Chapter 10
Hydrological and Geomorphological Significance of Riparian Vegetation in Drylands

Carlo Camporeale, Paolo Perona, and Luca Ridolfi

1 Introduction

Drylands are regions encompassing hyperarid, arid, semiarid, or subhumid climatic conditions (see also Chap. 1). They include cold and warm subtropical deserts, savannas, and the Mediterranean environments. Our focus here is 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 an 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. In this respect, geomorphological resilience to disturbances of either climatic or anthropic origin has recently been questioned (Tooth 2018). Dryland riparian ecosystems are (spatially) linear oases playing the role of humid spots in dryland regions (see Tooth and McCarthy (2007) for a review) used by people and wildlife (Fig. 10.1). However, such ecosystems have been affected by heavy anthropogenic disturbances and risks associated with the encroachment of invasive riparian species, with great reductions in spatial extent (up to 80%, as in certain USA sites) with respect to

C. Camporeale (✉) · L. Ridolfi
Department of Environmental, Land and Infrastructure Engineering, Politecnico di Torino, Turin, Italy
e-mail: carlo.camporeale@polito.it; luca.ridolfi@polito.it

P. Perona
School of Engineering, Institute for Infrastructure and Environment, The University of Edinburgh, Edinburgh, UK
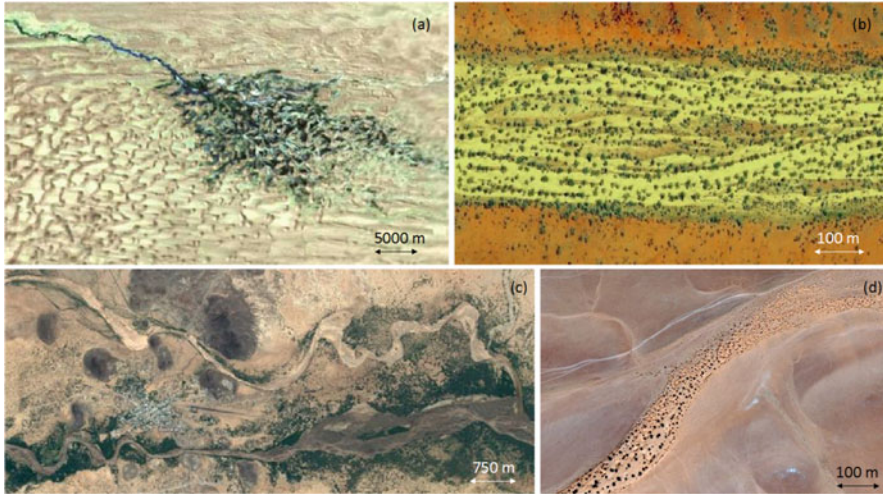e-mail: paolo.perona@ed.ac.uk

Fig. 10.1 Aerial photographs of some exemplary dryland riverine environments: (**a**) the slowly disappearing Keriya River near Qiawali in the Taklimakan desert (China); (**b**) Marshall River (Australian northern territory) anabranching patterns showing regular vegetated ridges and channels; (**c**) contrasting riparian corridors of the perennial Turkwel river and the ephemeral Kawalasee river near Lodwar (Kenya); (**d**) sparse in-channel vegetation slowly disappearing downstream in an ephemeral river (name unknown) in the Hamade de Tinrhert desert (Libya)

presettlement times (Smith et al. 1991; Tooth 2000a, b; Salinas et al. 2000; O'Connor 2001; Pettit et al. 2001; Williams et al. 2013). This also sets the risk of reducing common property resources in drylands, e.g., water bodies and related ecological functions being benefited by a community or a group of communities (Gaur et al. 2018) and ecosystem species (McGinnes et al. 2010).

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, e.g., Malanson 1993), upland vegetation will not be analyzed in this chapter.

Riparian vegetation can be defined as an "ecosystem adjacent to the river" (Malanson 1993), that is, "those plant communities (e.g., Fig. 10.1) 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 are 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 play more important roles 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; Vesipa et al. 2017; Palmquist et al. 2018). In turn, riparian vegetation has been recognized to be fundamental in influencing the morphodynamics of equilibrium or nonequilibrium of the river, depending on the different response to external forcing (see, e.g., Wolman and Gerson 1978; Carter Johnson et al. 1995; Tooth and Nanson 2000; Hooke and Mant 2002; Nanson et al. 2002; Camporeale et al. 2013). These dynamics are not yet 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, that is, 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). Moreover, riparian vegetation is often sparse, which seems to cause bank resistance to depend in large part on a high clay content (North et al. 2007).

This diversity of ecological landscapes may be due to the different impacts of climatic conditions on plant ecosystems. Thus, subhumid climates do not necessarily imply 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 a 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. The next section conceptually frames the type of interactions between river and riparian vegetation with a focus on the two roles (passive and active) played by vegetation in this interaction. The main hydrological and geomorphological characteristics of rivers in drylands are discussed in Sect. 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. Section 5 summarizes actual knowledge on dryland riparian vegetation with a river restoration perspective. Finally, some conclusions are drawn in Sect. 6.

2 Characteristics of the Interaction Between River and Riparian Vegetation

An instructive way to introduce 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 to 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 river morphodynamics. In this sense, the role of riparian vegetation can be interpreted as passive or active (see Fig. 10.2). 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 abiotic 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. A comprehensive review on the subject was written by Camporeale et al. (2013).

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, e.g., 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 dynamics. These difficulties are in particular related to (1) the evaluation of the geotechnical characteristics of riverbanks as well as of the erodibility of alluvial soils; (2) the spatial and temporal regime of soil moisture and groundwater near the river; (3) 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; and (4) the role of chemical and biological filtering played
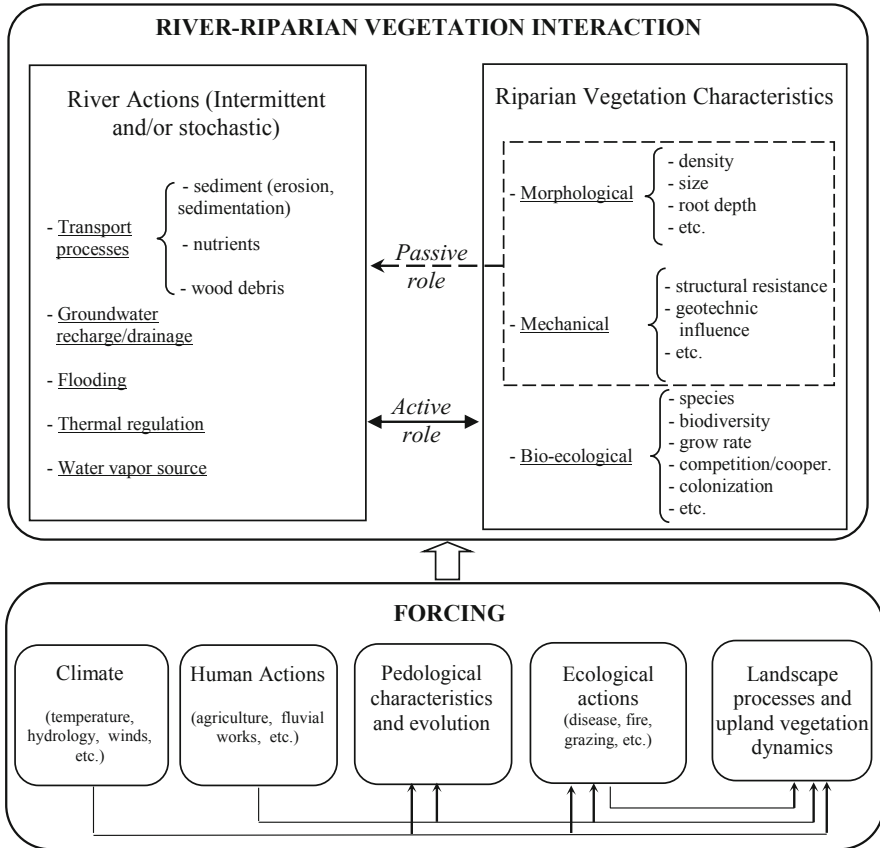
Fig. 10.2 General scheme of the interactions between river and riparian vegetation

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. Hence, the riparian zone should be considered in all its biotic and abiotic components, as an ecosystem with spatial and temporal patterns of interactions within the hydrological and geomorphological river regime (see Fig. 10.2). It is important to observe that the temporal scales of river geometry evolution can be comparable with those of the bioecological processes. In this case, the geomorphological and vegetation dynamics are closely coupled. This coupling leads to linear and nonlinear dynamics, which may drive the river-vegetation system into more or less stable ecomorphological patterns regulated by feedback mechanisms (Camporeale and Ridolfi 2010; Tealdi et al. 2011; Bertagni et al. 2018). The whole process can be subjected to the action of external forcings (see Fig. 10.2)

able to add further complexity to the ecological and geomorphological patterns. Moreover, a number of processes listed in Fig. 10.2 exhibit both deterministic and stochastic components, which are able to lead to nontrivial behaviors in the evolution of the river-vegetation system (e.g., see Ridolfi et al. (2011) for an overview).

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, (1) an adequate selection and knowledge of the key variables involved in the processes (e.g., Gurnell 2014); (2) the ability to quantitatively model the complex ecomorphodynamic mechanisms, such as plant recruitment, competition and cooperation of intra- and interspecies, colonization of sites abandoned by the river during its planimetric evolution, water stress, and death of vegetation (e.g., Camporeale et al. 2013); and (3) understanding and modeling the influence of the hydrological and hydraulic characteristics of the river on such mechanisms, e.g., the influence of floods and the groundwater regime on plant root growth (Camporeale and Ridolfi 2006; Tron et al. 2015) and their effects on sediment stability and the uprooting dynamics (Perona and Crouzy 2018) and on vegetation recovery times after disturbances (Vesipa et al. 2016).

Since the first version of this chapter was published in 2005, many studies have also started to address the ecological and social relevance of both climatic and anthropogenic forcing on dryland river ecosystems. These include woodland bird decay (McGinnes et al. 2010) and common property resources (Gaur et al. 2018). It is becoming increasingly clear that multidisciplinary approaches drawing from expertise in geomorphology, hydrology, ecology, biogeography, sociology, and economics are required in order to understand and model the complexity of dryland environments. Some of these disciplines have indeed been cooperating to form, for example, the modern ecohydrology, ecohydraulics, and ecomorphodynamics.

3 Main Aspects of Fluvial Geomorphology in Drylands

3.1 Hydrology

The fluvial hydrology of drylands has been studied by a number of authors, leading to the production of a significant body of literature on this topic (see, e.g., Graf 1981; Farquharson et al. 1992; Knighton and Nanson 1994; Thornes 1994; Hooke and Mant 2002; Lopez-Bermudez et al. 2002; Nanson et al. 2002). In spite of the difficulty in making measurements (Lopez-Bermudez et al. 2002), some mathematical models are available (Chebaane et al. 1995; Jarihani et al. 2015; Yao et al. 2018).

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 (Lopez-Bermudez et al. 2002), and change in their statistical occurrence can be
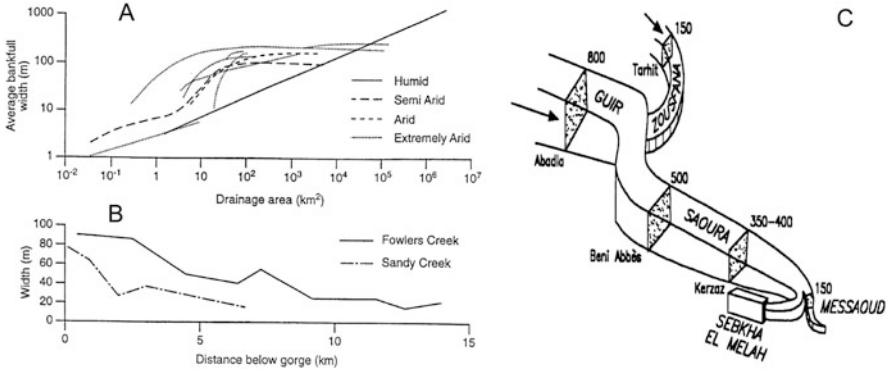
Fig. 10.3 (**a**, **b**) Contrasting patterns in channel width along dryland channels (from Tooth 2000b); (**c**) the downvalley decrease in the flood discharge (Guir-Saoura-Messaoud catchment, northwestern Sahara) (from Tooth 2000a)

interpreted as a potential indicator of desertification processes (Lopez-Bermudez et al. 2002).

The hydrological dynamics of dryland rivers are not yet clearly understood, and only a few basic characteristics have been identified as being really unique to such rivers. These include the high value of channel transmission losses due to both evaporation and infiltration (Hooke and Mant 2002; Nanson et al. 2002; Morin et al. 2009; Costa et al. 2013), the downstream decrease of channel size (Fig. 10.3a), the tendency of vegetation to colonize the riverbed, the alluvial induration and lithification, and the significant interactions between fluvial and Aeolian processes when the river is adjacent to dune fields. As a result, the dynamics of channel transmission losses show strong nonlinear dependence on streamflow magnitude and generally increase with it [e.g., Costa et al. (2013)]. 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 (Fig. 10.3b).

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 Nanson 1997; Tooth 2000a; Graf 2002; Bunn et al. 2006). Figure 10.4 shows as an example the flood magnitude (normalized with respect to the 2.33-year discharge) in some dry regions of North America compared to humid European regions (Lewin 1989; Farquharson et al. 1992; Knighton and Nanson 1997).

Fig. 10.4 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)
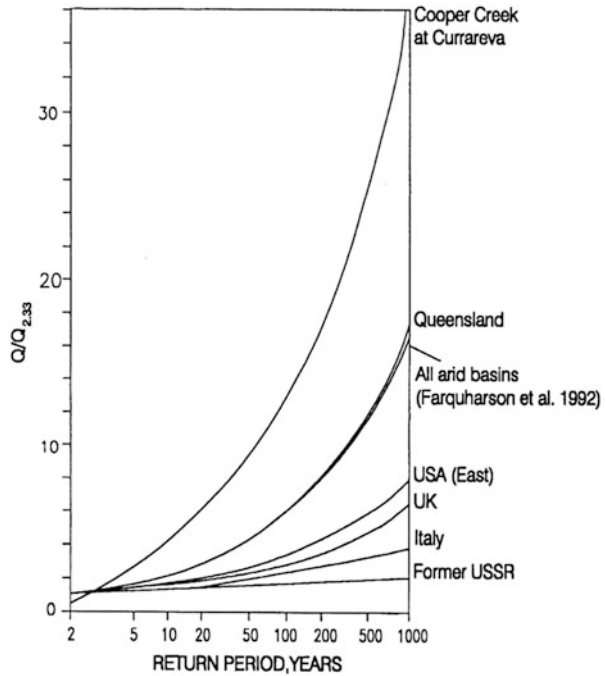
Dryland hydrology also has a strong influence on the spatial development of river systems: a first important classification needs to be made between allogenic and endogenic rivers (Fig. 10.5). Allogenic rivers (Fig. 10.5a) generally have long mainstreams connecting several subbasins; they can originate in humid and then cross semiarid, arid, or even hyperarid 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 (Fig. 10.5b), instead, are short and belong to small single basins. Channel 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). This would suggest that a correct representation of channel transmission losses is key for modeling hydrological and hydrodynamic phenomena in arid and semiarid regions. Likely, the degree of aridity may increase the prediction uncertainty (Costa et al. 2013).

An interesting hydrological feature is the effect of different sediment stratigraphy on flood propagation. One interesting case observed in 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, e.g., 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

Fig. 10.5 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
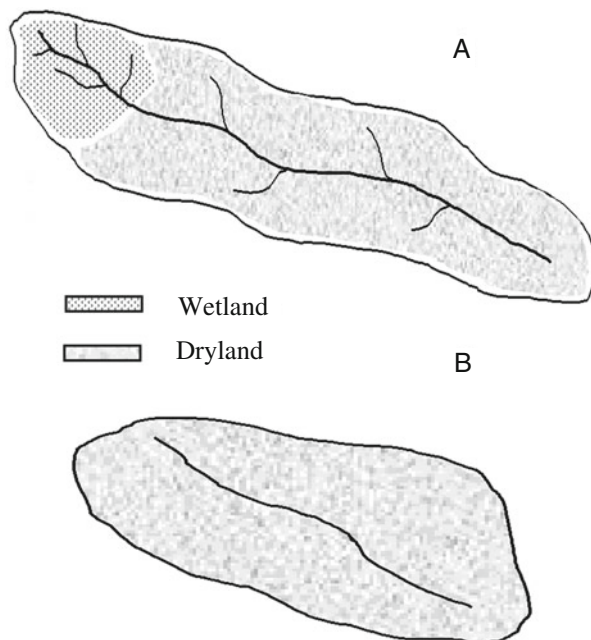
situation provides a variation to the alluvium-infiltration-flood problem and is the subject of recent discussions. This theory, however, has been criticized on the base of recent experiments that were conducted on a specific "red sedimentary" site (in the Nahal Yael desert, Southern Negev, Israel), which seemed to indicate that downstream flow propagation does not necessarily require that the medium is fully saturated (Lekach et al. 1998). More recently, a process-oriented semi-distributed channel transmission loss model, which also incorporates unsaturated soil moisture dynamics, has been assembled and applied to dryland rivers of different size and characteristics (Costa et al. 2012). However, some caution should be used as the scarcity of data typical of dryland environments limits the calibration of highly parametrized models.

3.2   Geometry

The geometry of dryland rivers is the result of the influence of hydrological and geomorphic processes, of 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 [e.g., 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 water holes and arroyos where the role of vegetation has been the subject of recent studies (Tooth and Nanson 2000; Dunkerley and Brown 2002; Demissie et al. 2015). 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 of river discharge. The numerical values of these exponents provided a 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 timescales, 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 anabranching geometries that constitute an interesting case of mutual adaptation between river and vegetation. However, it is becoming increasingly clear that such fluvial types can be further divided into humid and dryland classes, where each class has dissimilar characteristics to the other. Also, the often absence of lacustrine and organic deposits from dryland floodplains is responsible for moisture stress to riparian vegetation and has led to define dryland anabranching rivers as "inorganic" (see North et al. (2007) for a general overview). In some cases, streams form 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). In their notable review, North et al. (2007) conclude that anabranching (anastomosing) dryland rivers generally present a sedimentary record remarkably different than that from comparative analyses with their humid region counterparts. 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, water holes—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 and refugia for both aquatic and amphibian species (Bunn et al. 2006). While riparian and riverbed vegetation does not seem to have a direct influence on their formation, it may contribute to determine the persistence of their spatial distribution. This case is common 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, e.g., 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 documented by Tooth (2000a). He suggested that these channels can manifest either stability or instability. Stable channels can have an 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 of which only a few develop high sinuosity (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 have yet to be investigated in detail. This fact motivated our numerical simulations presented in Sect. 3.4. More recently, Storz-Perez and Laronne (2018) linked textural and morphological channel attributes with hydrogeomorphological processes. Their analysis reveals a rather universal character of ephemeral streams to form bars and prevent bed armoring regardless of their planform.

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). Sediment connectivity, namely, the physical transfer of sediment through a drainage basin is mainly determined by the spatial organization of the catchment's heterogeneity (Foerster et al. 2014). As part of such heterogeneity, riparian vegetation actively influences transport processes, thus playing a key role to determine river geomorphic complexity and its resilience to disturbances (Wohl 2016). 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 bed load transport than rivers in humid zones with the same shear stress (Laronne and Reid 1993). It has been estimated [see, e.g., 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 remodeling 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 armoring 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, e.g., Howard and Knudson 1984; Sun et al. 1996; Stølum 1996, Camporeale et al. 2007). 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 subhumid or semiarid 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 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 et al. 1981; Blondeaux and Seminara 1985; Johannesson and Parker 1989; Zolezzi and Seminara 2001; Lancaster and Bras 2002). These approaches have then been revised and hierarchically casted under a unique framework by Camporeale et al. (2007). Apart from the model by Johannesson and Parker (1989) and the detailed model by Zolezzi and Seminara (2001), the approach by Ikeda et al. (1981) is commonly used in the modeling 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 (but see also Parker et al. 2011), the river can be schematically represented as a curved line evolving onto a sloped plane; the points of this line migrate as 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 river bends is considered by assuming a semi-theoretical relationship between the topography of the bed and the local curvature of the river centerline. The downstream reduction in discharge is modeled according to the exponential law $Q = Q_0 \, \text{Exp}[-\tau s]$, 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 $\tau = 1.37 \times 10^{-5}$ m^{-1} (i.e., an equivalent transmission loss of 1.2 m^3/s km). The exceeding bank velocity u_{sb} for a bank-full discharge satisfies the following differential equation (Ikeda et al. 1981)

$$\frac{\mathrm{d}u_{sb}}{\mathrm{d}s} + 2C_\mathrm{f}\frac{U_0}{H}u_{sb} = bU_0\left(\frac{2C_\mathrm{f}}{H}Pk - \frac{\mathrm{d}k}{\mathrm{d}s}\right) \tag{10.1}$$

where U_0 and H are the mean velocity and the water depth of the uniform flow; C_f (0.0024) is a dimensionless friction factor; P (fixed equal to 8) is a constant that accounts for the bed slope, the centrifugal-induced superelevation of the water surface, and the convective transport of downstream momentum (Edwards and Smith 2002; Camporeale et al. 2007); 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, time is discretized in time intervals, Δt, and the algorithm performs the following four steps in each interval. Firstly, the exceeding bank velocity u_{sb} is evaluated by numerical integration of Eq. (10.1). 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 validated by field data (Beck 1984; Beck et al. 1984; Pizzuto and Meckelnburg 1989; Constantine et al. 2009). 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 in Camporeale (2005). The results of these analyses are shown in Fig. 10.6a–c. Figure 10.6a shows 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 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 10.6b shows the decrease of meander wavelength averaged in nonoverlapping spatial windows (window width equal to 10 km). Figure 10.6c 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
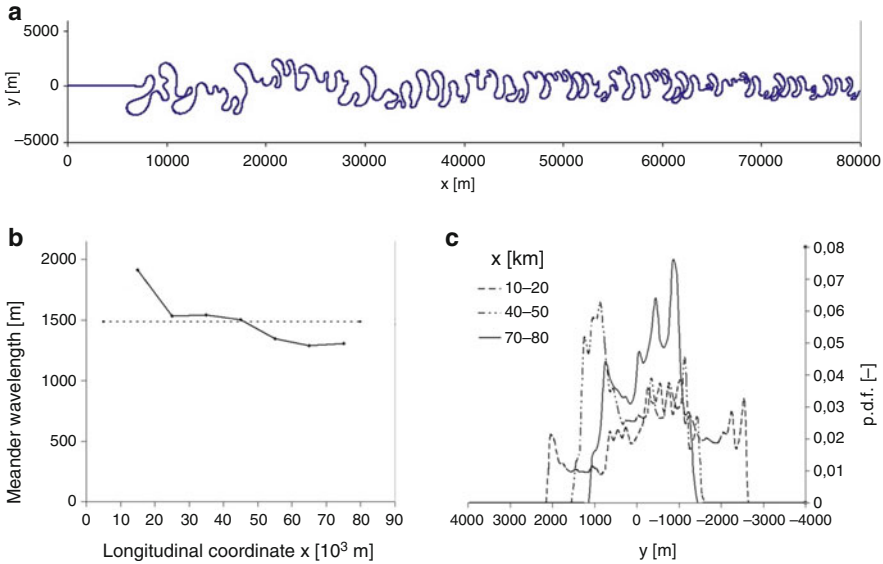
Fig. 10.6 (**a**) Example of a meandering pattern obtained after 5300 years of evolution starting from a straight line initially perturbed with uncorrelated Gaussian noise. (**b**) Longitudinal variation of the meandering wavelength and (**c**) the pdf of the transversal coordinate of the points occupied by the river on the floodplain. The characteristic reduction of the meandering belt width can be noted

mechanism controlling the river spread is the effect of cutoffs (see, e.g., Perona et al. 2002; Camporeale et al. 2005, 2008; Perucca et al. 2005). 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 Edward (1995).

These results seem to be coherent with field observations conducted on subhumid and semiarid 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 (Trodd and

Fig. 10.7 Riparian
vegetation along the slowly
disappearing Sandover
River, Central Australia
(from Tooth 2000b)

Dougill 1998; Hooke and Mant 2002), analyses of remote sensing data (Demissie
et al. 2015), or hydrogeomorphic channel classification (Shaw et al. 2018). Riparian
vegetation generally exhibits characteristic patterns (Fig. 10.7) organized along the
banks of the watercourse (see, e.g., 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. Eventually, desiccation of both rooted
and uprooted seedlings has been found to be a main cause of mortality and vegeta-
tion abundance decline in hyperarid environments (Stavi et al. 2015). Capon (2005)
found that the heterogeneity of floodplain species augments with a decrease in the
frequency of flooding with rarely flooded sites being more divergent from each other
than frequently flooded ones.

   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, USA) show that

Table 10.1 Example of a classification of plant species according to their behavior and adaptability

Characteristics	Species	Soil type
Pioneering	*Salix caprea*, *Cottonwood*, *Melaleuca argentea*, etc.	Riparian floodplain, water shelf
Invaders	*Tamarix ramosissima*, *Artemisia tridentata*, *Rosa woodsii*, etc.	Riparian floodplain, riverbed
Opportunistic	*Tea trees*	Sandy, mod. gravel bars
Native dominant	*Reichardia picroides*, *Phlomis fruticosa*, *Dian-thus vultaria*	Cultivated, very arid lands
	Artemisia barberia, *Inula viscosa*, *Lygeum spartum*	Dry rocky hillslopes, even. degradated

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 et 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 USA (Kauffman et al. 1983; Tucker Schulz and Leininger 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 (Douglas et al. 2016). Their main characteristics are briefly outlined in the following (see also Table 10.1), 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 coexistence, 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 riverbeds 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 (1) a rapid growth rate, (2) 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, e.g., Mosbrugger (1990)], (3) recruitment and encroachment that mostly occur in the bed of the river, and (4) 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 stages 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 multilayered 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 candidate 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). Shift in riparian vegetation species generally affects other ecosystem species in a different manner. For example, along the Swakop River, Namibia, encroachment and abundance of invader plants of the genus *Prosopis* have not been found to have a direct effect on mammal species richness, although this seems to contrast with other reported effects at more global scales. However, an effect on species-species responses to *Prosopis* abundance was detected with some species benefiting from its presence and vice versa (Williams et al. 2013).

Opportunistic species, such as *tea trees*, grow in the periods before 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 coexist with local species (Tooth and Nanson 2000).

Woody debris originated from both floodplain and in stream vegetation are known to affect ecogeomorphic processes to a great extent. Contrarily to rivers in humid regions, the fate and biological decay of river woody debris in drylands are less studied. The existing few reports (e.g., Ellis et al. 1999; Andersen et al. 2016) agree on suggesting that the frequency of inundation of the depositing location in particular desert environments is the key controller of wood biological decay rates. Low precipitation and infrequent inundation events ensure a longer half-life time for woody debris than in humid regions, thus enhancing the importance of such processes for the river carbon cycle.

## 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
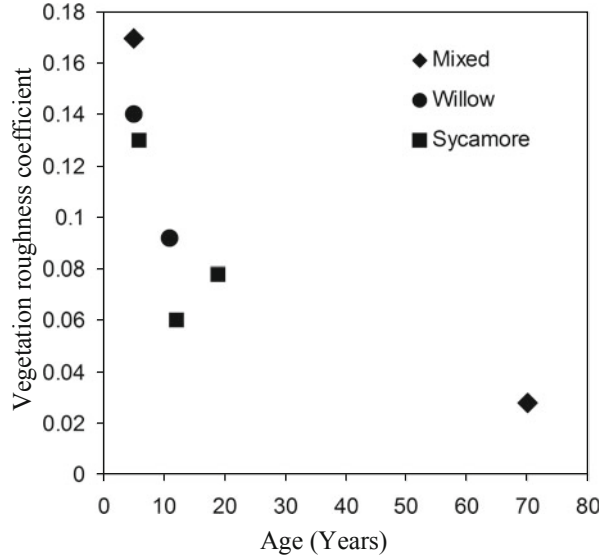
the mechanisms of erosion and sediment deposition (Ashworth 1996; Huang and Nanson 1997; Hooke and Mant 2002). Nanson et al. (2002) showed that channel morphogenesis is driven by the important role of vegetation due to its impact on the interaction between flow and sediment transport. However, sedimentation 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 riverbed), zonation, and season: these factors play a crucial role on vegetation influence and on the hydrological dynamics of the 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 was 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 vegetation, flow resistance decreases with the age (see Fig. 10.8). This result is particularly interesting because young and dense vegetation can significantly contribute to flow resistance; in low-energy zones, this favors 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. (2000), who investigated the role of highly developed root systems in riverbank stabilization in a semiarid 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 Fig. 10.9), thus showing the clear active role (in the sense explained in Fig. 10.2) of the riparian ecosystem. An example of the opposite influence of vegetation concerns the channel invasion of phreatophytes leaving little space for water flow.

Fig. 10.9 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)
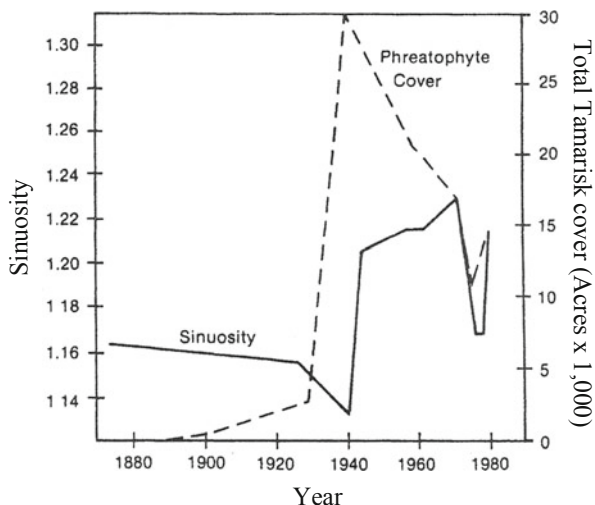
Because of the frequent water deficit and the high spatial-temporal variability of precipitation typical of drylands, plants can colonize the riverbed and develop a relatively dense vegetation. Despite the different effect of the various vegetation types (Hooke and Mant 2002) on the channel hydraulics, the bed colonization increases the frequency of bank-full 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; Camporeale and Ridolfi 2006).

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 provides shade 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 (Jacobson et al. 2000). These apportions of material, thanks to the combined contribution of the fertility of fine sediments and the postmortem role of wood debris, depend on the proximity to the river and are important for the soil's enrichment of new habitats (Forbes 1902). The way fine sediments augment fertility is closely related to how the silt layer influences soil moisture dynamics and, in turn, decomposition and nutrient cycling (Chap. 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 favorable for blue-green algae, fungi, lower plants, and invertebrates. It has also been 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 centimeters 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 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; Busch 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, USA) and found that invaders have a greater stress tolerance and competitive ability to extract water under increasing soil salinity than native species (Fig. 10.10). 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 albida* 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; Busch and Smith 1995; Jolly 1996; Vandersande et al. 2001). Thus, soil salinity is an important factor characterizing 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 Shick 1996; Jacobson et al. 2000; O'Connor 2001). In agreement with Zhang et al. (2017), soil influencing (i.e., edaphic) factors allow for the differentiation of plant species into three groups: (1) saline-alkali-tolerant plants, (2) drought-tolerant plants, and (3) high nutrient-demanding plants, the availability of acquiring phosphorous, P, being mainly related to the solubility of calcium phosphate under alkaline conditions.

Fig. 10.10 Average percent of soil moisture in root zones of riparian plants grown on four salinity treatments (after Vandersande et al. 2001)
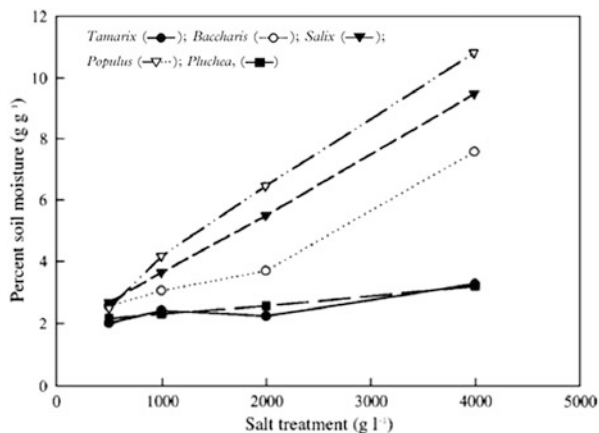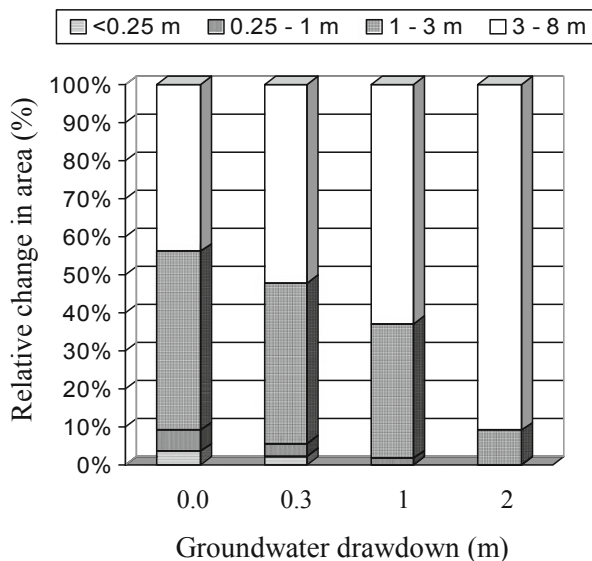

Fig. 10.11 Relative change in extent of four depth-to-groundwater zones of the San Pedro River floodplain, for four hypothetical groundwater decline scenarios (after Stromberg et al. 1996)

4.4 Role of Groundwater

Because riparian vegetation relies heavily on groundwater (Fig. 10.11; see also Malanson 1993; Stromberg et al. 1996; Higgins et al. 1997), an accurate understanding 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 10.11 shows the results of the experiments made by Stromberg et al. (1996) where four zones (with depth to groundwater ranging from 0.25 to 8 m) respond markedly to different scenarios of groundwater draw down. This picture represents the draining capacity of arid environments, and thus, it suggests that there is only a limited lateral zone where roots are still able to take up water. Water uptake is the main mechanism controlling vegetation survival in drylands, and zones characterized by shallow groundwater may show a vibrant ecosystem as a result of blooming vegetation (Yao et al. 2018). 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 riverbanks, uses groundwater. Access to groundwater resources allows riparian vegetation to survive longer during dry periods. This has important effects on the impact of anthropogenic disturbances to natural river flows 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). They found that 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 following 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 juveniles, 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), which may induce mortality due to desiccation (Stavi et al. 2015). 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). Interestingly, Wilcox and Huang (2010) reported an apparent contradicting trend of baseflow increase during periods of increasing vegetation encroachment for two dryland rivers of the Edwards Plateau region in Texas. As no increasing rainfalls were observed over the same period, it was concluded that the recorded baseflow positive trend would have to be ascribed to recovering woodland whose presence might have favored infiltration into the soil and positively balanced the loss for evapotranspiration. Mainly pertinent to drylands, these results would challenge the notion that vegetation increase may lead to decreasing groundwater recharge, thus providing new criteria for land and river restoration.

Finally, interesting positive feedbacks may arise from the interaction between riparian vegetation and the shallow groundwater whereby plant contributes to

prevent waterlogging conditions and consequently maintain good aeration of the root zone, which may be fundamental for the survival of some riparian species (Ridolfi et al. 2006). In other words, riparian vegetation may create its own habitat, a phenomenon also known as "ecosystem engineering." The removal of riparian vegetation may rise the water table close to the surface, thereby inducing water logging (Ridolfi et al. 2006). The resulting coupled vegetation-groundwater dynamics may exhibit alternative stable states of deeper water table with vegetation and waterlogging with no vegetation.

4.5   Modeling River-Vegetation Interaction

A primer on modeling river and vegetation interactions is the review by Camporeale et al. (2013). Models are essentially of two types: conceptual and mathematical. 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 Sect. 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 for the analysis of riparian vegetation descriptors (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 analyze the effects of grazing in Israel; Salinas et al. (2000) compared the effect of different anthropogenic disturbances and their relative effects in the Southeastern Iberian Peninsula. Their observations suggested that water channeling 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 communities that harbor important species of birds; see also McGinnes et al. (2010)].

   After the works by Wolman and Gerson (1978) and Stromberg (1993) dealing with the description of the complex vegetation-fluvial dynamics in semiarid and arid ecosystems in the USA, some new contributions have been made recently to the modeling of river-vegetation interaction in humid regions (McKenney et al. 1995; Perucca et al. 2007; Perona et al. 2009), 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 subhumid and semiarid environments such as parts of the Mediterranean basin where vegetation is present in significant quantities and nonaquatic vegetation can be found in channels. In this case, vegetation has a significant impact on flood propagation (Hooke and Mant 2002). While Brookes et al. (2000) aimed to model 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. An interesting analogy is the so-called Goldilocks Principle (named after the celebrated children's tale Goldilocks) that can be advanced for vegetation uprooting by flow. This principle has also been associated to some dynamics of the food web chain (Berlow et al. 2008). Similar to how Goldilocks chose the "not too hot–not too cold" soup, flood events are able to select in and among species riverbed and riparian vegetation having "just the right biomechanical characteristics" for that specific hydrogeomorphic environment (Perona et al. 2012; Crouzy and Perona 2012; Crouzy et al. 2013). River intermittency thus plays a key role in the whole dynamics and has also been shown to promote biodiversity particularly in dryland rivers (Katz et al. 2012). Recently, Bertagni et al. (2018) formulated the first analytical model linking flow variability, sediment dynamics, and vegetation evolution to quantitatively describe physical conditions for vegetation establishment.

Particularly interesting are dryland anabranching rivers whose commonly determinant mechanisms of avulsion (i.e., activation of new channels due to erosion and deposition processes) appear other than the crevassing so often dominant on humid regions (North et al. 2007). Low-stream gradients would thus seem to sustain anabranching because of the favorable combination between fine cohesive sediment deposition and lower erosional energy. Tooth and Nanson (2000) suggested an interesting interpretative model for river anabranching mechanisms in the presence of *tea trees* (see, Fig. 10.1). On the basis of their observations, the formation of anabranching channels would occur in three phases (Fig. 10.12) and would be driven by the interactions between vegetation growth and sediment deposition and erosion during flow events of ecogeomorphic relevance. The random 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 (i.e., elongated shape, which is asymmetric in the longitudinal direction) forms that show clues of self-similarity (Fig. 10.12, step a). In the second step (Fig. 10.12b), 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 (Fig. 10.12c), 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
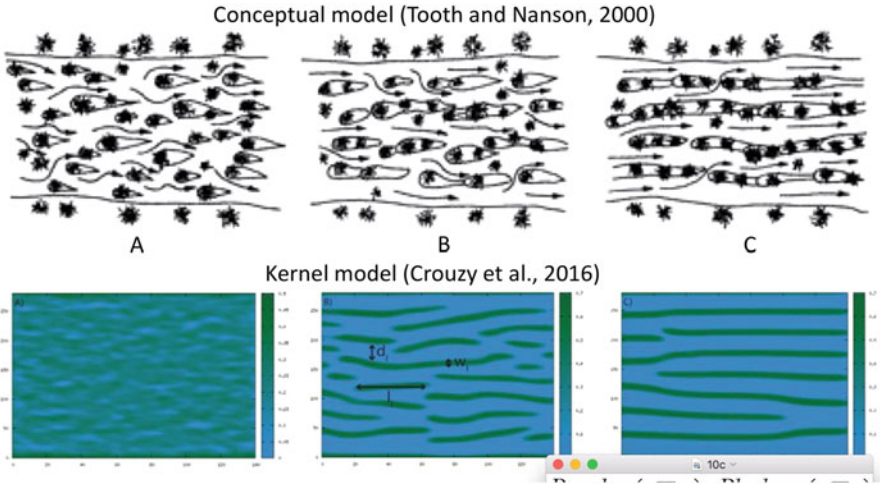
Fig. 10.12 The three basic steps of the conceptual model for river anabranching formation proposed by Tooth and Nanson (2000) and related results from the kernel model of Crouzy et al. (2016) with arbitrary space and timescales. Channel width, w, ridge width, w, and ridge length, l, appear at intermediate steps

high-energy zones (or riffles), i.e., where channel movement is dominated by avulsion (Graf 1981; McKenney et al. 1995; Tooth and Nanson 2000).

Crouzy et al. (2016) showed that the process described by Tooth and Nanson (2000) can be mathematically reproduced using a kernel modeling approach (e.g., see Ridolfi et al. 2011) where vegetation density, $\phi(s, n, t)$, changes along the longitudinal and transversal coordinates, s and n, respectively and in time, t, as

$$\frac{\partial \phi}{\partial t} = \alpha_g \phi(\phi_m - \phi) + \iint \phi(s', n', t) \mathcal{W}(s' - s, n' - n) ds' dn', \qquad (10.2)$$

plus some suitable boundary and initial conditions that are omitted here (see Crouzy et al. (2016) for details). In Eq. (10.2), α_g is vegetation growth rate, ϕ_m is the carrying capacity, and $\mathcal{W}$ is the interaction kernel, which appears as a convolution term influencing the rate of vegetation change in space and time. Notice that since $\mathcal{W}$ does not contain any explicit information about flow changes, then Eq. (10.2) can only be considered as a descriptive equation, which lumps and mimics interacting phenomena depending on the mathematical form of the kernel. Hence, in order to provide a physical flavor to the ansatz, one can split the kernel into a positive interaction, $\mathcal{W}^+$, and into a negative one, $\mathcal{W}^-$, having different interacting spatial length scales along the longitudinal and the transversal directions. The positive part of the kernel thus represents the protective role of vegetation (e.g., reduction of the local shear stress and sediment stabilization by roots) whose effects prevail in the longitudinal direction. The negative part of the kernel describes erosion processes that act predominantly around the obstacle and are stronger in the transversal

direction (e.g., due to flow divergence and velocity increase) compared to the longitudinal one. In the range where the model is unstable (see Crouzy et al. (2016) for details) and starting from randomly sparse vegetation cover, then the model organizes itself (Fig. 10.12) into regular longitudinal vegetated ridges (in green) periodically alternated by channels (in blue).

5 Relevance and Perspectives for Restoration of Dryland Riparian Environments

The main source of diversity between riparian environments in arid and humid regions is essentially due to the frequency of moisture stress and the soil and sediment type, which are likely the result of pedological processes occurring over timescales longer than the biological ones of vegetation. These two key elements contribute to the selection and adaptation of species to an extent that on anthropic timescales, also for drylands, water-driven environmental patterns are essentially the result of flow variability, sediment dynamics, and vegetation growth. These three dynamics are characterized by thresholds, nonlinearities, and (positive and negative) feedbacks, and their interaction seems to explain how riparian species are selected and encroach (Goldilocks effect). In this respect, our process-based understanding has substantially improved compared to that available a few decades ago and can be used to make effective dryland riparian restoration projects, which is a common practice in humid regions today (Wohl et al. 2015). For example, some minimalist models may be used to capture the overall vegetation biomass growth of the phreatophyte riparian species neglecting interspecies interactions and geomorphological processes, such as sedimentation and erosion, but rather considering a steady river morphology. Under these hypotheses, the local stochastic dynamics of the dimensionless biomass density, v, of single-species riparian vegetation can be modeled as a generic plot of the riparian transect according to a dichotomous process switching randomly between two mechanisms (e.g., Camporeale and Ridolfi 2006, 2007): (1) the decay of the vegetation biomass caused by flooding (i.e., anoxia, burial, uprooting, etc.) and (2) a generalization of the commonly used Verhulst logistic function which simulates the growth of a phreatophyte species that taps the groundwater. The statistical characteristics of the dichotomous switching are dictated by the river stages and are described by the probability distribution, $p(h)$, and the correlation timescale, τ, of the water-level time series, the latter representing the linear "memory" of the hydrological forcing. The above-described two-equation model can be recast as a single stochastic differential equation, driven by multiplicative dichotomous noise (Kitahara et al. 1980; Ridolfi et al. 2011), whose solution in steady-state conditions is the probability distribution of the vegetation density, $p(v)$,
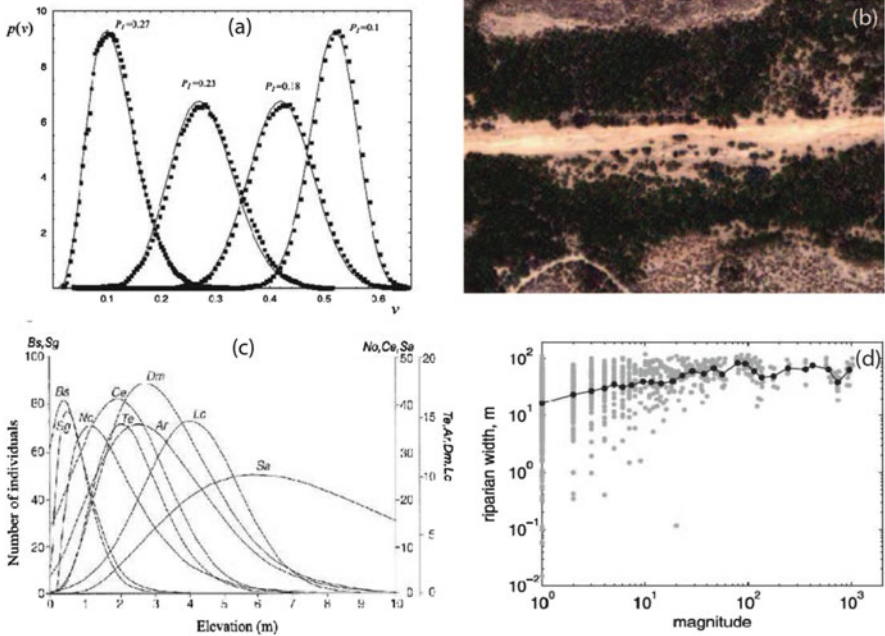
Fig. 10.13 Stochastic characterization and modeling of riparian zone. (**a**) Different behaviors of p (v) for different inundation probabilities. Solid curves: predictions to Eq. (10.3); dots: numerical solution. (**b**) San Pedro River (Arizona). (**c**) Abundance of mature individuals of selected tree species versus elevation of Sabie River riparian corridor (South Africa): Breonadia salicina (Bs), Syzygium guineense (Ar), Nuxia oppositifolia (No), Combretum erythrophyllum (Ce), Trichilia emetica (Te), Acacia robusta (Ar), Diospyros mespiliformis (Dm), Lonchocarpus capassa (Lc), and Spirostachys africana (Sa). Reprinted from Naiman et al. (2005). Copyright (2005), with permission from Elsevier. (**d**) Empirical relation between the stream magnitude and the riparian width of the Sand Creek, Oklahoma (USA), obtained from remote sensing data. The black circles connected by the line represent average binning values (from Muneepeerakul et al. 2007)

$$p(v) = \frac{N}{\alpha} v^{\frac{\beta(1-\alpha\tau)-(\alpha+\beta)P_I}{\alpha\beta\tau}} (\beta - v)^{\frac{P_I}{\beta\tau}-1} (\alpha + \beta - v), \qquad (10.3)$$

where β is the carrying capacity of the plot (i.e., the maximum sustainable biomass), N is the normalization constant, P_I is the inundation probability, and α is the growth rate of the vegetation. An example of computation of $p(v)$, for different values of inundation probability, is provided in Fig. 10.13a. Once the probability distribution is obtained, the stochastic dynamics of biomass is well characterized and one may compute, starting from (3), the transversal distribution of the plot-dependent mean value or standard deviation. Close relationships are reported in Camporeale and Ridolfi (2006). This approach was proven to be successful to the study of noise-induced behavior of riparian vegetation dynamics, in terms of transversal distribution of biomass and width of riparian zone. This is fundamental in the case of dryland rivers, where the lateral extension of the riparian zone is constrained by the flood-

induced water availability (an example is provided in Fig. 10.13b for the San Pedro River). It is well known that besides the hydraulic forcing, the lateral distribution of biomass is also species-dependent (see Fig. 10.13c), an aspect that is accounted for in the above modeling approach by the quantities α and β. Muneepeerakul et al. (2007) followed the model by Camporeale and Ridolfi (2006) but introduced some small changes in order to obtain a finite width for the riparian belt. In this way, they were able to study the relationship between the geomorphological scaling rules that are typical of the river flow (Rodriguez-Iturbe and Rinaldo 1997) and riparian zone width (Fig. 10.13d).

In the context of stochastic modelling, another research line has explored deep planting as a simple though effective expedient to increase the survival probability of some riparian plants (Hall et al. 2015). Without pretending to exhaustively discuss the argument, in the following, we attempt a quantitative explanation thereof by using the stochastic model for riparian plant root growth of Tron et al. (2014, 2015) as a proxy.

Tron et al. (2014, 2015) mathematically modeled the effect of river stage variability on plant root growth under the assumption that water and oxygen availability in the soil are the key drivers for root development in riparian corridors. First, the water stage dynamics are analytically modeled as a stochastic Compound Poisson Process (Ridolfi et al. 2011). Water levels increase as a result of randomly distributed and instantaneous Poisson shots (white shot noise of rate λ and mean magnitude α) and decrease deterministically between two shots following an exponential decay of constant α. The resulting probability density function of the water level reads

$$p(z) = \frac{\alpha^{-\overline{\lambda}}}{\Gamma(\overline{\lambda})} e^{\frac{z-h}{\alpha}} (h-z)^{\overline{\lambda}-1},$$

where z is the soil depth, $\Gamma(\cdot)$ is the Gamma function, and h is the minimum water table level and $\overline{\lambda} = \lambda/\eta$. Root growth and decay over soil depth, z, are driven by the fluctuations of the water table level, which determines water and oxygen availability within the unsaturated zone above the saturated capillary fringe. Thus, at a certain soil depth, roots grow or die depending on the groundwater stage. These two alternating dynamics, regulated by the stochastic water table fluctuations, are described as a dichotomous noise (Ridolfi et al. 2011). A more detailed explanation can be found in the work of Tron et al. (2014). The mean vertical root profile has an analytical expression (not reported here) whose parameters are physically based and linked to plant type, soil properties, and groundwater dynamics. As shown by Tron et al. (2015), this model is able to correctly identify the vertical distribution of roots of several plant species grown in different soil textures and subjected to different water table dynamics. The model is now freely available in the form of Graphical User Interface upon contacting the authors (PP).

As an example, Fig. 10.14 shows the resulting root profiles for the same plant species growing on a lateral embankment and experiencing water-level fluctuations typical of humid (i.e., perennial) and arid (i.e., ephemeral) streams. As can be seen,
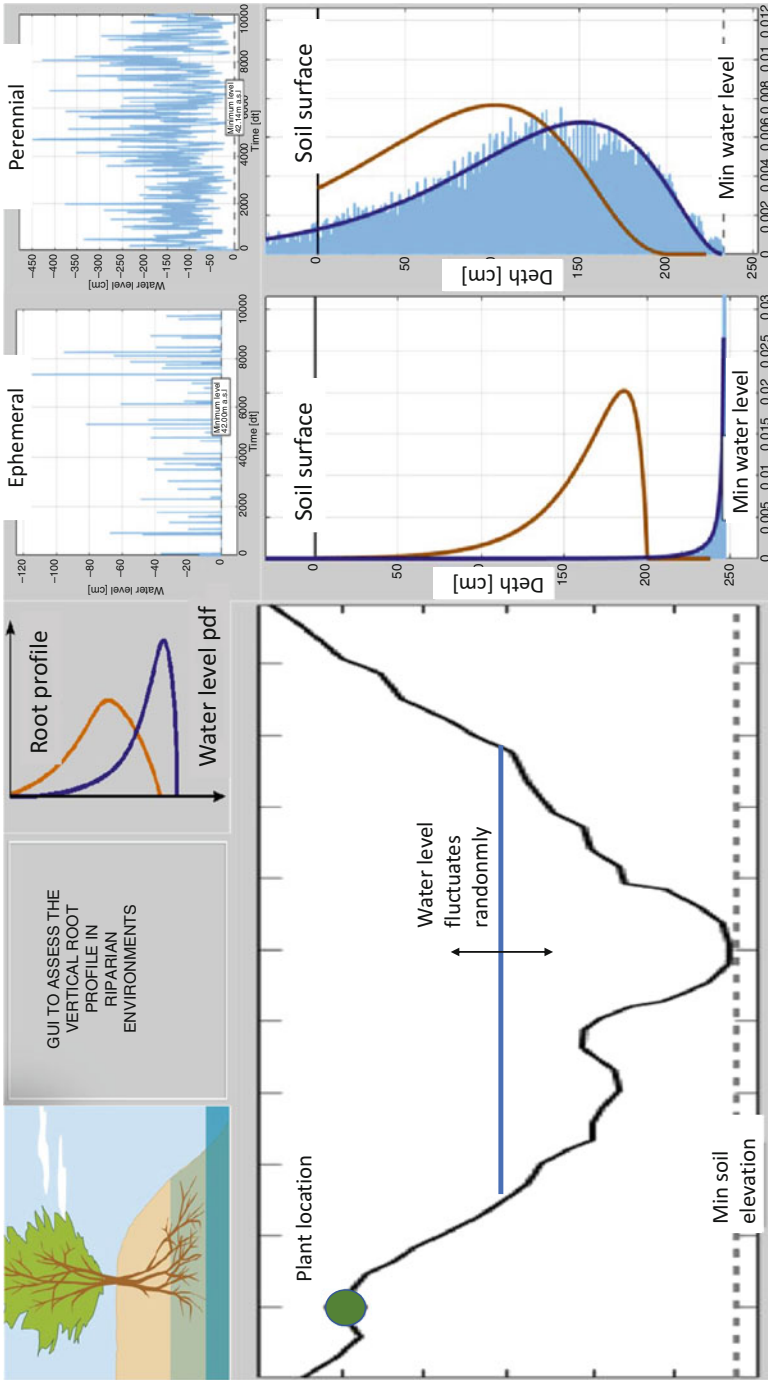
Fig. 10.14 The model of Tron et al. (2014): effect of random water-level fluctuations on plants vertical root profile (brown continuous line) for a plant subject to either an ephemeral or a perennial stream. The blue bins represent the histogram of the water-level changes for the two streams

the vertical root profile resulting from the fluctuations of the perennial stream shows a larger variance, with mode and average shallower in the soil than that of the ephemeral stream. This would explain the observations performed by Hall et al. (2015) as being the joint result of a higher probability for the plant of both tapping water from the deep water table and higher survival probability to erosional events.

In order to develop and/or complement new restoration strategies, Zhou et al. (2017) proposed an integrated probabilistic assessment based on a Bayesian type of approach. This allows one to incorporate the effect of spatial heterogeneity in soil erosion processes applied to restored vegetation types and evaluate the efficacy of soil control practice in semiarid environments (Zhang et al. 2017).

6   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 indicates 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 ecohydraulic 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 to also 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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