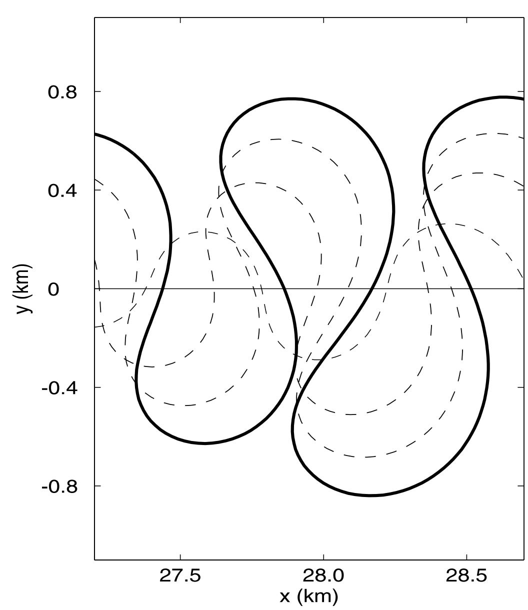

Figure 1. Evolution of a river reach from the initial condition (thin solid curve) to the cutoff event (thick curve) for case S1. The initial condition is a straight line weakly perturbed with Gaussian white noise.

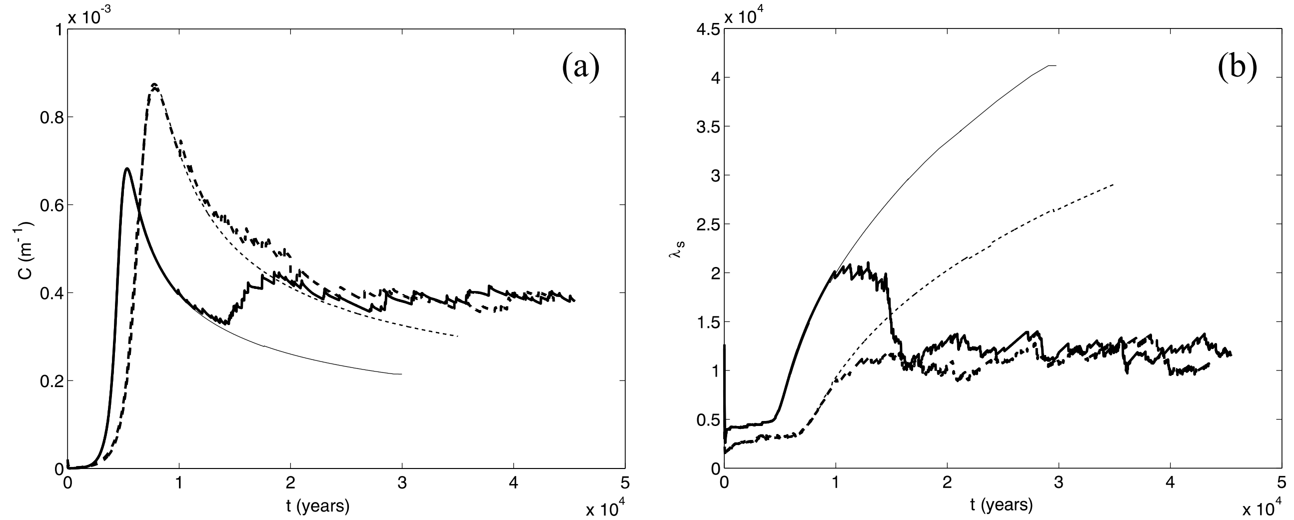

Figure 2. Time series of (a) the mean curvature and (b) the curvilinear wavelength for simulation S4 using the IPS model (dashed curves) and ZS model (solid curves), both with and without cutoff.

be adopted [*Camporeale et al.*, 2007]. On the contrary, in the long term (i.e., when several cutoffs are produced) the differences between the IPS and ZS predictions decrease, until both the mean curvature and the mean curvilinear wavelength stabilize around the same values for the two models. Again, the same behavior is also observable for the other geometrical quantities investigated. We argue that this feature can be attributed, at least partially, to the geometric role of cutoff: the cutoff meanders are, in general, the oldest river reaches, where the differences between the two modelings of the fluid dynamic processes (IPS and ZS) have had the time to have the most important effects and to be stored in the form of different geometrical characteristics. Cutoff, by removing the most developed bends, cancels out part of such geometric records which are stored in the planform and somehow puts a limit on the effect of the different fluid dynamic mechanisms on the long-term characteristics of the river. In other words, since cutoff tends to remove older parts of the river, the lifetime of meanders in the active river is limited, and therefore the differences that different dynamic models can create on the river geomorphology are also limited. Only the main mechanisms regulating the short-term dynamics, which are described by both models, remain in "younger" part of the river planform after the cutoff.

[24] The fact that cutoffs eliminate (on average) the most mature reaches is quite intuitive if one observes that cutoff happens close to a self-intersection condition and therefore after the river reach has been given the time to develop in order to assume the characteristic goose neck shape. However, quantitative evidence is demonstrated in Figures 3a and 3b, which shows the probability density functions

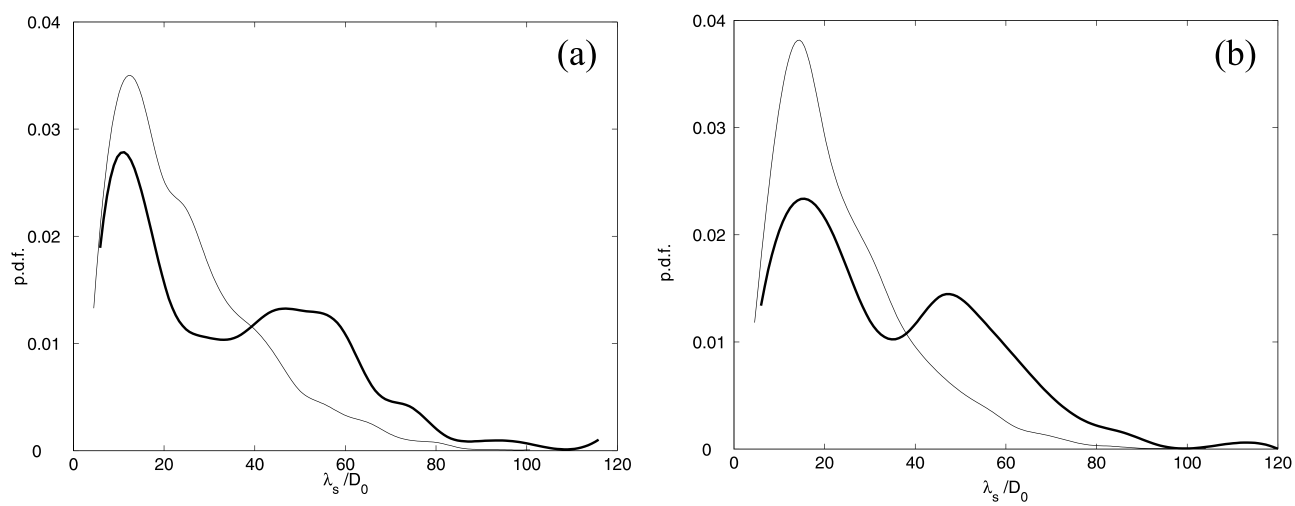

Figure 3. Probability density function of the dimensionless curvilinear wavelength for the active channel (thin curve) and the oxbow lakes (thick curve) for simulations S_1–S_4 using (a) the IPS model and (b) the ZS model.

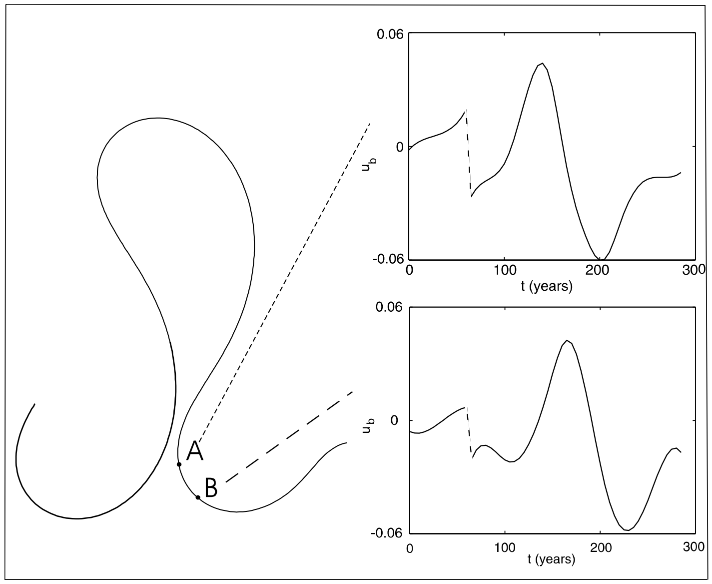

Figure 4. Temporal series of the excess bank velocity u_b for two points A and B downstream of a cutoff meander (simulation S1, ZS model). The planform corresponds to $t = 0$, while the jump marks the cutoff occurrence.

(pdfs) of the mean curvilinear wavelength λ_s for the active river (thin line) and for the cut meanders (bold line). The two distributions have the same domain, but their shapes are quite different. The pdfs for the active river show just one peak (in $\lambda_s/D_0 \approx 18$) that is also associated with the formation of compound lobes, which originate before cutoff occurrence and develop on older and larger meanders, and give rise to a superimposed "multilobed" pattern. On the right of the peak, the pdfs shows a monotone behavior that indicates that the longer (and older) the meanders, the rarer they are. On the contrary, the pdfs of the cut bends show a bimodal structure, regardless of the model used in the simulation (i.e., IPS or ZS model). The second peak (in $\lambda_s/D_0 \approx 40-80$) corresponds to long meanders whose age is greater than the predominant age in the river. This bimodality implies that these long and old meanders are more frequent in the cut reaches than in the active river. It follows that cutoffs privilege older reaches. In this sense, cutoff performs a sort of filtering of the information stored in the river planform.

[25] The geometrical role of the cutoff on the long-term evolution (i.e., the elimination of river reaches) shows only that the differences between different modeling do not diverge: it does not justify that the steady state is exactly the same for the different fluid dynamic models. In fact, the dynamics are driven by different models. Therefore an additional role of cutoff must be elucidated in order to provide an explanation for the attainment of the same steady state, as is shown in the next section.

3.2. Dynamical Role: Cutoff as a Noise Generator

[26] The removal of old patterns is not the only effect imposed by cutoff on the spatiotemporal dynamics of a meandering river. The peculiarity of the cutoff to bring points of the active river which were far from each other closer introduces another subtle mechanism, which we call the dynamical role. The starting point is observing that the dependance of the flow field on the upstream (or the downstream) river geometry makes the planimetric evolution of any point of the river dependent on both local and nonlocal geometrical properties. In the IPS and ZS models, the nonlocal component is contained in the integral terms in equations (4) and (3), respectively. This component of spatial memory in the meandering dynamics is the key point of the dynamical role of cutoff. As the cutoff event eliminates a portion of river, its occurrence entails a sudden change in the nonlocal component for the downstream (upstream) points if the river is subresonant (superresonant). From a mathematical point of view, cutoff implies a sudden change of the domain of the integrals in Equation (3), with a consequent jump in the evolution of the longitudinal flow field perturbation, u_b (see Figure 4).

[27] According to the previous picture, cutoff behaves as a generator of noise that intermittently affects the short-term dynamics (in space and time). In this sense the effect of cutoff resembles a shot noise, namely a casual sequence of spike-like disturbances, where both the interarrival times and spike magnitude are random [*Cox and Miller*, 1965]. Three aspects are worth underlining. First, the temporal scale of the cutoff event is much shorter than the morphodynamic scale. For this reason, the effect of cutoff can be interpreted as a sudden jump in the long-term evolution of u_b. Second, jumps in u_b do not entail jumps in the planimetric evolution, which obviously remains continuous. Third, the structure and magnitude of the jump depend on the geometry of the river planform before and after the cutoff occurrence; in any case, the jump magnitude decreases with the distance from the cut point because of the exponential weight contained in the nonlocal terms. Figure 5 shows how the magnitude of the jumps (normalized with the maximum value of each event) depends on the dimensionless downstream coordinate (to avoid clutter only

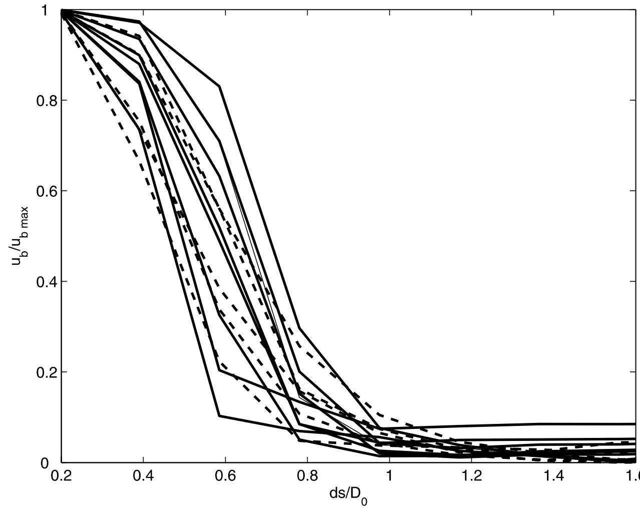

Figure 5. Magnitude of the change in the excess bank velocity u_b following the cutoff occurrence versus the downstream distance for simulation S1 using the IPS model (dashed curves) and the ZS model (solid curves).

a few events are displayed). The monotone decreasing behavior descends on a curvilinear distance of the order of D_0. It is worth noticing that such a behavior is common to both models, which further confirms that the latter scale has a general validity as it captures the underlying dynamics.

[28] The rarity of cutoff events and the short length of the river reach where jumps of u_b are observed could lead one to conclude that the dynamical role is quantitatively negligible. However, this is not true. In fact, the effect of the random jumps due to cutoffs does not disappear from the meandering dynamics, but persists and involves all points downstream (or upstream, depending on the morphodynamic conditions). Because of the action of the spatial memory in the deterministic short-term dynamics, the noise introduced by the cutoff assumes the characteristics of a wave that propagates downstream (or upstream). In this way, single sporadic cutoff events are able to disturb the morphodynamics of all points of the river, contributing to making some modeling differences negligible. This is the main reason why the planimetric quantities attain the same steady state, irrespective of the model used (see Figure 2).

[29] In order to investigate how the spatial memory affects such waves generated by cutoff effects, some numerical simulations have been carried out by tuning the nonlocal behavior of the bank erosion dynamics. This has been done through a simple device: the exponent of the convolution integral in the u_b computation has been multiplied by a weighting parameter, $\alpha \leq 1$. For example, the solution of excess bank velocity provided by the IPS model (e.g., equation (4)) has been modified according to

$$u_b = -bUC + \frac{UbC_f}{H}\left[F^2 + A + 1\right]\int_{-\infty}^{s} e^{-\alpha\frac{2C_f}{H}(s-z)}C(z)dz. \quad (5)$$

In this way, since the spatial scale $D = H/(2C_f)$, which appears in the exponent of the integral, controls the upstream memory of the curvature series on the local movement of the river [*Howard*, 1984], only the nonlocal behavior of the river bank erosion is modified, while the local dependence remains unchanged. In the case $\alpha = 1$, the standard IPS model is obtained [*Ikeda et al.*, 1981]. Similarly, for the ZS model, all four convolution integrals in equation (3) have been multiplied by the weight α.

[30] A decrease in α implies an increase in the spatial memory, and therefore induces a different planimetric evolution. Figures 6 show an evolution example of a meandering reach for different values of the weight parameter, with and without the cutoff occurrence. The initial condition is a planform where the cutoff is incipient (the thin line). We use the case in which cutoff is disabled as a reference term of an evolution (although artificial) where the dynamical role is absent. Figure 6a shows the planforms obtained by setting $\alpha = 1$, i.e., the physically correct value. The planforms obtained taking the cutoff into account or not coincide upstream of C, while downstream, the letter A marks the limit of the zone of influence of the propagation of the noise due to cutoff. The same simulations are reported in Figures 6b and 6c but with α equal to 0.25 and 0.1, respectively. With respect to the previous case (i.e., $\alpha = 1$), the kernel in the convolution term increases. Consequently, the scale of the spatial memory grows, the range of influence of the cutoff becomes larger and point A moves downstream. It follows that the upstream influence in the meandering river migration is increased and the noise effect induced by cutoff is extended.

[31] The occurrence of a wave generated by a cutoff is also evident if the spatiotemporal evolution of the curvatures along the river is analyzed. Figure 7 shows the formation and propagation downstream of the disturbance wave. Its propagation velocity is about 0.6 m/year, which is coherent with the values observed in some real meandering rivers [e.g., *Hickin*, 1975].

[32] The above results confirm that the sudden change in the river geometry, induced by the cutoff, generates noise in the dynamics of evolution of the curve. Because of the spatial memory that is present in the morphodynamic

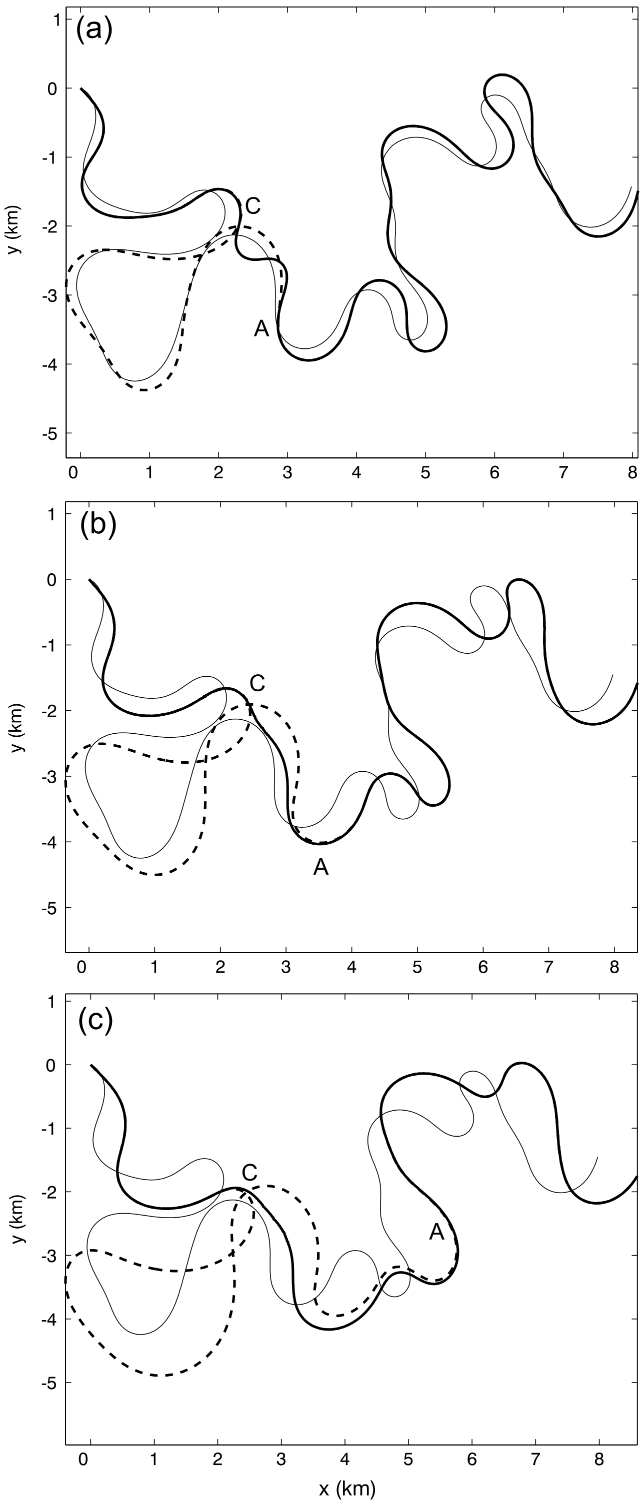

Figure 6. Simulation S1 developed with the IPS model. The thin solid curves correspond to the planimetry chosen as the initial condition (t = 0 years; the letter C marks the point of incipient cutoff), while the thick solid curves and the dashed curves provide the subsequent scenario with and without cutoff occurrence, respectively, after 3000 years (the letter A marks the limit of the zone of influence of the propagation of the noise due to cutoff). Shown are (a) α = 1, (b) α = 0.25, and (c) α = 0.1.

equations, such a noise propagates along the river disturbing the short-term deterministic dynamics.

[33] A similar analysis, carried out by *Sun et al.* [2001b], focused on the localized effect of cutoff on the bar deformation. The authors observed that cutoff can lock the downstream channel segment in a local state of resonance. However, their results cannot be compared with the present analysis since the simulations here developed are far from the resonance conditions.

4. Effects on the Geometric Nonlinearities

[34] The geometric and dynamic role of the cutoff can also be detected by investigating the reduction of the geometric nonlinearities existing in the long-term river planimetry. On one hand, the dynamics of elongation and migration of a meandering river are described by the nonlinear evolution equation (1), which introduces a deterministic spatial cubic nonlinearity in the evolution of the curvature series along the river due to the product between the derivative of **r** and the integration of curvature times the normal velocity [e.g., *Seminara et al.*, 1994, 2001]. On the other hand, cutoff occurrence tends to limit the effect of such deterministic nonlinearity, so that the spatial series of the curvatures along the river gradually loses the nonlinear spatial links and tends to resemble a series generated by a quasi-linear process. In order to show this, a test of nonlinearity [*Kantz and Schreiber*, 1997] is here applied to the spatial series of the curvatures. In particular, we use the reversibility test formulated by *Diks et al.* [1995, 1996] which is based on the fact that the spatial reversibility of a series is a property that characterizes linear dynamics [*Weiss*, 1975; *Diks et al.*, 1995; *Daw et al.*, 2000].

[35] Provided $C_i = C(s_i)$ (i = 1, .., N) the curvature series with a sampling interval Δs, a new series of m-dimensional delay vectors can be defined as $\mathbf{C}_n = \{C_n, C_{n-\Delta}, .., C_{n-(m-1)\Delta}\}$ where $n = 1 + (m-1)\Delta, .., N$ and Δ is the space lag. The curvature series C_i is reversible if the joint probability of the distribution of the delay vectors $p(\mathbf{C})$ is invariant when the series is inverted for all m and Δ, i.e., $p(P \cdot \mathbf{C}) = p(\mathbf{C})$, where $P^{m\times m}_{i,j} = \delta_{i,1+m-j}$ and δ is the Kronecker delta.

[36] According to *Diks et al.* [1995], an unbiased estimator $\hat{Q} = \sum_{k>j} w_{kj}/N$ of the distance between the distribution on the original series and the inverted series can be formulated, where N is the number of pairs,

$$w_{kj} = e^{-|\mathbf{C}_k-\mathbf{C}_j|^2/d_0^2} - e^{-|\mathbf{C}_k-P\mathbf{C}_j|^2/d_0^2}, \tag{6}$$

where d_0 is a fixed distance, and $|\cdot|$ is the Euclidean norm. A test statistic S is then computed as the ratio of $\hat{Q}$ and its standard deviation. The reversibility is rejected when the test statistics take on a large fixed value. In this way, S can be considered a surrogate of the level of nonlinearity (further details on Diks' test can be found in work by *Perucca et al.* [2005]).

[37] Figure 8 reports the computation of S for two simulations (S1 and S4 developed by the ZS model) both with and without cutoff occurrence. Again, the behavior of the two classes of simulation coincides in the first part of the run, before the cutoffs, where a rapid growth of the nonlinearities is forced by the nonlinear evolution equation (1).

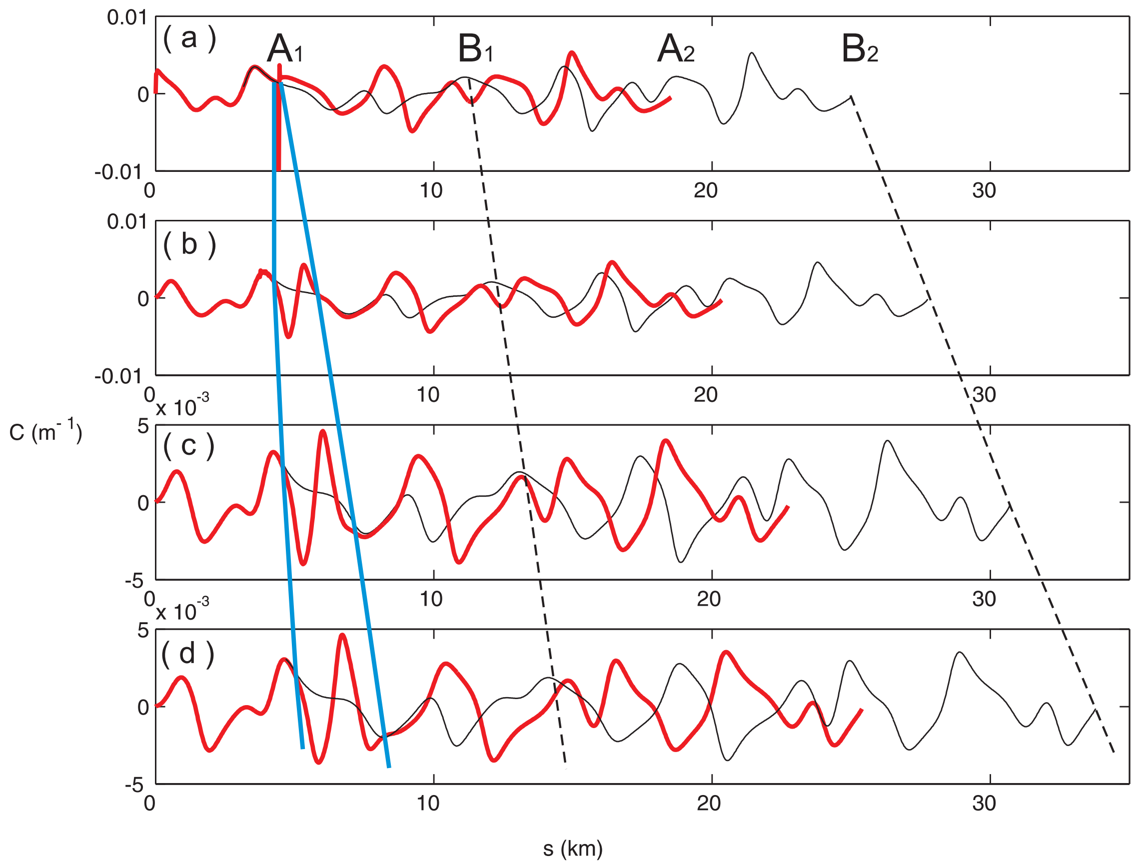

Figure 7. Series of the curvatures for simulation S1 with the cutoff occurrence (thick red curves) and without cutoff (thin curves) at (a) $t = 0$ years, (b) $t = 2000$ years, (c) $t = 4000$ years, and (d) $t = 6000$ years. The reach A_1B_1 is the portion of river eliminated by cutoff but which remains in the case without cutoff; therefore the thick curve A_1A_2 has to be compared with the thin curve B_1B_2. The solid subvertical lines isolate the evolution of the wave generated by cutoff-induced perturbation (i.e., the dynamical role). The dashed lines mark the evolution of the reach delimited by points B_1 and B_2 at $t = 0$.

Afterward, when cutoffs start to appear, the quantity S undergoes a dramatic reduction and stabilizes at low levels, while S continues to increase in the simulation where cutoff is disabled. It follows that the mechanism of cutoff, by removing long reaches from the river and generating a noise component in the dynamics, limits the growth of a nonlinear structure in the curvature series, and eventually in the planform. Thus cutoff acts as a filter in the spatial dynamics which are then simplified with respect to the nonlinear dynamics of a pure elongation mechanism. These results are in agreement with the analysis by *Perucca et al.* [2005] where some different nonlinearity tests were applied to four real river curvature series. However, in that work, the interactions with other stochastic external forcings contributed to further reduce the nonlinearity in comparison with the values obtained in the present case.

5. Conclusions

[38] In this paper, we have attempted to elucidate the different ways by which cutoff is able to influence long-term river dynamics. The analysis of some model-generated planimetric simulations have permitted two roles of cutoff,

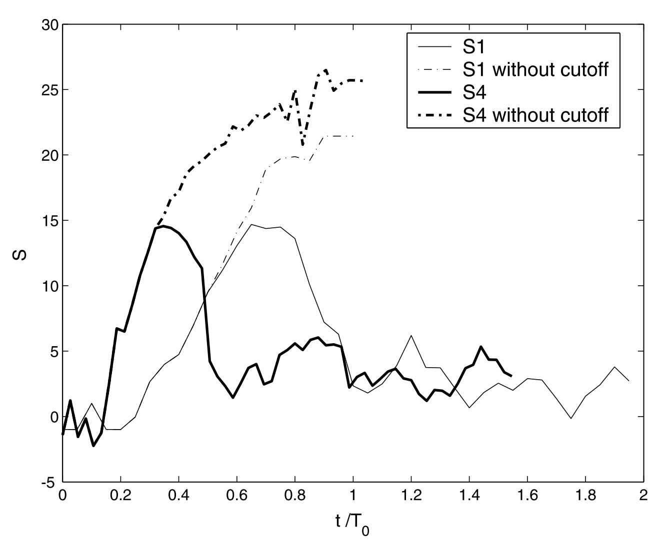

Figure 8. Application of the nonlinearity test by *Diks et al.* [1995] to the time series of the curvature provided by the ZS model in cases S1 and S4.

geometrical and dynamical, to be isolated and identified. The former entails the systematic elimination of older reaches from the active river, while the latter can be interpreted as a shot noise that randomly disturbs (in space and time) the deterministic dynamics and propagates along the river. Although we have analyzed each role individually, they are mutually dependent and related. Through the application of a reversibility test, we have detected quantitative evidence of the overall effect, namely a reduction in the degree of the nonlinearity in the curvature spatial series.

[39] The key point is that both roles have the effect of reducing the influence of several fluid dynamic processes on long-term dynamics. This effect allows one to explain why two (or more) models with different levels of fluid dynamic detail (i.e., IPS and ZS model) give rise to the same statistically steady state of the river planform. This is also consistent with the results of *Camporeale et al.* [2005], where a single spatial scale permitted some long-term planimetric statistics, obtained from different simulations, to collapse, regardless of the model used.

[40] We conclude by pointing out that further analyses are needed for a full understanding of the intriguing dynamics of cutoff processes and their interaction with the long-term behavior of meandering rivers. For example, future developments will require coupling between the numerical modeling of the morphodynamics and some real-world mechanisms, such as overflow processes, the influence of riparian vegetation and river flow variability. The mechanism of chute cutoff and its interaction with the riparian vegetation patterns in the intrameander region also deserves more attention in the future.

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C. Camporeale, E. Perucca, and L. Ridolfi, Department of Hydraulics, Politecnico di Torino, C. so Duca degli Abruzzi 24, I-10129 Torino, Italy. (carlo.camporeale@polito.it)