Chapter 10

HYDROLOGICAL AND GEOMORPHOLOGICAL SIGNIFICANCE OF RIPARIAN VEGETATION IN DRYLANDS

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1. Introduction

Drylands are regions encompassing hyper-arid, arid, semi-arid or sub-humid climatic conditions (see also, Chapter 1). They include cold and warm subtropical deserts, savannas, and the Mediterranean environments. Our focus is here on warm drylands, which are generally characterized by the existence of a well-defined dry season dominated by subtropical high pressure (Malanson, 1993), and a rainy season with average precipitation of less than 700 mm/year. Such regions cover approximately 50% of the continents, with about 20% of the world's population living in these areas (Le Houerou, 1982; Nanson et al., 2002). This explains the growing scientific interest in the study of drylands. Here we focus on the interactions between fluvial geomorphology and riparian vegetation. These interactions act at different spatial and temporal scales, suggesting the existence of an intrinsic and remarkable sensitivity of riparian ecosystems to hydrological and geomorphological modifications. Riparian ecosystems have often been affected by heavy anthropogenic disturbances, with great reductions in spatial extent (up to 80%, as in certain U.S.A. sites) with respect to presettlement times (Smith et al., 1991; Tooth, 2000a,b; Salinas et al., 2000; O'Connor, 2001; Pettit et al., 2001).

From a geomorphological point of view, vegetation near rivers can be classified as upland or riparian. Upland vegetation is present in those areas that do not belong to channels that are potentially still active. Despite its importance for a number of geomorphological processes (see for example, Malanson, 1993) upland vegetation will not be analysed in this chapter.

Riparian vegetation can be defined as an 'ecosystem adjacent to the river' (Malanson, 1993), that is, 'those plant communities which are restricted to the zone directly influenced by the stream' (Hancock et al., 1996). These characteristics suggest that differences between upland and riparian vegetation should be stronger in drylands than in humid areas (Smith et al., 1993). In fact, in semiarid and arid regions vegetation distribution and abundance is largely controlled by water availability in the nearby rivers. Thus, water availability is - fundamental to sustain the richness of species (Hancock et al., 1996) and explains why some species are only found within or close to river channels (Tooth and Nanson, 2000). Dryland rivers control the surrounding vegetation through manifold actions; for example, when the duration and intensity of flood events are not too destructive in relation to the ability of vegetation to withstand relatively infrequent submergence, floods provide debris, moisture and nutrients to the riparian soil. In this sense, short-term rainfall variability and the consequent runoff would be more important to vegetation dynamics than average long-term climatic parameters. These hydrological characteristics, along with several other environmental factors such as evapotranspiration, soil type, groundwater regime and land use, are relevant to grant the survival of the ecotone and to drive the related zonation of species (Hooke and Mant, 2002). In turn, riparian vegetation has been recognized to be fundamental in influencing the morphodynamics of equilibrium or non-equilibrium of the river, depending on the

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different response to external forcing (see, for example, Wolman and Gerson, 1978; Carter Johnson et al., 1995; Tooth and Nanson, 2000; Hooke and Mant, 2002; Nanson et al., 2002). These dynamics are yet not completely clear though some features are being studied and understood. The interaction between riparian vegetation and river dynamics is still one of the key points: this interaction would explain the peculiarity of the geometries observed in drylands both in fluvial and in vegetation patterns suggesting the need to consider the two components, i.e. river and vegetation, as dynamically coupled.

The high variety of geomorphological and riparian vegetation characteristics existing in drylands suggests that there are no geomorphic features really unique to drylands (Smith et al., 1993; Tooth, 2000a; Nash, 2001; Nanson et al., 2002). This diversity of ecological landscapes may be due to the different impacts of climatic conditions on plant ecosystems. Thus, subhumid climates do not imply necessarily the lack of water deficit. For instance, Australia has a high annual rainfall, but the corresponding high evaporation rate makes it the world's driest continent (Nanson et al., 2002). In this sense, aridity can be further emphasized by seasonal factors (Puckridge et al., 2000; Tooth, 2000a; Nanson et al., 2002) and by significant infiltration into the alluvium, with high transmission losses and important effects on river flow conditions. These losses can, for example, lead to rapid downstream decline in mean and peak discharges per unit (contributing) area (McMahon, 1979; Nanson et al., 2002). Due to the consequent irregularity and intermittence in river flow, streams can be ephemeral and discontinuous leading to fluvial dynamics, which alternate between aggradation and degradation both in time and space (Bull, 1997). The occurrence of either one of these mechanisms depends on the interplay between sedimentation, erosion and water availability, and, in turn, determines the presence and the distribution of vegetation resulting from sporadic flooding. Along the same line, the ability of dryland rivers to adjust more rapidly to climatic changes than the whole landscape, suggests that in the short term the geomorphological characteristics of these water courses may reflect contemporary climatic conditions and changes. The complexity of the fluvial and ecological processes occurring in the river channel and in the riparian zone explains the difficulty in finding a few distinctive features of dryland rivers. In the following we will focus on to the main geomorphological characteristics of the river-vegetation interaction observed worldwide in arid and semiarid regions.

The present review is organized in the following manner. Section 2 conceptually frames the type of interactions between river and riparian vegetation with a focus on the two roles (passive and active) played bt vegetation in this interaction. The main hydrological and geomorphological characteristics of rivers in drylands are discussed in Section 3. A numerical investigation of the dynamics of meandering rivers in drylands is also presented. Section 4 is devoted to riparian vegetation and to its significance within the whole fluvial ecosystem. Finally, some conclusions are drawn in Section 5.

2. Characteristics of the interaction between river and riparian vegetation

An instructive way of introducing the subject discussed in this chapter, is by focusing on the reciprocal interaction between vegetation and river dynamics: on the one hand, the river provides water to the nearby riparian environment according its hydrological, hydraulic and geomorphological characteristics; on the other hand, vegetation uses water for life and growth, and significantly affects the hydraulic and geotechnical characteristics of bed and banks, with an impact on the river morphodynamics. In this sense, the role of riparian vegetation can be interpreted as passive or active (see, Figure 1). In the first case (i.e., the passive role), the biological activity of the vegetation is not considered and only the effect of vegetation morphological and mechanical characteristics on river dynamics is discussed. From this point of view vegetation merely affects roughness, hydraulic resistance, and bank erodibility in the same manner as any a-biotic element with the same mechanical and morphological characteristics. *Vice* *versa*, vegetation is considered to be an active element if its biological activity – e.g., birth, growth, and death - and ecological dynamics are able to interact with the fluvial processes leading to changes in the evolution of river patterns and, in turn, in the whole river-riparian vegetation system.

The investigation of the passive role of vegetation is the usual approach followed in hydraulic engineering, which led to important theoretical and applied results (see, for example Kouwen and Li, 1980; Masterman and Thorne, 1992; Darby, 1999; Millar, 2000; Graf, 2002). However, some difficulties still exist in quantifying and in modeling riparian vegetation. These difficulties are in particular related to (i) the evaluation of the geotechnical characteristics of river banks as well as of the erodibility of alluvial soils; (ii) the spatial and temporal regime of soil moisture and groundwater near the river; (iii) the effect of vegetation on the flooding of the overbanks, on the kinematics of overbank flow, and on the related processes of deposition and erosion; (iv) the role of chemical and biological filtering played by riparian vegetation in the exchange processes occurring between river and upland vegetation.

The concept of an active role emerges when vegetation is no longer considered as a static element in the river dynamics but instead its temporal and spatial dynamics are included in the bio-geomorphological evolution of the river-riparian vegetation system. Thus the riparian zone should be considered in all its biotic and abiotic components, as an ecosystem with spatial and temporal patterns of interactions with the hydrological and geomorphological river regime (see,

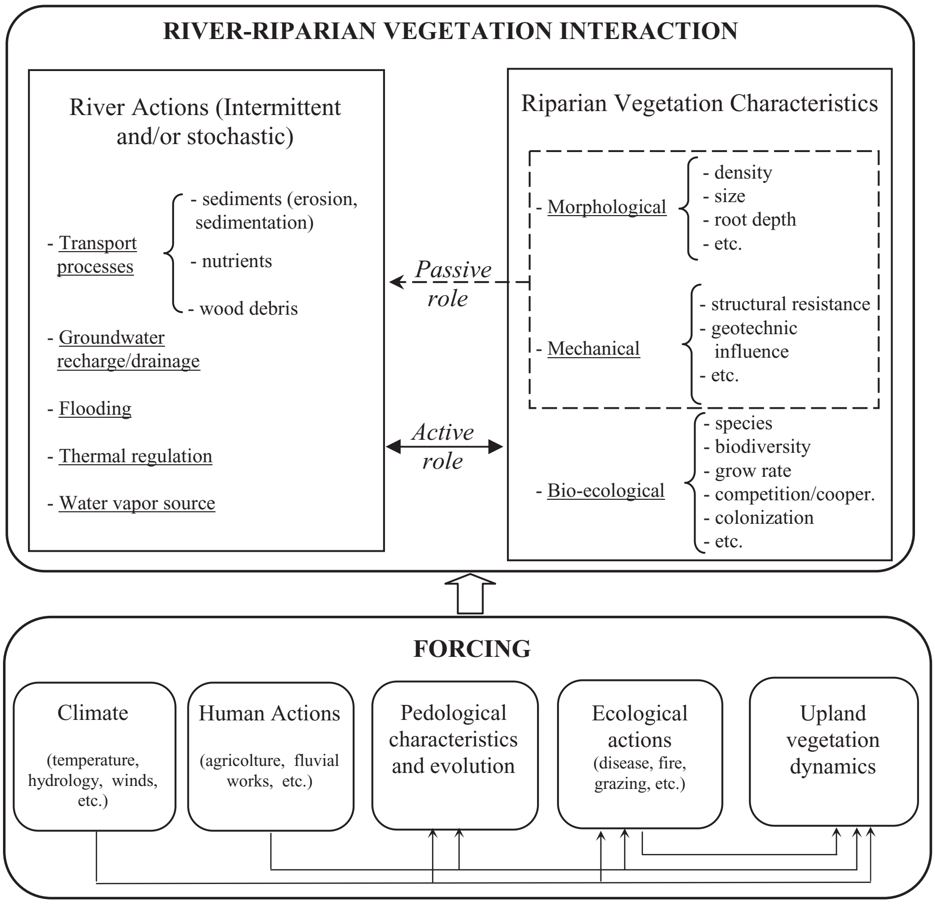


Figure 1. General scheme of the interactions between river and riparian vegetation.

Figure 1). It is important to observe that the temporal scales of river geometry evolution can be compared with those of the bio-ecological processes. Therefore, the geomorphological and vegetation dynamics are closely coupled. This coupling leads to linear and nonlinear dynamics, which may drive the river-vegetation system into an equilibrium state regulated by feedback mechanisms. Furthermore, the whole process can be subjected to the action of external forcings (see, Figure 1) able to add further complexity to the ecological and geomorphological patterns. Moreover, a number of processes listed in Figure 1 have both deterministic and stochastic components, which are able to lead to nontrivial behaviors in the evolution of the river-vegetation system (Perona et al., 2002).

It is worth remembering some of the requirements that seem to be fundamental to study the complex and fascinating picture that links river and riparian vegetation, namely: (i) an adequate selection and knowledge of the key variables involved in the phenomenon; (ii) the ability to quantitatively model the complex ecological mechanisms, such as plant recruitment, competition and cooperation intra- and inter- species, colonization of sites abandoned by the river during its planimetric evolution, water stress, and death of vegetation; (iii) to understand the influence of the hydrological and hydraulic characteristics of the river on such mechanisms, i.e. the influence of floods and the groundwater regime; (iv) to use a multidisciplinary approach with a cooperation of expertise in geomorphology, hydraulics, ecology, and bio-geography.

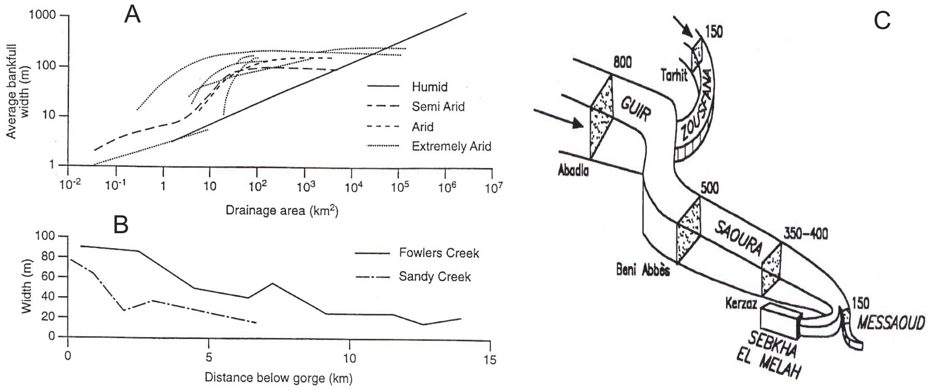
3. Main aspects of fluvial geomorphology in drylands

3.1. HYDROLOGY

The fluvial hydrology of drylands has been recently studied by a number of authors, leading to the production of a significant body of literature on this topic (see, for example, Graf, 1981; Farquharson et al., 1992; Knighton and Nanson, 1994; Thornes, 1994; Hooke and Mant, 2002; Lopez-Bermudez, 2002; Nanson et al., 2002) in spite of the difficulty in making both measurements (López-Bermudez et al., 2002) and mathematical models (Chebaane et al., 1995).

Rainfall regimes typical of arid and semiarid climates are characterized by either low and persistent or high and impulsive precipitation events, with an average annual rain of about 300-400 mm/year and the occurrence of strong isolated events. For example, sudden and intense rainfall events are responsible for the critical inundations observed in the Mediterranean regions in recent years, e.g. in Spain (López-Bermudez et al., 2002), and change in their statistical occurrence can be interpreted as a potential indicator of desertification processes (López-Bermudez et al., 2002).

The hydrological dynamics of dryland rivers are yet not clearly understood and only a few basic characteristics have been identified as being really unique to such rivers. These include: the high value of transmission losses due to both evaporation and infiltration (Hooke and Mant, 2002; Nanson et al., 2002); the downstream decrease of channel size (Figure 2a); the tendency of vegetation to colonize the river bed; the alluvial induration and lithification; the significant interactions between fluvial and aeolian processes when the river is adjacent to dunefields. Evaporation and rapid infiltration are responsible for slow and distributed water losses which may cause re-precipitation of minerals in solution (thus promoting the abovementioned effect of induration) and the consequent decrease both in peak discharge and flow volume in the downstream direction (Figure 2b). Extreme arid climatic conditions enhance transmission losses of ephemeral channels (Knighton and Nanson, 1994; Tooth, 2000b), with the consequent disappearance of some of these rivers along their course (Tooth, 2000a-b). This behavior is one of the peculiar aspects of dryland fluvial systems and it greatly influences the river-vegetation interaction (Nanson et al., 2002). In arid and semiarid regions runoff is generally dominated by Hortonian overland flow. This explains the occurrence of flash floods and the steep rising limbs of the flood hydrograph, with relatively high and frequent peak flow values (see, Knighton and



Figures 2. (a, b) Contrasting patterns in channel width along dryland channels (from Tooth, 2000b); (c) The downvalley decrease in the flood discharge (Guir-Saoura-Messaoud catchment, northwestern Sahara) (from Tooth, 2000a).

Nanson, 1997; Tooth, 2000a; Graf, 2002). Figure 3 shows as an example the flood magnitude (normalized with respect to the 2.33 yr discharge) in some dry regions of North America compared to humid European regions (Lewin, 1989; Farquharson, 1992; Knighton and Nanson, 1997).

Dryland hydrology has also a strong influence on the spatial development of river systems: a first important classification needs to be made between allogenic and endogenic rivers (Figure 4). Allogenic rivers (Figure 4a) generally have long mainstreams connecting several sub-basins; they can originate into humid and then cross semiarid, arid or even hyper arid regions. This type of river has a hydrological regime that is usually characterized by multiple intense or seasonal peaks and is likely to sustain perennial flow (Nanson et al., 2002). Endogenic rivers (Figure 4b), instead,

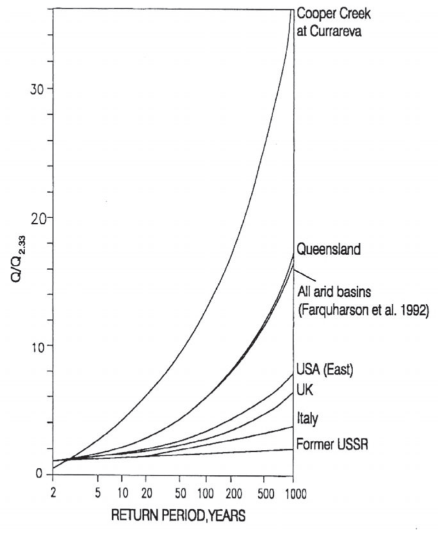
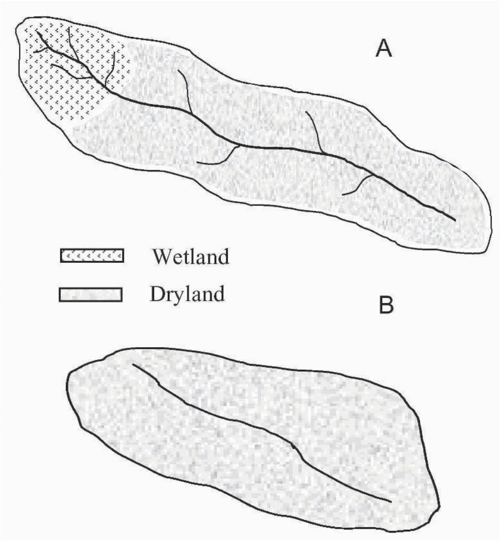


Figure 3. Regional flood frequency curve, illustrating the large increase in relative flood magnitude ($Q/Q_{2,33}$) that is characteristic of dryland regions compared to humid regions in Europe and North America (from Tooth, 2000a).



Figures 4. Scheme of allogenic (a) and endogenic (b) rivers in drylands. Because of the spatial scale, long dryland rivers belong mainly to the first category, whereas only the shorter ones are truly endogenic ephemeral or intermittent.

are short and belong to small single basins. Transmission losses are usually more pronounced for this kind of river configuration (Hooke and Mant, 2002) and the corresponding hydrological regime is usually characterized by flash floods or single peaks in the flood hydrograph, that are usually less intense and with short duration (Nanson et al., 2002).

An interesting hydrological feature regards the effects of different sediment stratigraphy on flood propagation. An interesting case observed in the extremely arid regions deals with the so-called 'red sedimentary unit' that is a continuous, compacted geological unit lying below the surficial non-cohesive alluvium (see, for example Schick, 1988; Lekach et al., 1998). In these cases, the presence of a superficial soil with high porosity and permeability hides a less permeable substrate (sub-alluvial bedrock), with the consequence that during the rare but intense rainfalls, infiltration is rapid in the first soil layer. Such a situation provides a variation to the alluvium-infiltration-flood problem and is the subject of recent discussions. Schick (1988) claimed that during inundation the wetting front is arrested by the substrate, thus giving rise to flood waves that travel on top of the saturated medium. This theory, however, has been criticized on the base of recent experiments that were conducted on a specific 'red sedimentary' site (in the Nahal Yael desert, Southern Negev, Israel), which seemed to indicate that downstream flow propagation does not necessarily requires that the medium is fully saturated (Lekach et al., 1998).

3.2. GEOMETRY

The geometry of dryland rivers is the result of the influence of hydrological and geomorphical processes, water-vegetation interaction and of the pedological characteristics of the planform. As dry regions are widely diffused throughout the world, allogenic and endogenic planforms show a large variety of landscape characteristics and slopes (for example, Mediterranean areas are mainly drained by steepland allogenic rivers and many landscapes are often shaped by the action of surface runoff water (Lopez-Bermudez et al., 2002)). This aspect explains the wide variety of geometries typical of these rivers, including braiding, meandering, anabranching or more complicated patterns, like waterholes and arroyos where the role of vegetation has been the subject of recent studies (Tooth and Nanson, 2000; Dunkerlay and Brown, 2002). In general, ephemeral channels are poorly defined, rather wide, shallow, and with low and indistinct banks (Hooke and Mant, 2002); this leads to configurations such as braiding (Graf, 1981; Clark and Davies, 1998; Tooth, 2000a, b; Nanson et al., 2002) or more confined shapes, but always with irregular patterns, such as anabranched reaches. Park (1977) and Wolman and Gerson (1978) showed that the channel width of several ephemeral channels varies nonlinearly in the downstream direction: both increasing (widening) and decreasing (narrowing) of channel width are commonly observed; this feature is in contrast to the widening generally exhibited by rivers in humid regions due to the presence of tributaries. Park (1977) calculated the values of the exponents of the power law models used to describe the scaling of width, mean depth and flow velocity with the river discharge. The numerical values of these exponents provided a first quantitative indication of the effects of both the discontinuous nature of the flow and of the high transmission losses. Such values reflect the widening and narrowing mechanisms observed along ephemeral streams: widening and narrowing occur at different time scales, ranging from hours (e.g. in the case of widening due to extreme floods), to decades (in the case of gradual narrowing associated with vegetation growth (Friedman and Lee, 2002)). Some examples exist of anabranched geometries that constitute an interesting case of mutual adaptation between river and vegetation. There are in fact some cases of streams forming sand ridges which can be colonized by vegetation and transformed into wide and vegetated islands or can give rise to deep anabranches, as in the case of the Marshall River in Australia (Wende and Nanson, 1998; Tooth and Nanson, 2000). A similar behavior is also observed in several ephemeral streams flowing across smooth valleys: these streams gradually form shallow discontinuous channels, which can also transform into arroyos (Bull, 1997). Similarly, waterholes – i.e., enlarged channel segments generated by particular concentrations of flow and by the consequent strong erosion – are also very important from an ecological point of view as they provide water to vegetation, while vegetation does not seem to have a direct influence on their formation (see, for example only a few of them being true alluvial meanders. This case is particular frequent in Mediterranean regions. The meandering geometry typical of dryland rivers has seldom been investigated, but it seems to show a lower sinuosity compared to that commonly observed in meandering rivers in humid regions (see for example Leopold and Wolman, 1960; Clark and Davies, 1998; Tooth, 2000a; , Knighton and Nanson (2000)).

Along with the aforementioned patterns, some examples of single-thread channels have also been recognized and recently documented by Tooth (2000a). He suggested that these channels can manifest either stability or instability. Stable channels can have inherited shape that comes from a past of more morphodynamic activity; in such cases the actual intrinsic stability is often associated with the presence of vegetation in the alluvium (Tooth, 2000b; Nanson et al., 2002). On the contrary, unstable channels can evolve forming series of meanders with Hooke and Mant, 2002). However, further quantitative analyses to assess the differences existing - both in the fluvial geometry and the evolutive dynamics – between rivers in dry and wet regions, still have to be investigated in detail. This fact motivated our numerical simulations presented in section 3.4.

3.3. TRANSPORT PROCESSES

Transport processes are very important for both the life of the fluvial ecotone and the planimetric evolution of the river. Most of the transport processes take place, in particular, during floods, with a significant movement of sediment load and debris (wood, waste, etc.) which modify the soil morphology and the chemical characteristics of the floodplain, thus influencing the soil moisture content as well as the quality of the water and nutrient cycling (Puckridge et al, 2000; Tooth, 2000a). In this context, it is important to observe that the amount of phosphorus, nitrogen and organic carbon in the soil, generally increases downstream and variations of such components tend to be positively correlated to the amount of silt (Jacobson et al., 2000). A positive trend in the soil salinity downstream has also been measured (Flügel, 1995; Jolly, 1996).

Dryland rivers appear to be much more efficient in bedload transport than rivers in humid zones with the same shear stress (Laronne and Reid, 1993). It has been estimated (see, for example, Langbein and Shumm (1958)) that for rivers of similar characteristics, sediment yields reach a maximum when the mean annual effective precipitation is between 250 mm and 350 mm. Sporadic inundation on dry terrain produces erosion both of the bank and of the bed so that scour material is mobilized and entrained continuously downstream (Tooth, 2000a-b). This mechanism, apart from being important for the successive remodelling of river reaches, seems to contribute significantly to increase the soil salinization of those sites where entrapment of sediments is facilitated (Jolly et al., 1993; Busch and Smith, 1995; Jacobson et al., 2000). In the transport processes, the differences with respect to humid regions have generally been attributed to the relative lack of armouring of rivers flowing in drylands (Laronne and Reid, 1993; Reid and Laronne, 1995; Reid et al., 1998).

3.4. A NUMERICAL MODEL FOR MEANDERING RIVERS IN DRYLANDS

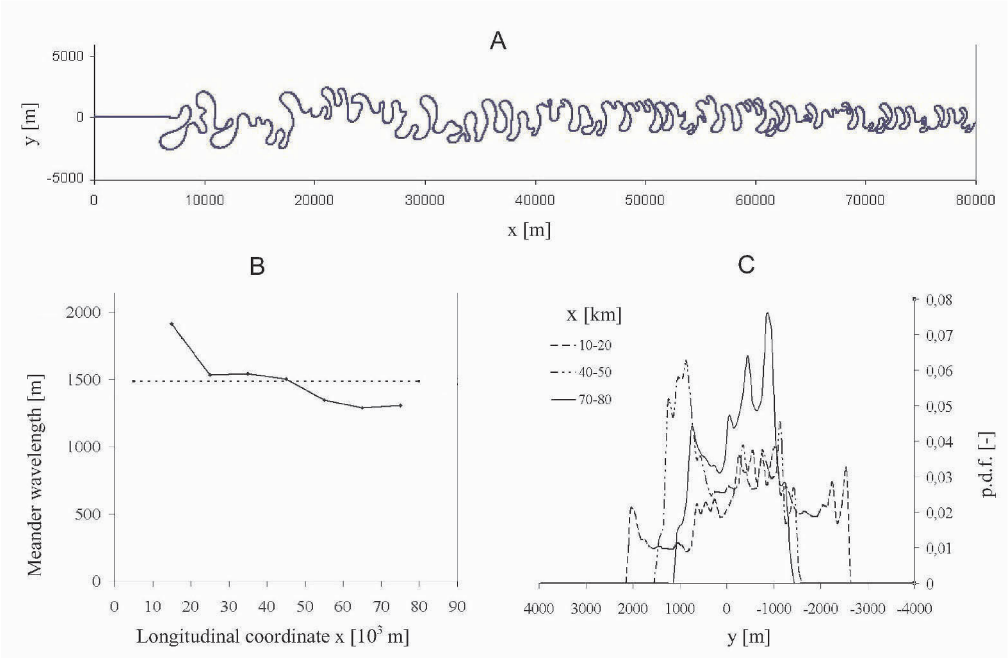
In recent years, numerical models of meandering dynamics have been used to investigate some geometric characteristics of the long term evolution of rivers in humid regions (see, for example, Howard and Knudson, 1984; Sun et al., 1996; Stølum, 1996, Perona et al., 2002). To the authors' knowledge, similar simulations have never been made for drylands. In this paragraph, therefore, we present and briefly discuss a preliminary example of such meandering processes that could occur in sub-humid or semi arid areas. In particular, we focus on the morphodynamics of potentially unstable rivers where the influence of evaporative and infiltration rates is able to reduce the flow rate downstream giving rise to a spatially decreasing discharge $Q = Q(s)$, where s is the intrinsic coordinate along the river. This hydrological effect is expected to produce interesting differences from the typical patterns that can be observed in the humid regions, where flow rate is either uniform or increases in the downstream direction.

Different models of meandering evolution have been proposed in the past by several authors (Ikeda at al., 1981; Blondeaux and Seminara, 1985; Johannesson and Parker, 1989; Zolezzi and Seminara, 2002; Lancaster and Bras, 2002). Apart from the model by Johannesson and Parker (1989) and the detailed model by Zolezzi and Seminara (2002), the approach by Ikeda et al. (1981) is commonly used in the modelling of river meandering. Despite its simplicity, this model is based on a consistent, process-based analysis of the fluid dynamical processes – through the de Saint Venant equations for shallow steady turbulent flow in a sinuous channel - and it explains some of the main features of real meanders, including wavelength selection, elongation, deformation and downstream migration (Ikeda et al., 1981). Thus, the Ikeda model is used in this section because of its ability to model the main physical processes with only a limited numerical complexity.

From a mathematical point of view, because meandering rivers have the tendency to maintain a locally constant width in time (see, for example Camporeale et al., 2004), the river can be schematically represented as a curved line evolving onto a sloped plane; the points of this line migrate driven by the local velocity in direction normal to the curve (e.g., Perona et al., 2002). Complicated mechanisms such as bank collapsing, interaction with riparian vegetation, and temporal evolution of local erodibility, are not considered in the present simulations. The essential role of cutoffs is instead taken into account, while the effect of secondary currents in the river bends is considered by assuming a semi-theoretical relationship between the topography of the bed and the local curvature of the river centreline. The downstream reduction in discharge is modelled according to the exponential law $Q = Q_0$ Exp[$-\tau s$], where Q_0 represents the initial discharge (i.e., at abscissa s=0) and τ is a parameter that regulates the discharge decay. In the simulation we choose Q_0=300 m^3/s and τ=1.37·10^{-5} m^{-1} (that is, an equivalent transmission loss of 1.2 m^3/s km). The exceeding bank velocity u_{sb} for a bankfull discharge, satisfies the following differential equation (Ikeda et al., 1981)

$$\frac{\mathrm{d}u_{sb}}{\mathrm{d}s} + 2C_f \frac{U_0}{H} = bU_0\left(\frac{Fr^2 + A + A_s - 1}{H} C_f k - \frac{\mathrm{d}k}{\mathrm{d}s}\right) \quad , \tag{1}$$

where U_0 and H are the mean velocity and the water depth of the uniform flow, Fr is the Froude number, C_f (0.0024) is a dimensionless friction factor; A and A_s (both fixed equal to 8.5) are constants that account for the bed slope and for the convective transport of downstream momentum respectively (Edwards and Smith, 2002; Camporeale et al., 2004), k is the local curvature, and b is the river half-width, assumed to vary in the downstream direction according to the relation proposed by Hey and Thorne (1986), $b=0.5aQ^c$ (a=3.74, c=0.5). In the numerical simulation, the time is discretized in time intervals Δt and the algorithm consists of the following four steps in each interval. Firstly, the exceeding bank velocity u_{sb} is evaluated by numerical integration of Eq. (1). Secondly, the relationship $v = E\, u_{sb}$ is used to obtain the bank erosion, where v is the normal-to-the-curve migration rate and E (equal to 3·10^{-5}) is the local erodibility; this relation has frequently been used (Howard and Knudson, 1984; Stølum, 1996; Sun et al., 1996) and experimentally verified (Beck, 1984; Beck et al., 1984; Pizzuto and Meckelnburg, 1989). Thirdly, the points of the river are then moved along the normal coordinate according to the scheme proposed by Sun et al., (1996). Finally, the bed slope and the discharge are updated according to the new river sinuosity. Other numerical details are reported elsewhere (Perona et al., in preparation). The results of these analyses are shown in Figures 5a-c. Figure 5a reports a meandering pattern generated by the model starting from a straight line of length L=80 km which is perturbed with additive white noise with zero mean and unit variance. It should be noted that



Figures 5a-c. (a) Example of a meandering pattern obtained after 5300 years of evolution starting from a noised straight line. (b) Longitudinal variation of the meandering wavelength and (c) the pdf of the transversal coordinate of the points occupied by the river on the floodplain. The characteristic reduction of the meandering belt width can be noted.

some cutoffs had already occurred. The effect produced by the decrease in discharge is a significant reduction of the amplitude and the wavelength of the meanders. Figure 5b shows the decrease of meander wavelength averaged in non-overlapping spatial windows (window width equal to 10 km). Figure 5c shows the time-averaged frequency density function of the transversal coordinate (*y*) of the points occupied by the meandering river after the initial transient; the amplitude of the function gives a reasonable estimation of the width of the meandering belt: the effect of the decreasing streamflow is that in the different river segments there is a reduction in the width of the "migration belt" of the river within the floodplain. It is important to recall that, at the statistical steady state, the only mechanism controlling the river spread is the effect of cutoffs (see, for example Perona et al., 2002). Such a highly nonlinear mechanism plays a fundamental role in driving the dynamics toward a probable critical self-organized statistical steady state in which the river shows geometrical characteristics that are statistically constant confirming the mechanism of self- confinement already hypothesized by Stølum (1996) and Liverpool and Edwards (1995).

These results seem to be coherent with field observations conducted on sub-humid and semi-arid regions (Clark and Davies, 1998; Tooth, 2000a-b; Hooke and Mant, 2002) and confirm some peculiar geometrical characteristics of dryland rivers.

4. Riparian vegetation

4.1. GEOMETRY AND SOME ECOLOGICAL CHARACTERISTICS

The patterns of riparian vegetation are greatly influenced by the local hydrological conditions. Unlike humid regions, seasonally arid and semiarid environments exhibit visually well-defined and easily distinguishable patterns of riparian vegetation that can be interpreted easily, by means of, for example, the quadrant analysis or other methods (Trodd and Dougill, 1998; Hooke and Mant, 2002). Riparian vegetation generally exhibits characteristic patterns (Figure 6) organised along the banks of the watercourse (see, for example Malanson, 1993). Sparse vegetation is considered to be mainly the result of heavy erosion during floods, however this effect can be enhanced by other concomitant disturbances (e.g., deep groundwater level, severe local aridity) from which vegetation may take many years to recover (Nanson et al., 2002). Conversely, regularly distributed vegetation is typical of conditions with more regular and sufficient water availability.

Riparian vegetation species are usually *phreatophytes*, i.e. species with a tangled root system that is directly connected to the groundwater table (Robinson, 1958; Graf, 2002). Grass and shrub communities generally prevail among riparian floodplain species and their zonation along valley floors can vary considerably, as is the case in Mediterranean regions (Hooke and Mant, 2002). Analyses of the sources of water used by these species carried out in the San Pedro River (Arizona, U.S.A.) show that grasslands basically rely on recent precipitation, while mesquite shrubs obtain water from deeper zones in the soil profile and are therefore more sensitive to groundwater changes (Scott at al., 2000). Other field observations have shown significant differences in vegetation species due to the geographical location of sites and the local climate (Hupp and Osterkamp, 1985; Wainwright et al., 2002). Hancock et al. (1996), for instance, argued that arid catchments exhibit riparian vegetation with more complex structure, survival ability and competitive strategy than upland vegetation which, is instead more inclined to tolerate water stress. This agrees with predictions made by the Competitor-Stress tolerator-Ruderal (C-S-R) model proposed by Grime (1979) and interesting examples have been found in some sites across the western U.S.A. (Kauffman et al., 1983, Tucker Shulz et al., 1990; Hancock et al., 1996).

The dynamics of riparian vegetation in drylands seems to be predominantly influenced by the competition (or cooperation) between different communities classified as native dominant, pioneering, invader or opportunistic. Their main characteristics are briefly outlined in the

Figure 6. Riparian vegetation along the slowly disappearing Sandover River, Central Australia (from Tooth, 2000b).

Table I. Example of a classification of plant species according to their behaviour and adaptability.

Characteristics	Species	Soil type
Pionering	*Salix Caprea, Cottonwood, Malaleuca argentea, etc*	riparian floodplain, water shelf
Invaders	*Tamarix Ramossis*ima, *Artemisia Tridentata*), *Rosa Woodsii, etc*	riparian floodplain, river bed
Opportunistic	*Teatrees*	sandy, mod. gravel bars
Native dominant	*Reichardia picroides,Phlomis fructicosa, Dianthus vultaria*	cultivated, very arid lands
	Artemisia barberia, Inula viscosa Lygeum spartum	dry rocky hillslops, even. degradated

following (see also Table I), but it should be noted that this classification is not closely connected to any particular species, since in some cases these could potentially belong to either one or another class, depending on the geographical and climatic conditions.

The native dominant species become well established locally and organized in a cooperative co-existence, with a yearly life cycle that is characterized by seasonal growth. Depending on flood frequency, the season of flood occurrence, flood intensity, and land use, such species can be found rather close to the watercourses (Hughes, 1990). The density of dominant species can vary in space (along rivers and within them as partial invaders) and time (invasions of river beds can be destroyed by even moderate floods), while the hydrological characteristics of floods seems to have a remarkable effect on the evolution of this type of vegetation (Hooke and Mant, 2002). The pioneering species (see, Malanson (1993) and Hancock et al. (1996) for a more detailed classification) show (i) a rapid growth rate, (ii) enough flexibility and adaptation to form reclined habits (this is called 'f-strategy' and is adopted by trees when strong external forces are applied (see, for example Mosbrugger, 1990)), (iii) recruitment and encroachment, that mostly occur in the bed of the river, and (iv) a good group strategy. Therefore pioneering species have the typical characteristics that are necessary for efficient rooting. *Malaleuca Argentea*, for instance, spends 90% of the time in low stage of an ephemeral river in tropical environments and has a multiple stem form (which ensures that at least a part of the tree remains intact during severe flood events), modified bark (thick and multi-layered as a protection against traveling debris), modified crown and root development to adapt to extreme variation in water supply, and adventitious buds, which allow for rapid recovering after damages (Fielding et al., 1997).

The invader species are often associated with exotic species imported from other sites that in some cases are even geographically distant. Because of their water tolerance these plant communities sometimes have a competitive advantage over native species (Graf, 2002). This quality makes them the ideal candidates for sites where streamflow diversion, whether natural or anthropic, can be particularly severe. Examples found in literature include the case of Bishop Creek (Nevada), where the invasion of sagebrush (*Artemisia Tridentata*) and *Rosa Woodsii* produced a consequent reduction of the native riparian vegetation (Smith et al., 1991) or Southwestern Australia, where the invasion of *Tamarix* was clearly induced by river regulation (Griffin et al., 1989; Tooth, 2000a).

Opportunistic species, such as *teatrees*, grow in the periods subsequent to infrequent floods; their stems are sufficiently flexible to allow them to survive moderate inundation and damage during floods; they are able to live in highly stressed channel-bed habitats and are likely to co-exist with local species (Tooth and Nanson, 2000).

4.2. VEGETATION EFFECT ON ROUGHNESS AND SEDIMENT TRANSPORT

It is commonly recognized that the presence of vegetation greatly affects local channel roughness (Graeme and Dunkerlay, 1993; Nanson et al., 2002) as well as the mechanisms of erosion and sediment deposition (Ashworth, 1996; Huang and Nanson, 1997, Hooke and Mant, 2002). Nanson et al. (2002), showed that channel morphogenesis is driven by the important role of vegetation due to its impact on the interaction between flow and sediment transport. However, sedimentation is not necessarily high in all vegetated reaches since it depends on the cover density, which is in turn influenced by many other variables. For example, Hooke and Mant (2002) observed that, in some drylands in Spain, the mechanism of flow-vegetation interaction depends also on species, age, position (i.e. transversal or longitudinal and elevation above the river bed), zonation, and season: these factors play a crucial role on vegetation influence and on the hydrological dynamics of river channel and riparian zone. A quantitative assessment based on field campaign measurements and calculation of the dependence of hydraulic roughness on density and average diameter of woody vegetation were proposed by McKenney et al. (1995); their analyses were made on groups of trees of different age and indicated that, in the case of adult

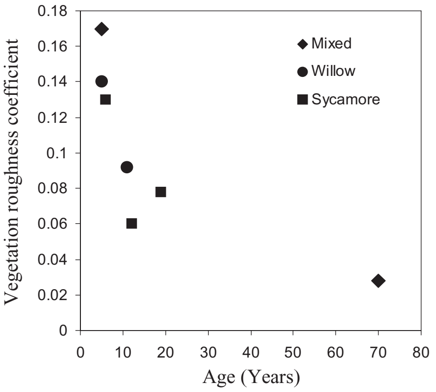


Figure 7. Graph of roughness values versus age for vegetation groups. The vegetation becomes less effective in providing flow resistance with age (after McKenney at al.,1995).

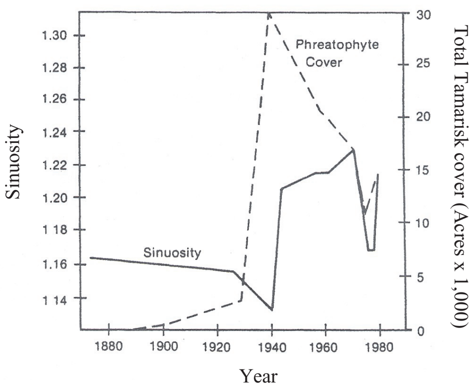


Figure 8. Gila River, Arizona. Relationship between density, coverage and channel sinuosity; this latter occurred mainly during flood periods, thus explaining the lag with vegetation changes (after Graf, 1981).

vegetation, flow resistance decreases with the age (see Figure 7). This result is particularly interesting because young and dense vegetation can significantly contribute to flow resistance; in low-energy zones, this favours the formation of sedimentation sites with an effect on the stabilization of the river morphology. An example of these dynamics is reported in Salinas et al. (2002), who investigated the role of highly developed root systems in river bank stabilization in a semi-arid region of Spain. This effect was discussed also by Hooke and Mant (2002), and explains why in many cases the stabilizing effect is associated with a gradual channel narrowing (Tooth, 2000b) or a reduction in channel sinuosity (Graf, 1981) (see Figure 8), thus showing the clear active role (in the sense explained in Figure 1) of the riparian ecosystem. An example of the opposite influence of vegetation concerns the channel invasion of phreatophytes leaving little space for water flow. Because of the frequent water deficit and the high spatial-temporal variability of precipitation typical of drylands, plants can colonize the river bed and develop a relatively dense vegetation. Despite the different effect of the various vegetation types (Hooke and Mant, 2002) on the channel hydraulics, the bed colonization increases the frequency of bankfull discharge as well as that of overbank floods, which, in turn, remove part of the vegetation and consequently change the fluvial morphology (Graf, 1980; Thornes, 1994; Tooth, 2000b). This uprooting mechanism is considered to be responsible for channel widening and lateral erosion. Moreover, the return period of floods plays an important role; in fact, flash floods can be more destructive than useful for the growth of young vegetation, while moderate floods significantly recharge the ground, providing soil moisture which is used by vegetation during the growing season (Hooke and Mant, 2002).

After heavy floods have occurred, the active role of vegetation becomes fundamental for channel recovery (Hooke and Mant, 2002) or can lead to the formation of intriguing shapes such as anabranching channels. This type of channel would represent the optimal equilibrium configuration to carry water and sediments, and is therefore also important for apportion and distribution of nutrients along rivers (Nanson et al., 2002).

4.3. ROLE OF SOME SOIL CHARACTERISTICS

The role of riparian vegetation, whether active or passive, is fundamental as it provides nutrients to the ecotone and affects the water quality. Vegetation also controls algae proliferation as it offers shadow to the river. The passive effect given by both bed and bank vegetation encourages the local deposition of fine material (Salinas et al., 2000) rich in organic matter and nutrients

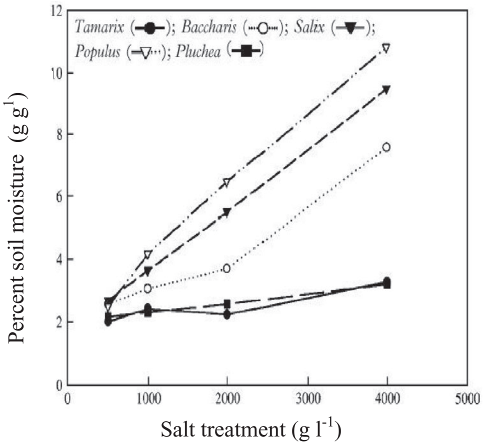


Figure 9. Average percent of soil moisture in root zones of riparian plants grown on four salinity treatments (after Vandersande et al., 2001).

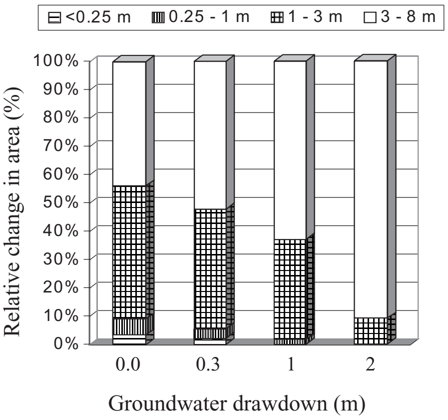


Figure 10. Relative change in extent of four depth-to-groundwater zones of the San Pedro river floodplain, for four hypothetical groundwater decline scenarios (after Stromberg et al., 1996).

(Jacobson, 2000). These apportions of material, thanks to the combined contribution of the fertility of fine sediments and the post-mortem role of wood debris, are important for the soil enrichment of new habitats (Forbes, 1902). The way fine sediments augment fertility is closely related to the silt layer that influences soil moisture dynamics and, in turn, decomposition and nutrient cycling (Chapter 8). Moreover, silt layers act as hydraulic barriers: in conditions of overbank flow moisture is stored on the floodplain (Higgins et al., 1997), thus providing a microhabitat, which is favourable for blue-green algae, fungi, lower plants and invertebrates. It has been also found that high values, i.e. peaks, in vegetation density correspond to peaks in soil silt and nutrient contents (Jacobson et al., 2000). Some connections have emerged from interesting observations monitored in the Namib desert (Namibia, Africa) by Jacobson et al. (2000), between the soil moisture regime and the related soil properties. While sands can become dry at depths of tens of cm, several centimetres of silt can maintain subsurface soil moisture levels of some percent (by weight) for several months or weeks after a flood (Jacobson et al., 2000).

Another factor considered as important to the biological activity of some vegetation species is the soil salinity, which usually increases downstream. This increase in salinity can be attributed to the combined effect of leaching and evaporation. The ability to spread under such conditions is a characteristic of some riparian tree species and is sometimes enhanced by their distribution, morphology and productivity (Jolly et al., 1993; Bush and Smith, 1995). As an example, Vandersande et al. (2001) compared the effects of both salt and water stress between native and invasive species in the Colorado River (Arizona, U.S.A) and found that invaders have a greater stress tolerance and competitive ability to extract water under increasing soil salinity than native species (Figure 9). The reduction in the mean flow discharge and the consequent increase in salinity have therefore been used to explain the absence or the disappearance of some species (i.e., the *Faidherbia albidia* in some riparian sites of ephemeral rivers in the Namib desert), with the successive replacement by halophytic (Jacobson et al., 2000) or phreatophytic species wherever the dieback and decline of dominant riparian species have occurred (Jolly et al., 1993; Bush and Smith, 1995; Jolly, 1996; Vandersande et al., 2001). Thus, soil salinity is an important factor characterising the current evolution of the ecotone and can be used to predict environmental changes resulting from natural or anthropogenic diversions of river flow (Jolly, 1996; Rozin and Schick, 1996; Jacobson et al., 2000; O'Connor, 2001).

4.4. ROLE OF GROUNDWATER

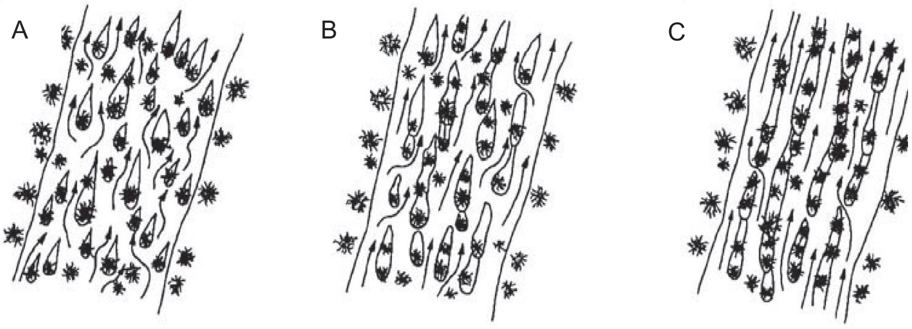
Because riparian vegetation relies heavily on groundwater (Figure 10, see also Malanson, 1993; Stromberg et al., 1996; Higgins, 1997), an accurate knowledge of groundwater dynamics is therefore necessary. Dryland sediments generally have a higher porosity than in wet regions, thus causing groundwater processes near rivers to be strongly dependent on the stratigraphy. In some riparian zones groundwater is recharged mostly by infiltration into the alluvium and groundwater flow from the river to the nearby area (Malanson, 1993; Stromberg, 1993; Carter Johnson et al., 1995; Stromberg et al., 1996). In the absence of major unconfined aquifers, the water table decreases away from the river. Figure 10 shows the results of the experiments made by Stromberg et al. (1996) where four zones (with depth-to-groundwater ranging from 0.25 – 8 m) respond markedly to different scenarios of groundwater drawdown. This picture represents in a sense the draining capacity of arid environments and, thus it suggests that there is only a limited lateral zone where roots are still able to uptake water. Water uptake is the main mechanism controlling vegetation survival in drylands. Smith et al. (1991), for example, showed some interesting differences in water use for species in uplands or in riparian areas. Only riparian vegetation, which grows along the river banks, uses groundwater. The access to groundwater resources allows riparian vegetation to survive longer in dry periods. This has important effects on the impact of anthropogenic disturbances to the natural river flow as indicated for example by O'Connor (2001) in a study on the effects of dam construction on downstream vegetation in small catchments in the Northern Province (South Africa): during low flow periods the reduced soil water availability may not be sufficient to meet the high evaporative demands of the atmosphere under typical late summer climatic conditions, leading to changes in vegetation patterns. Smith et al. (1991), for instance, investigated the effects of stream diversion consequent to the construction of hydroelectric plants on the Bishop Creek (Nevada) and showed that, in the diverted reaches, the reduction of the groundwater table increases the frequency and the level of water stress in vegetation. As a consequence, changes in the physiological behavior (e.g. of reduced leaf size, reduced leaf area per unit length and increased leaf thickness) were observed for all species. These effects were more pronounced for juvenils, indicating that in the early stages of life plants are particularly vulnerable to extreme drought conditions. It was concluded that these changes are typical of adaptations of broad leaf vegetation to water deficit (Smith et al., 1991). Streamflow diversion and the elimination of high flows can have important effects on aquifer recharge, leading to the depletion of groundwater, with a negative impact on plant communities in the riparian zone (Stromberg, 2001).

4.5. CONCEPTUAL MODELS OF RIVER-VEGETATION INTERACTION

Conceptual models of river-vegetation dynamics aim to understand and, consequently, describe the interactions between fluvial processes and riparian vegetation as well as their impact on the geomorphological modifications occurring at time scales ranging from years to several decades. These models concentrate qualitatively on some aspects of the passive and active role of vegetation in fluvial geomorphology described in Section 2. Their mathematical formalization allows for numerical or analytical solutions, which provide quantitative predictions. Conceptual models are of fundamental importance from both a speculative and applicative point of view. These models allow the analysis of the behavior of riparian vegetation (in terms of percentage cover, species richness, degree of connectivity, number of exotic plants, and natural regeneration) in relation to environmental changes and to identify zones that need restoration. For example, Rozin and Shick (1996) used models to analyse the effects of grazing in Israel; Salinas et al. (2000) compared the effect of different anthropogenic disturbances and their relative effects in the South-eastern Iberian Penisula. Their observations suggested that water channelling and modern agriculture can alter or even eliminate natural vegetation, while the effects of mining and sewage are quite limited in space and time (paradoxically the disturbed zones can give rise to heophyte communities that harbour important species of birds).

After the works by Wolman and Gerson (1978) and Stromberg (1993) dealing with the description of the complex vegetation-fluvial dynamics in semi-arid and arid ecosystems in the U.S.A., some new contributions have been made recently to the modelling of river-vegetation interaction in humid regions (McKenney et al., 1995), in Mediterranean areas (Brookes et al., 2000; Hooke and Mant, 2002) and in Australia (Tooth and Nanson, 2000; Tooth, 2000b). The observations proposed by Wolman and Gerson (1978), and also discussed by Hooke and Mant (2002), support the hypothesis that significant changes in vegetation would take place only during a limited number of high and infrequent flow events, and that only small adjustments occur in between these events. The model does not lead to any equilibrium state for ephemeral streams, but illustrates the effects caused by flows of different magnitudes. Hooke and Mant (2002) noticed that these models describe too extreme conditions for some sub-humid and semi-arid environments such as parts of the Mediterranean basin where vegetation is present in significant quantities and non-aquatic vegetation can be found in channels. In this case vegetation has a significant impact on flood propagation (Hooke and Mant, 2002). While Brooks et al. (2000) aimed to modelling such an effect, McKenney et al. (1995) suggested a more detailed analysis and explained the progressive decrease in the geomorphic threshold for bar erosion after germination of a vegetation band.

Tooth and Nanson (2000) suggested an interesting interpretative model for river anabranching mechanisms in the presence of *teatrees*. On the basis of their observations the formation of anabranching channels would occur in three phases (Figure 11 a-c) and would be driven by the interactions between vegetation growth and sedimentation. The chaotic growth of vegetation on the channel bed in ephemeral channels induces flow separation which influences the local patterns of velocity, bed shear, erosion, deposition and accumulation of sediment in the lee of the obstacles, thus forming lemniscate forms that show clues of self-similarity (Figure 11a). In the second step (Figure 11b), lemniscate shapes of sediment deposits, which concentrate the flow giving rise to stable vegetated sand deposits over which local clusters of vegetation aligned along the stream. Finally (Figure 11c), the clusters of vegetation coalesce and form longitudinal ridges so that the stream is concentrated in relatively narrow channels that are free of vegetation. Strong floods can damage these structures and the cycle starts again (Nanson et al., 2002). Reaches disturbed by the interplay between flooding and dry periods are characterized by more intriguing dynamics of vegetation interacting with erosion and deposition processes. This would explain the formation of vegetation islands in high-energy zones (or riffles), i.e. where channel movement is dominated by avulsion (Graf, 1981; McKenney et al., 1995; Tooth and Nanson, 2000).



Figures 11a-c.The three basic steps of the conceptual model for river anabranching formation proposed by Tooth & Nanson (2000).

5. Conclusions

This chapter concentrated on the importance of riparian vegetation in dryland river morphodynamics. Due to the variety of hydrological and geomorphological characteristics of arid and semiarid regions and to the difficulties involved in carrying out reliable measurements, it is not yet clear whether a general classification of the main features of dryland rivers and riparian vegetation can be made. Most of the existing literature on this topic remarks that river dynamics and vegetation evolution in drylands are closely linked and it is not possible to study them separately. This calls for cooperation within the science community to develop an interdisciplinary eco-hydrological and eco-hydraulic approach to the study of the effect of the interactions between fluvial processes and riparian vegetation. An example of a possible quantitative framework for the study of fluvial-vegetation dynamics is suggested in this chapter by our study on the effect of transmission losses on the dynamics of meandering rivers.

The review of existing studies on river- riparian vegetation interactions suggests two fundamental directions for future research in this field. On the one hand, there is the need for more detailed and extensive analyses of real cases of riparian environments, with measurements of hydrological, hydraulic, ecological, and geomorphological quantities. On the other hand, new qualitative and quantitative conceptual models need to be developed, which are able to connect and organize the experimental observations. These models should describe the complex river-riparian vegetation system as a whole, and lead to a better understanding, prediction, and control of its response to external forcing. These models could be subsequently used also to assess river system sensitivity to environmental change as well as to test future management strategies (Cummins, 1993; Halse and Jensen, 1993; Zalewski et al., 1998; Zalewski, 2000; Stromberg, 2001).

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