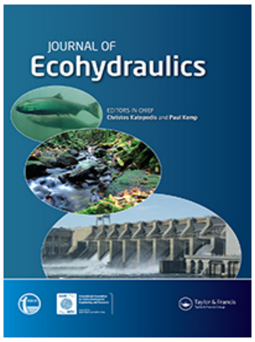

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Flood impacts on vegetation and hydraulics in ephemeral channels and dynamics of recovery

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ABSTRACT

Vegetation can have a particularly strong effect on hydraulics and processes in dryland, ephemeral channels, where plants often occupy the channel bed. To understand the hydraulics, feedback effects and ecological dynamics for use in modelling and management, data on flow effects and vegetation dynamics are needed. Evidence from sites in southeast Spain, monitored for decades, is analysed here in relation to an extreme flood in September 2012 to identify thresholds for damage and destruction of plants, to assess rates of recovery, and to quantify effects of varying vegetation density and height on channel hydraulics. Repeated quadrat measurements provide data on vegetation cover, health and heights of plants, and were analysed in relation to measured flow stage and cross-section topographic surveys before, after and since the 2012 flood. Much of the vegetation was destroyed in the flood event, including the dominant *Retama*, resetting the vegetation. Threshold levels of shear stress for mortality and removal of the plants have been calculated. Rates of recovery have varied spatially, with little regrowth in main channels or on elevated floodplains, but strong growth occurring on bars. The different degrees of vegetation cover and height are calculated to have a very large effect on the flow hydraulics. The results support the proposal that dense vegetation cover can be highly effective in channel management by slowing flow, reducing erosion and increasing sedimentation.

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KEYWORDS
Plant resilience; ephemeral channel; vegetation growth; flood impact; hydraulics

Introduction

In dryland channels, with only occasional flow of water, it is common for vegetation to grow within the channel as well as on bars and the floodplain, with the channels in such environments also tending to be quite mobile. Growth of vegetation, particularly shrubs and trees, can alter the resistance to flow but degree of growth and resistance can vary over time, especially in relation to effects of high flows, to seasonality, or longer periods of drought and wetness. Plants within flow zones have the effect of increasing roughness, resulting in velocity reduction, and erosion prevention by decrease in shear stress and by adding strength from plants, particularly roots (Sandercock et al. 2007). Velocity reduction can increase sedimentation, often producing vegetation wake features. Flows of various magnitude can have impacts on the vegetation (e.g. Surian et al. 2015) and the interactions and feedbacks can affect the fluvial processes, the morphodynamics and longer-term trajectories of the channel (e.g. Corenblit et al. 2007; Sandercock et al. 2007; Tabacchi et al. 2009; Corenblit et al. 2011; Bertoldi et al. 2014; Lightbody et al. 2019). Trees and other plants are recognised as ecological engineers (Gurnell and Petts 2006) and vegetation can contribute to river recovery and restoration in degraded systems (Harvey and Bertoldi 2015). Cycles of disturbance and succession have been recognised for riparian vegetation and conceptual frameworks developed (Stoffel and Wilford 2012; Corenblit et al. 2014) but greater quantification of thresholds for plant damage and mortality and for rates of regrowth and recovery in dryland channels is needed. Much of the data available even for "drylands" are from perennial or intermittent flowing streams. Field data on the dynamics of vegetation in ephemeral channels and interactions with flow over periods of years are rare. Here, evidence from sites in southeast Spain that have been monitored for decades is analysed in relation to the occurrence of floods to identify the magnitudes of flow necessary for damage and destruction of plants, to assess rates of recovery of vegetation, and to quantify effects of varying coverage and heights of vegetation on hydraulics of flow in these ephemerally-flowing channels, where flow is very infrequent and mainly occurs as very short flash floods.

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Distributions of vegetation zones and relations to flow conditions have been studied quite extensively in ephemeral channels (Stromberg et al. 2006; Sandercock et al. 2007; Shaw and Cooper 2008; Reynolds and Shafroth 2017). Dryland channels differ from the commonly studied, humid channels because the major woody plants are phreatophytes, with very long taproots (Sandercock et al. 2007). Marked zonation of vegetation and species is common to most fluvial environments but Tabacchi et al. (1996) found that patterns of vegetation in the Spanish semi-arid rivers are more influenced by local patterns than other rivers, having irregular patterns of species richness along channels, thought to be largely linked to irregularities in water availability. Early on, Bendix (1999) showed vegetation varied both across the channel and along a reach in response to variations in stream power, water-table depth, elevation, aspect, valley width, and fire history. Many studies in the SW USA have shown the close relationship of vegetation type and distribution to hydrological conditions, at various scales (Lite et al. 2005; Stromberg et al. 2005; Shaw and Cooper 2008; Bywater-Reyes et al. 2017). In the ephemeral channels of SE Spain, a zonation tends to occur of greater amounts of herbs in the channels, and with and shrubs and phreatophytes on the bars (Mant 2002). The dominant species in the braided, gravel-bed stream with schistose substrate, studied here, is the phreatophyte *Retama sphaerocarpa*, whereas Tamarisk dominates on the neighbouring marl channels, but both species have similar traits. Tamarisk, a phreatophyte, and also trees, particularly *Populus nigra*, have tended to receive much attention in the literature on dryland streams but such trees are not present in these channel zones. *Retama sphaerocarpa* has a deep rooting system that can extend 16–28 m and growth rates are strongly related to seasonal influences (Blamey and Grey-Wilson 1993). Mant (2002) identified a positive response to flow events and negative reaction to droughts in the channels studied here and Hasse et al. (1996) noted some strong association and growth of an understorey dwarf shrub *Artemesia barreliera* as Retama size increases with age.

In order to understand the possible influence on channel change in the Mediterranean region of climate and land use change and probable trend to greater desertification, Brookes et al. (2000) constructed a simulation model, which incorporated vegetation effects and feedbacks produced by variations in hydrological regime. The model incorporated processes of vegetation growth, ageing, death, germination, spread and stressing due to moisture and/or temperature conditions, as well as direct flow effects and morphological change. Three functional types of vegetation, herbs, shrubs and phreatophytes, each with four stages of maturity, were modelled and various conditions were simulated (Hooke and Mant 2002a; Hooke et al. 2005). However, at the time of initiation of the project in 1996, little validation data was available and so field sites were established in three catchments in SE Spain to provide quantification of the components. Research was extended in a further project (Recondes) (Sandercock and Hooke 2006; Hooke and Sandercock 2012, 2017) that investigated how vegetation could be used to reduce flows and sediment flux within these channels, with their high supply of sediment from soil erosion. The conditions for growth within different parts of the fluvial environment were measured and the effects of the plants on resistance assessed. The effectiveness of different species for the control and use in management was evaluated (Hooke and Sandercock 2012, 2017). The research, using quadrats, cross-sections and reach surveys monitored since 1996 and continuing to the present, had provided some data on the impacts of flood events, including the destruction and removal of some species in a flood in 1997 and their subsequent recovery or stimulated growth (Hooke and Mant 2000, 2002b, 2015; Mant 2002). Data from some other smaller events in the range of catchments and calculations of roughness effects and velocities allowed thresholds for various types of impacts of flows on different plant species to be identified (Sandercock and Hooke 2010) and therefore their susceptibility to flood disturbance. However, it was shown that the phreatophytes of Tamarisk and Retama were highly resilient and for the latter it was not possible to establish the threshold for destruction until an extreme flood event took place in 2012. This article now quantifies the effects of that event in the catchment with the greatest magnitude, the Nogalte, and the subsequent recovery or response.

In various locations, the differences in vegetation and its effects on morphology in reaches with and without flow regulation, or before and after dam closure, have been compared to assess hydrological effects on vegetation and their feedbacks (del Tanago et al. 2021; Hamdan and Myint 2016; Kui et al. 2017), reduction of flow magnitudes mostly leading to channel narrowing and extension of floodplains by accretion, with subsequent vegetation colonisation which usually enhances accretion rates (Dean and Schmidt 2011; Sandercock and Hooke 2011; Dean and Topping 2019; Lightbody et al. 2019; de Jalon et al. 2020). The survival of seedlings is crucial to the development of a denser vegetation cover and particular attention has been paid to Tamarisk, with questions arising on effects of wet and dry periods and on its effects as an invasive species in the SW USA (Graf 1978, 1988; Hooke 1996; Manners et al. 2014).

The details of mechanisms and processes of vegetation growth and destruction have been examined to some extent in the field, with particular focus on *Populus nigra* trees and their influence on channel morphodynamics and effects of flood sequences, notably in the large body of research based on the Tagliamento in Italy (e.g. Bertoldi et al. 2009; Henshaw et al. 2014; Corenblit et al. 2015; Gurnell and Bertoldi 2020). Field measurements that encompass high flow events in drylands are rarely documented, partly because flow events are infrequent and long measurement periods are needed to detect the range of conditions, though exceptions exist, producing some quantification of conditions for damage or uprooting of plants (e.g. Parsons et al. 2006; Corenblit et al. 2007; Bertoldi et al. 2009; Corenblit et al. 2014; Surian et al. 2015). Bywater-Reyes et al. (2015) applied pull tests to seedlings, replicating flood forces with and without scour to test conditions for uprooting. Effects of plant traits have been studied both in the field and in flume experiments, examining effects of aerial parts and roots (De Baets et al. 2007, 2008; Bertoldi et al. 2009; Edmaier et al. 2015) with Bywater-Reyes et al. (2022) contrasting the trait effects of Tamarisk and Populus on fluvial processes. Much research has been focused on quantifying effects of vegetation type, traits and density on roughness and velocity, including the susceptibility to and effects of bending of vegetation within flow (e.g. Mant 2002; Xia and Nehal 2013; Manners et al. 2015). The effect of increasing vegetation in reducing velocities and flood conveyance has been used to assess practices of cutting or clearance of vegetation (Stromsoe and Callow 2012; Kourgialas and Karatzas 2013) and is the basis of much natural flood management/nature-based solutions (Rowinski et al. 2018). It was the basic premise of the Recondes project and provided the framework for guidance on use of vegetation to reduce the consequent erosion and sediment flux from flows by increased resistance and sedimentation, thus decreasing connectivity of water and sediment downstream (Hooke and Sandercock 2012, 2017).

At the wider conceptual level, there is much discussion of feedback effects on overall channel evolution and trajectories. For example, many of the findings have been combined into higher level models such as that of Bertoldi et al. (2014). Development of diversity and occurrence of multiple states influence resilience in river systems subject to high disturbance and understanding acquired from the detailed research can be implemented in such frameworks as the basis for restoration and management (Tabacchi et al. 2009). However, the complexity of fluvial-ecological interactions continues to pose research challenges (Packman et al. 2021).

A major aim of this overall research is to understand the effect and dynamics of vegetation in ephemeral channels to produce guidance on how vegetation could be used as a sustainable strategy for control of erosion and sediment flux in dryland channels (Hooke and Sandercock 2012, 2017). Field observations and quantitative data on vegetation dynamics, the effects of flood and the interactions with fluvial processes are still relatively rare. This article provides evidence of the impact of an extreme flood on vegetation in an ephemeral, braided channel system in SE Spain. It quantifies the conditions for a major resetting of the vegetation and the thresholds for mortality and removal of a major riparian phreatophyte species. It analyses data over a period of years of the recovery and growth rates, identifying the effects (such as damage or pronation) of subsequent lower flood events on various types of vegetation. Such results contribute significantly to our understanding and provision of data for modelling, restoration and management of such fluvial environments and their valuable ecosystems.

Site background and methods

Three reaches of the Rambla Nogalte in SE Spain (Figure 1) were established in 1996 as monitoring sites to measure the occurrence of flow events, changes in morphology and sediment characteristics, and variations in vegetation cover, in order to quantify these components for modelling effects of flows and hydrological variations and channel changes in these catchments of SE Spain and as part of wider research on desertification (Brookes et al. 2000; Hooke et al. 2005) in southern Europe. The Rambla Nogalte has a catchment area of 137 km^2 to Puerto Lumbreras at the downstream end of the channel. It has a catchment relief of >500 m and an overall channel gradient of 0.02 (Hooke and Mant 2002b). The area is composed of phyllite schist, producing a dominantly fine-medium gravel channel. The catchment land cover comprises natural patchy vegetation of Mediterranean shrubs on slopes and land use increasingly dominated by almond and olive groves on the steeper valley slopes. Mean annual rainfall is 250–300 mm but with high interannual variability. Flow in the main channel only occurs occasionally, and in only 14 of the of the 24 years of monitoring has flow been registered, with only four flows exceeding 0.5 m depth at the downstream site (Figure 2). The earlier period from 1996 to 2012

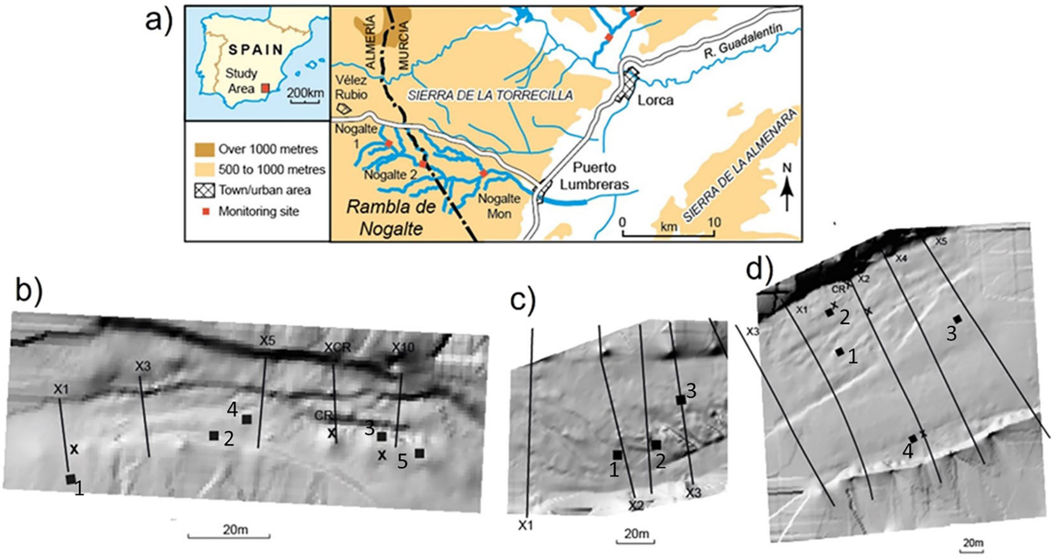


Figure 1. a) Location of the study sites; b) Nog 1, c) Nog 2, d) Nog Mon, with positions of cross-sections, quadrats (black squares) and crest-stage recorders (X) marked on DEMs derived from ground surveys.

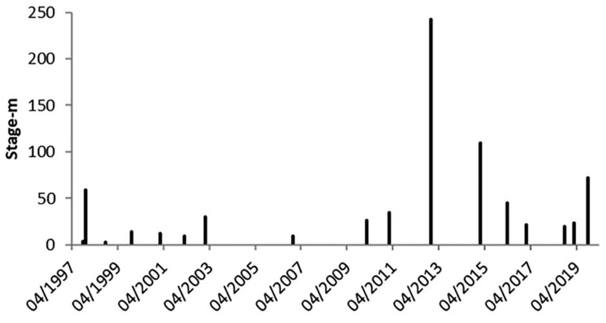


Figure 2. Stage levels measured on the Nogalte site NogMon, 1997–2020.

was much drier than the last 10 years. A major flow took place in September 1997 and its effects analysed (Hooke and Mant 2000). A very large flood occurred on 28th September 2012, assessed as the highest for 50 years and probably exceeding the tragic 1973 flood that led to many fatalities in Puerto Lumbreras. The 2012 flood event resulted from a rainfall of 163 mm at Puerto Lumbreras, but possibly as much as 250 mm in the upper catchment, and produced a gauged peak flow at the downstream end of 2500 m^3 s^{-1} (Hooke 2016, 2019). The flow had a duration of four hours and an extremely sharp rise to peak of 1 hr. Some small check dams were present in the catchment prior to 2012 but, as a result of the high magnitude 2012 flood, a series of much larger check dams have since been built in the upper catchment and tributaries.

The channel itself is mainly composed of loose gravel and is braided along much of the course, with low-relief primary and secondary channels. The three monitored reaches, Nog1, Nog2 and NogMon, are located in the upper, middle and lower part of the course, with catchment areas of 6.9, 39.1 and 102.7 km^2, respectively (Figure 1). Vegetation grows within all parts of the channel and floodplain. It is dominated by the phreatophyte, *Retama sphaerocarpa*, with its long roots penetrating the deep gravels (Sandercock et al. 2007). A variety of herbs and shrubs grow in favourable locations, with greater floristic diversity in the more elevated and less disturbed parts of the channel. In this environment, water is the limiting factor for growth of smaller plants and periodic droughts can cause disappearance or stasis of shallow rooting plants (Hooke and Mant 2015).

Each of the reaches is 100–200 m in length and a series of measurements have been made routinely since their establishment in 1996 (Hooke 2007). Between two and five cross-section profiles were established in each site (Figure 1) and have been resurveyed on multiple occasions since 1996, especially after channel flows, and at least annually since 2007. In addition, the topography of the whole reach has been resurveyed on each occasion, latterly using an RTK GPS Topcon Hiper-Pro instrument. Measurements are to ± 2 cm accuracy and produce a DEM with key features such as bank lines distinguished. Changes in morphology have been analysed in previous research (Hooke 2016). Up to five 3 m square quadrats were established in each reach to measure vegetation (Figure 1) and a 0.5 m quadrat for measuring sediment located within that. The quadrats were placed in the channels, on bars, and on floodplain to assess varied effects in zones with differing frequencies of flow. In each quadrat on each survey date, zones and types of vegetation cover and sediment characteristics are mapped. The quadrats are photographed, and the height and state of vegetation recorded. Maximum heights of the tallest plant in each quadrat are measured. For the analyses here, % ground cover and maximum height of plants have been extracted (Figure 3).

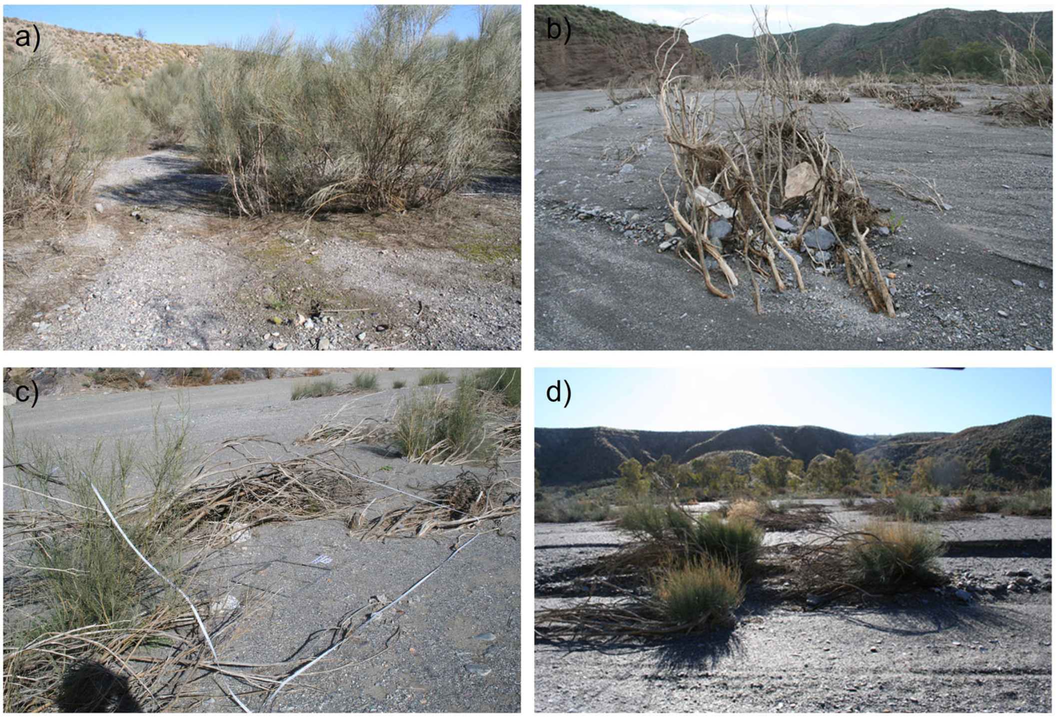


Figure 3. Photographs of a) mature Retama, b) damaged Retama with large sediment in the base as a result of the 2012 flood, c) remains of Retama, but with some sprouting and seedlings, d) Sprouting of Retama at NogMon site.

Table 1. Calculated most probable hydraulic parameters in each reach for pre-flood vegetated state and post-flood minimal vegetated state, using pre- and post-flood morphology, respectively, and for post-flood morphology with vegetated (regrowth) state.

	Manning *n* value	Velocity m s^{-1}	Discharge m^3 s^{-1}	Shear stress N m^{-2}	Power W m^{-3}	Unit power W m^{-2}
Maximum vegetation state, pre-flood morphology						
NOG1	0.07	1.38	24.6	108	4399	181
NOG2	0.07	2.57	321	287	68204	832
NOGMON	0.07	3.22	765	413	182986	1336
Minimum vegetation state, post-flood morphology						
NOG1	0.03	4.41	63	185	14851	672
NOG2	0.03	6.55	917	316	170678	2220
NOGMON	0.03	7.48	1770	404	398862	3071
Maximum vegetation state, post-flood morphology						
NOG1	0.07	1.89	27	185	6364	228
NOG2	0.07	2.81	393	316	72431	907
NOGMON	0.07	3.2	758	404	170941	1316

The occurrence and height of flows is monitored by simple crest-stage recorders at each site (Hooke 2007). Mean velocity and discharge are calculated for each cross-section using the Manning equation. Additional flow heights are provided by numerous surveyed flood marks throughout the reach. In the 2012 event the recorders were destroyed so calculations of hydraulics are from those floodmarks (Hooke 2019). Calculations of mean velocity and of peak discharge in the 2012 event using the velocity-area method were made for each surveyed cross-section in each reach for three different states, because of the morphological and vegetation changes produced by the flood (Table 1). The timing within the flood is unknown so the calculations have been made with pre-flood and post-flood morphology and with high roughness for pre-flood and both low roughness (representing the state immediately after the flood) and high roughness, for state after several years of regrowth, with post-flood morphology. Assessment of roughness produced by vegetation is much debated but the guidance from Arcement and Schneider (1989) was used (Sandercock and Hooke 2010). The range of values for discharge in the reach were then matched with upstream and downstream study reaches, and with cross-sections surveyed post-flood all along the channel course, and the measured flow at the Puerto Lumbreras gauge to produce the most probable convergent values (Hooke 2019) (Figure 4). Ranges of possible values also incorporated ranges of water surface slope derived from floodmarks around each cross-section. Calculations were also made in HEC_RAS as a check. These uncertainties are discussed in Hooke (2019).

Variations in velocities and shear stresses for cross-sections are not revealed using mean values but it is the forces on the plants that are important in order to identify thresholds. These vary with the topography and the vegetation cover. Direct velocity profile and hydraulic calculations were not possible during the flood so the methods of Manners et al. (2015) applied in a flume are not feasible. Calculation of values in sub-zones have therefore been made using the WinXSPRO program and tool of the USDA Forest Service (Hardy et al. 2005), designed for steep coarse channels and consistent

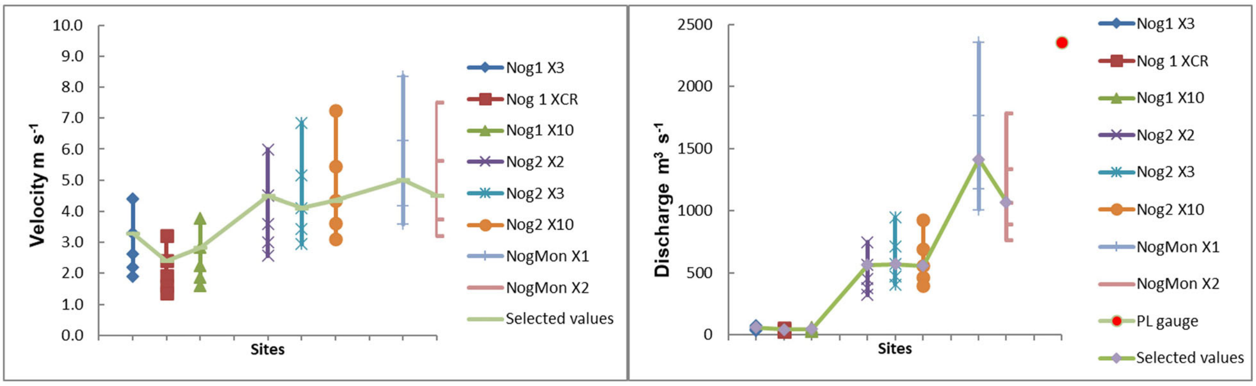


Figure 4. Values of velocity and discharge for range of values of Manning *n* 0.03–0.07, using pre-flood morphology at surveyed cross-sections in each site with most probable values selected.

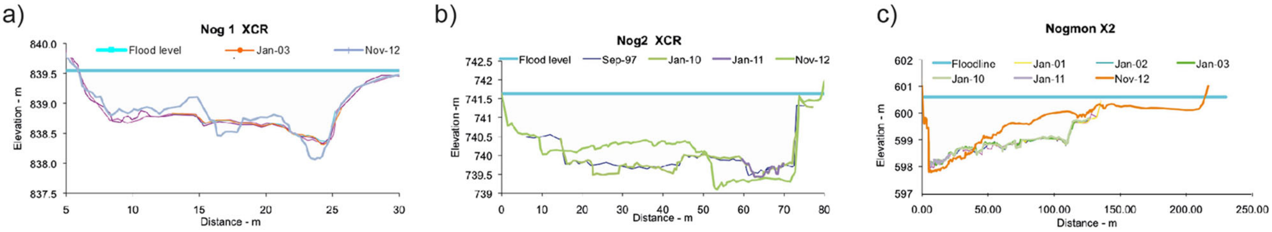


Figure 5. Representative cross-section profiles at each site surveyed before and after the 2012 flood, showing the morphological changes.

with the method used by Sandercock and Hooke (2010) in previous research on these channels to identify thresholds. Subdivisions have been demarcated at the position of marked changes in topography and/or vegetation (though the two are usually closely associated). Analysis is focused on the shear stress values because of the considerable uncertainty in the roughness values for velocity calculations. Shear stress data for the most probable flood levels from the flood marks, gradients and discharge, as above, are presented.

Results

When the flood of September 2012 occurred the vegetation was in a state of profuse growth (Figure 2a) after a long period of low flow since the flood of 1997, which had damaged some plants (Hooke and Mant 2000; Sandercock and Hooke 2010). The peak flows on September 28 2012, in the Nogalte were the highest for at least 40 years. Flow stage reached average heights of 1.20 m, 2.13 m and 2.58 m in the sites Nog 1, Nog2, NogMon, respectively. The morphological effects were to produce some limited erosion, mainly in the inner channels/lowest elevation zones and much deposition on the bars (Figure 5). Maximum erosion was 0.64 m at Nog1, 0.83 m at Nog2 and 0.46 m at NogMon but such depths were not widespread. At Nog1 the maximum deposition was 0.42 m, 0.85 m at Nog2, and 0.91 m at NogMon (Hooke 2016). The overall discharges and average velocities, shear stress and unit power for both pre-flood and post-flood morphologies are given in Table 1. The overall impact on the vegetation was to reduce the vegetation cover, the species present, and the maximum height of plants, mainly the Retama. The degree of impact did vary with site, generally increasing downstream as discharge and forces increased (Table 1). The greatest effect was at the downstream NogMon site where a pre-flood dense coverage of Retama, averaging 3–4 m in height was reduced to a sparse cover of dead-looking remains of branches of some of the plants (Figure 6). Likewise, at Nog2 the Retama and total vegetation cover was severely reduced (Figure 7) but at Nog1 more of the aerial parts survived, though many were flattened and damaged.

The detailed effects of the flood flow on the % cover of all vegetation are seen on the individual quadrats (Figure 8). All show a steep decline as result of the peak flow. The position of each vegetation quadrat (VQ) in terms of whether in the inner channel, on a bar, or on the floodplain is indicated. At Nog1 the decline is much greater for VQ3 and VQ4 because these zones were much more densely vegetated before the flood. The VQ5 quadrat, although covering the channel also includes dense vegetation on the channel bank, which declined much less (Figure 7). At Nog2 the pre-flood vegetation was sparse, though with high biodiversity and some Retama (Figure 7). Quadrats VQ1 and VQ2 were on degraded small channels and parts of bars before the flood, which had experienced little flow for several years, but these quadrats were eroded

Figure 6. Nog Mon reach in 2010 (pre-flood), November 2012 (immediate post -flood) and 2019 (after regrowth).

Figure 7. Comparison of example quadrats pre-flood (top row), post-flood (middle row) and in 2020 (bottom row) at Nog 1(left), Nog 2 (middle) and Nog Mon (right).

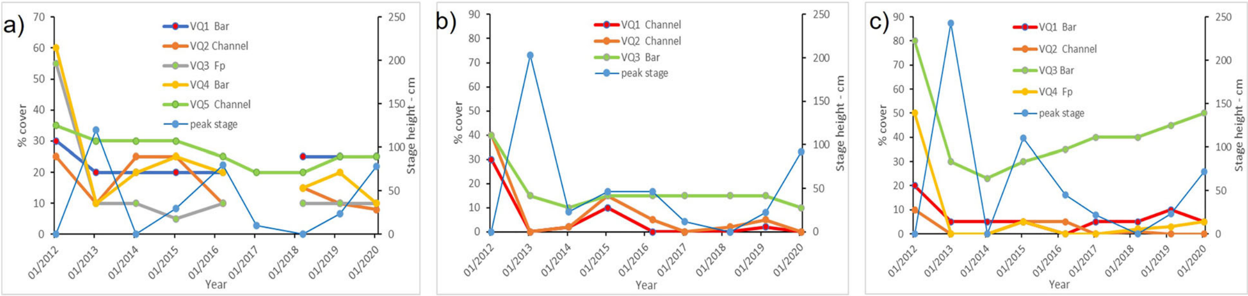


Figure 8. Changes in % vegetation cover, January 2012 (pre-flood) to January 2020, a) Nog 1, b) Nog 2, c) Nog Mon and peak flow occurrence. VQ = Vegetation Quadrat (as numbered on Figure 1).

into a wide main channel in the flood (Figure 7). The third quadrat, on the bar, contained Retama, which was severely damaged and other vegetation was removed. This was mainly a depositional zone (Figure 5). At NogMon, again the quadrats on the higher bar and floodplain (VQ3 an VQ4) were those in the main mature Retama zones (Figure 6) where coverage declined very strongly, with almost all vegetation removed but a few Retama branches remained as in VQ3 (Figure 7). In the two lower elevation quadrats (VQ1 and VQ2) pre-existing coverage was much less but some plants were present, including in the inner/main channel, and these were completely removed.

The heights of the tallest plant in each quadrat are plotted in Figure 9. The tall plants of >1.50 m are all Retama and show large declines. Mostly, the main aerial parts were destroyed; some were "removed," in others flattened, brown main branches, looking dead, remained (Figure 3b,c). These prone branch clumps averaged 0.4–0.5m, so still offered some frictional component to subsequent flows. The quadrats containing only shrubs and herbs, or only very small seedlings, declined to zero in site Nog2 and NogMon but a few survived at Nog1, partly by sheltering effects from Retama.

The probable average velocities and discharge at each cross-section (Table 1, Figure 4) can be used to identify possible thresholds for destruction and mortality of plants. Destruction of *Retama* took place at Nog Mon where average peak velocities probably reached 5 m s^{-1} but Retama were also destroyed at Nog1 and Nog 2 in flows of 3 m s^{-1}. Herbs were removed in all quadrats and very few shrubs or perennials survived, an exception being some *Juncus*. Average cross -section shear stresses for Retama destruction were of the order of 300–400 N m^{-2}. However, these average hydraulic values for each cross-section do not indicate the forces on the plants in different zones, which differ significantly depending on the position and depth of flow and the amount of vegetation. To calculate the shear stresses in zones across the channel the cross-section profiles were divided into sub-zones according to morphology, and the shear stress calculated for the height of flow at that cross-section (derived from surveyed flood marks). The effects on the plants in each zone have been categorised from notes on the state as indicated by the categories of damage (Figure 10), in the zone taken during survey, from photographs across the profiles, and from vegetation quadrats located in or near the profiles. These categories are based on those of Sandercock and Hooke (2010), with the following effects on plants in the zone for which the shear stress is calculated: Bare = plant type absent; battered = leaves removed and slight bending; flattened = bent to <45°; mortality = appearing dead but with some flattened remains; removed = plant no longer present. The shear stresses calculated for each effect are compiled for Retama in all sites and profiles (Figure 10a). The lower limit of the interquartile range is taken to be a probable lower limit, excluding the lowest extreme values (indicated by minimum). This indicates a probable threshold of 210 N m^{-2} (but absolute minimum of 100 N m^{-2}) for the main aerial parts of the mature Retama to be destroyed but woody branches remaining (mortality category) (some possibly still rooted as shown by variable recovery) (Figure 3c), and a probable threshold of nearly 300 N m^{-2} (but possible minimum of 140 N m^{-2}) for complete removal/disappearance of the plants. This may have been by uprooting or complete destruction of aerial parts or in some cases, particularly at NogMon, by complete burial. However, very few such plants seem to subsequently reappear in the same location by sprouting. Many of the shear stress values in zones are much higher and the averages are 288 N m^{-2} for mortality (with remains) and 360 N m^{-2} for removal. Shear stress values for mortality and for removal of shrubs and herbs are shown in Figure 10b, and in comparison with Retama. Shrubs were fairly sparse in these sites, limiting data points. Most were removed but those that survived were mostly sheltered by remaining Retama branches. Herbs almost entirely disappeared across all profiles and in all vegetation quadrats. The data include values calculated from both pre-flood and post-flood morphology, but using the flood mark elevations, because it is not known at what stage in the event the destruction and damage took place (though it seems likely to be in the early stages before massive deposition, which is assumed to be on the receding flow). In some of the Retama remains, large cobble-sized particles were found and this may have contributed to damage and mortality, particularly at the heads of bars (Figure 3b).

The changes and extent of recovery are recorded in % cover and in maximum height of a plants in each VQ in the period subsequent to the 2012 flood,

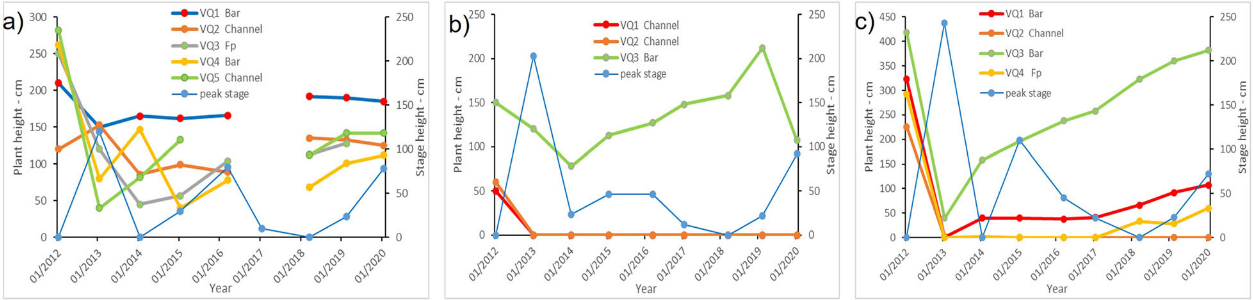


Figure 9. Changes in maximum height of plants, January 2012 (pre-flood) to January 2020, a) Nog 1, b) Nog 2, c) Nog Mon and peak flow occurrence.

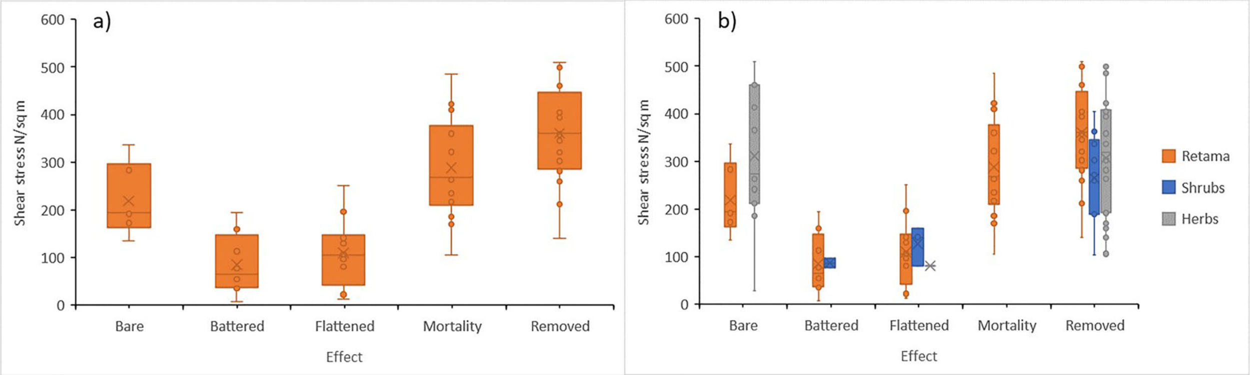
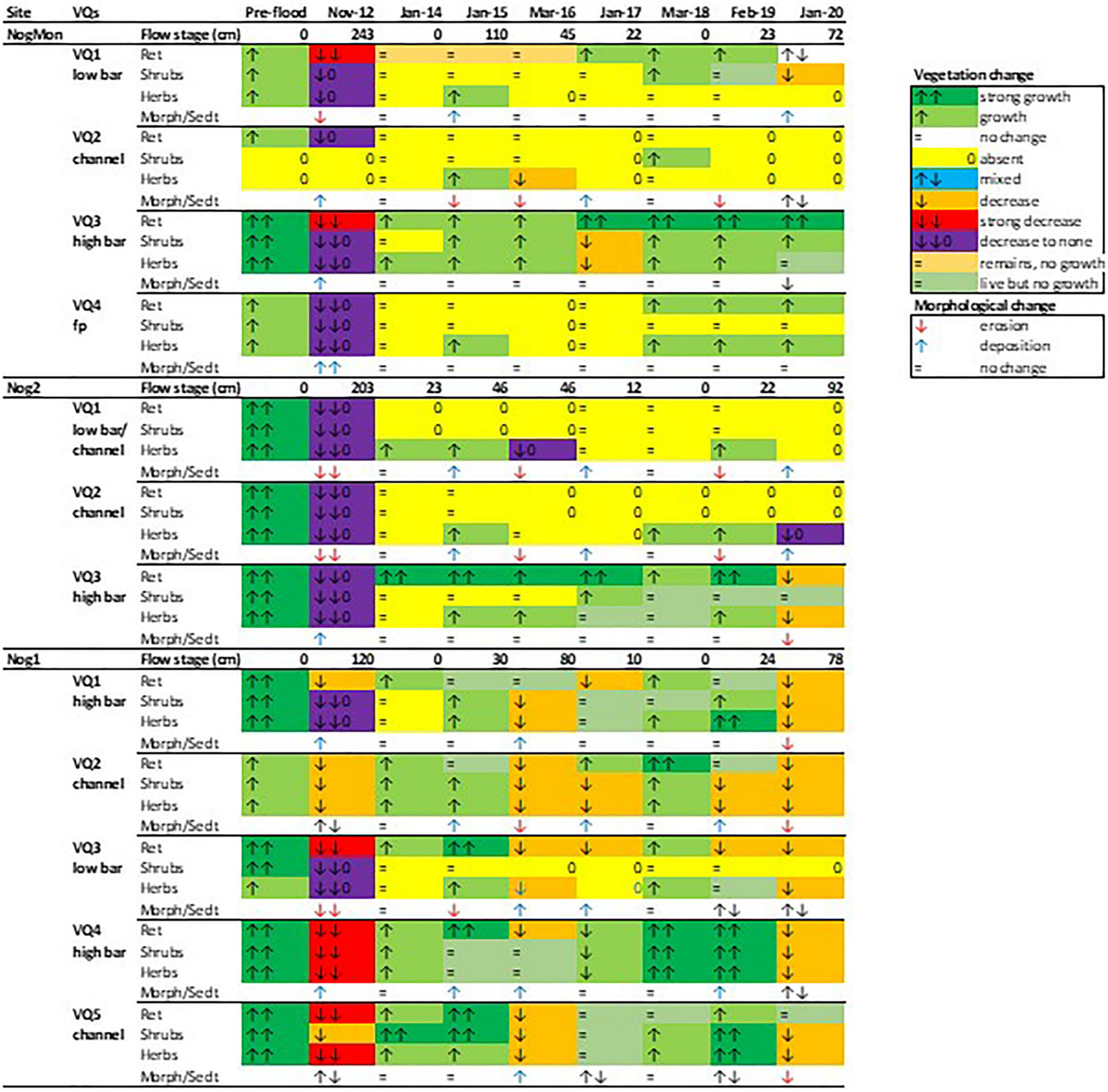


Figure 10. Values of shear stress calculated for sub-zones within cross-sections for different effects on the plants of the 2012 peak flow, a) Retama, b) Retama, shrubs and herbs.

up to 2020 (Figures 8 and 9), in relation to maximum flow levels each year in the sites. The presence, number and heights of the three main groups of plants have been assessed for each quadrat on each date of observation (mainly January each year) and the changes recorded by comparison of quadrat mappings/notes and photos from each year to indicate growth, decline and stasis (Figure 11). At NogMon it can be seen that VQ3 quadrat has shown rapid revival and continuous growth since January 2013 (Figure 7). This was mainly by resprouting (Figure 3) but subsequently some seedlings grew. Not all remains resprouted. In some quadrats Retama have begun to grow but with much delay, not until 2016–17 in VQ1 and 2017–18 in VQ4 at NogMon (Figure 11). These are where growth has been by new seedlings. The other quadrats have shown very little revival. VQ4 has experienced little growth of any plants but the few herbs have a varied response that appears related to flows as an index of moisture since no flows after 2012 reached there. In other cases, revivals of plant growth have not persisted, but these are from herbs that are annual anyway. The herb growth in channel sites has been affected by even the low flows, as calculation of shear stresses at low flows also showed (Figure 10b). At Nog2 VQ3, on the bar and with remains of Retama present after 2012, plants revived and started growing but only in 2014. The Retama was affected again by the relatively high flow in 2020 (Figure 9b). The other quadrats at Nog2 show variable development but all at low levels of coverage, with some relation to flow, except 2020 which was strong enough to destroy the plants. The revival is entirely from herbs, and few shrubs have recolonised the quadrats, though some have grown nearby, in spite of this being a zone with a variety of shrubs pre-flood. At site Nog1 VQ1, the Retama remains did start sprouting soon after the flood but showed slow growth and were bent in the 2020 flow. There was some delayed growth of an understorey of shrubs and herbs, and their growth and health has varied with conditions. In the channel quadrat of VQ2 the small Retama has shown limited growth and been affected by subsequent flows. The coverage of shrubs and herbs, including Juncus, has varied with the variable amounts of erosion and deposition in the quadrat in the flows since 2012. The quadrat VQ3 is on a low bar that has been affected by variable erosion and deposition in subsequent flows, producing initial growth of the Retama then damage. The shrubs have not revived, and the herbs have been sparse because flow is more frequent in this zone since morphological changes in 2012, associated with development of a secondary braided channel. VQ4 is on a higher bar and the originally large Retama plant has shown strong regrowth, though affected by a couple of flows since the 2012 peak. The shrubs and herbs have all revived and shown varied growth over the years, but all were affected by the 2020 flow. The channel quadrat at the downstream end (VQ5) includes a densely vegetated bank in which some Retama survived, though declined in 2012 but then showed vigorous growth to 2015 and slower growth since. The shrubs and herbs, which are an understorey to the Retama, have shown a similar pattern, but again affected by the 2020 flow.

Overall, within quadrats that contained Retama pre-flood, there were four plants with dead-looking woody remains after the flood that resprouted, mostly by 2014, and two plants with remains that never resprouted, implying a 67% regeneration rate. In one quadrat no trace remained and in that and four other quadrats with remains new seedlings also appeared, though after several years. All the individual Retama that were bent but living regrew, though at varying rates. Maximum growth rates are of Retama and have been of the order of 34.6 cm a^{-1} at NogMon VQ3 and 26.8 cm a^{-1} at Nog2 VQ3. The plant there grew 54 cm, in one period of 10 months 2017–18. Increases in width and density of the Retama are also associated with the growth in height. Overall, it is notable that the most vigorous recovery



Site	VQs		Pre-flood	Nov-12	Jan-14	Jan-15	Mar-16	Jan-17	Mar-18	Feb-19	Jan-20
NogMon		Flow stage (cm)	0	243	0	110	45	22	0	23	72
	VQ1	Ret	↑	↓↓	=	=	=	↑	↑	↑	↑↓
	low bar	Shrubs	↑	↓0	=	=	=	=	↑	=	↓
		Herbs	↑	↓0	=	↑	0	=	=	=	0
		Morph/Sedt		↓	=	↑	=	=	=	=	↑
	VQ2	Ret	↑	↓0	=	=	=	0	=	0	0
	channel	Shrubs	0	0	=	=	=	0	↑	0	0
		Herbs	0	0	=	↑	↓	0	=	0	0
		Morph/Sedt		↑	=	↓	↓	↑	=	↓	↑↓
	VQ3	Ret	↑↑	↓↓	↑	↑	↑	↑↑	↑↑	↑↑	↑↑
	high bar	Shrubs	↑↑	↓↓0	=	↑	↑	↓	↑	↑	↑
		Herbs	↑↑	↓↓0	↑	↑	↑	↓	↑	↑	=
		Morph/Sedt		↑	=	=	=	=	=	=	↓
	VQ4	Ret	↑	↓↓0	=	=	0	=	↑	↑	↑
	fp	Shrubs	↑	↓↓0	=	=	0	=	=	=	=
		Herbs	↑	↓↓0	=	↑	0	=	↑	↑	↑
		Morph/Sedt		↑↑	=	=	=	=	=	=	=
Nog2		Flow stage (cm)	0	203	23	46	46	12	0	22	92
	VQ1	Ret	↑↑	↓↓0	0	0	0	=	=	=	0
	low bar/	Shrubs	↑↑	↓↓0	0	0	0	=	=	=	0
	channel	Herbs	↑↑	↓↓0	↑	↑	↓0	=	=	↑	0
		Morph/Sedt		↓↓	=	↑	↓	↑	=	↓	↑
	VQ2	Ret	↑↑	↓↓0	=	=	0	0	0	0	0
	channel	Shrubs	↑↑	↓↓0	=	=	0	0	0	0	0
		Herbs	↑↑	↓↓0	=	↑	=	0	↑	↑	↓0
		Morph/Sedt		↓↓	=	↑	↓	↑	=	↓	↑
	VQ3	Ret	↑↑	↓↓0	↑↑	↑↑	↑	↑↑	↑	↑↑	↓
	high bar	Shrubs	↑↑	↓↓0	=	=	=	↑	=	=	=
		Herbs	↑↑	↓↓0	=	↑	↑	=	=	↑	↓
		Morph/Sedt		↑	=	=	=	=	=	=	↓
Nog1		Flow stage (cm)	0	120	0	30	80	10	0	24	78
	VQ1	Ret	↑↑	↓	↑	=	=	↓	↑	=	↓
	high bar	Shrubs	↑↑	↓↓0	=	↑	↓	=	=	↑	↓
		Herbs	↑↑	↓↓0	=	↑	↓	=	↑	↑↑	↓
		Morph/Sedt		↑	=	=	↑	=	=	=	↓
	VQ2	Ret	↑	↓	↑	=	↓	↑	↑↑	=	↓
	channel	Shrubs	↑	↓	↑	↑	↓	↓	↑	↓	↓
		Herbs	↑	↓	↑	↑	↓	↓	↑	↓	↓
		Morph/Sedt		↑↓	=	↑	↓	↑	=	↑	↓
	VQ3	Ret	↑↑	↓↓	↑	↑↑	↓	↓	↑	↓	↓
	low bar	Shrubs	↑↑	↓↓0	=	=	0	0	=	=	0
		Herbs	↑	↓↓0	=	↑	↓	0	↑	=	↓
		Morph/Sedt		↓↓	=	↓	↑	↑	=	↑↓	↑↓
	VQ4	Ret	↑↑	↓↓	↑	↑↑	↓	↓	↑↑	↑↑	↓
	high bar	Shrubs	↑↑	↓↓	↑	=	=	↓	↑↑	↑↑	↓
		Herbs	↑↑	↓↓	↑	=	=	↓	↑↑	↑↑	↓
		Morph/Sedt		↑	=	↑	↑	=	=	↑	↑↓
	VQ5	Ret	↑↑	↓↓	↑	↑↑	↓	=	=	↑	=
	channel	Shrubs	↑↑	↓	↑↑	↑↑	↓	=	↑	↑↑	↓
		Herbs	↑↑	↓↓	↑	↑	↓	=	↑	↑↑	↓
		Morph/Sedt		↑↓	=	=	↑	↑↓	=	↑↓	↓

Vegetation change

↑↑	strong growth
↑	growth
=	no change
0	absent
↑↓	mixed
↓	decrease
↓↓	strong decrease
↓↓0	decrease to none
=	remains, no growth
=	live but no growth

Morphological change

↓	erosion
↑	deposition
=	no change

Figure 11. Changes in state of plants in vegetation groups, Retama, shrubs and herbs, recorded on each vegetation quadrat in the three study sites in the period January 2012-January 2020.

Table 2. Measurements of % cover and maximum regrowth, 2012–2020, grouped by positions of quadrats.

Zone	No. quads	Min % cover	Max % cover	Max growth cm
Inner channel	4	0	10	40
Outer channel	3	2	15	80
Bar	3	10	50	340
Floodplain	2	0	20	72

is in the bar areas, less affected by the frequent low flows that have occurred quite frequently in the inner channels since 2013 but close to the moisture source in those inner channels (Table 2). Many of the channel areas have remained very sparsely vegetated and this has resulted in a clearer differentiation of zones, particularly apparent at NogMon (Figure 6). In no case had any quadrat reached its pre-flood density of cover by January 2020.

Calculation of the hydraulics of the peak 2012 flow have been made for two differing sets of values to assess the possible range of conditions, in relation to the roughness values applied to calculation of velocity and discharge and also because of the differing morphology before and after the flood (Table 1, Figure 4). These values demonstrate the possible effect that the presence of vegetation can have on the velocities attained and on the stream power. Comparison of the two sets indicates that the effect of the vegetation could possibly have altered the hydraulic parameters by the order of 2–3 times (Table 2) but there is wide uncertainty, associated with the assessment of the *n* values and with the conditions of flow, including the sediment transport, and the timing within the event (Hooke 2019). They also show that the capacity of the channel to the level of the 2012 flood can be decreased.

Accommodation of the flow in this case was by increased stage because the flood flows mostly occupied the whole valley floor.

Discussion

The long and detailed sequence of field observations and measurements of effects of flows on vegetation in channels and fluvial environments of an ephemeral stream, that includes an extreme event, provides opportunity to identify, quantify and discuss the dynamics of effects and responses. It includes the resetting of the vegetation at two monitored sites representative of much of the channel course, as a result of the extreme flood. This has enabled the threshold conditions for destruction or removal of phreatophytes, notably the *Retama sphaerocarpa* in this case, to be identified, which in other lower flows at these and other sites has proved remarkably resilient, partly due to its long tap root, that can reach many metres. It has shown that it is only in these extreme events that mature Retama is destroyed, thus illustrating its high adaptation to this fluvial environment, with its loose gravel beds, infrequent flows and deep groundwater. In this event on the Nogalte the impacts, shear stresses and stream power increased downstream, unlike the opposite trend found by Shaw and Cooper (2008). Floristic diversity in the Nogalte also tends to be higher in the upper sites, partly due to higher rainfall and possibly less human disturbance.

Retama is much less common and less studied than the similar phreatophyte Tamarisk. Bywater-Reyes et al. (2015) showed in pull tests on Tamarisk that high forces, with velocities in the range 3–6 m s^{-1}, are necessary for removal of even seedlings, and that the forces required increase with size of plant so mature plants, as were present for Retama in the Nogalte prior to the flood, would require extreme events. Likewise, Wilcox and Shafroth (2013) found that the size of vegetation was a significant factor in mediating the effect of floods on vegetation and morphology. In board tests of the force needed for bending Retama, Mant (2002) found results are highly related to stem diameter, with required forces of 5–30 N m^{-2} for stems of 10 mm diameter and 70 N m^{-2} for 25 mm diameter. This is comparable with the values of shear stress found here for flattening of mature Retama. The threshold shear stresses for mortality and removal calculated here are rather higher than those computed for Tamarisk in earlier floods in the region (Sandercock and Hooke 2010). Other situations of large-scale removal of vegetation by high magnitude flows have been reported (e.g. Parsons et al. 2006; Corenblit et al. 2014), but much of this is for trees such as *Populus nigra*. In the Nogalte sites for this event, it was not possible to compare the effects of the Retama traits with other trees, mainly due to their absence within the floodplain. Data compiled from previous floods in other sites had shown that single-stemmed trees without deep tap roots, such as Populus and almond, were more susceptible to destruction in moderate -high floods, mortality occurring by snapping off trunks (Sandercock and Hooke 2010) at lower velocities and shear stresses than for Tamarisk and Retama destruction.

Herbs have been shown here to be easily removed, with low thresholds of forces, of the order commonly occurring in even low flows in these channels. The stability of these shallow-rooting plants in the Nogalte channel is reduced by the very mobile nature of the gravels and that, even in low flows, an active layer of several cm depth of gravel can be mobilised, as personally observed in some previous events. Shrubs were not all that abundant in these quadrats in any zone of the channel environment (i.e. channel, bars and floodplain) prior to the 2012 flood, except at Nog2 where there had been no flow for several years prior to the September 2012 flood and where biodiversity was much greater than at other sites (Mant 2002). The shrubs in the channel were removed by the 2012 flood. The few shrubs and perennial parts that survived were mostly in the understorey and shelter of surviving Retama branches. One of the most resilient plants is Juncus, which did survive in places, and is known to have strong roots (Hooke and Sandercock 2017).

The growth rates and regeneration of Retama was highly variable, with some remains or quadrats formerly with mature Retama not showing any regrowth. Regeneration was by two mechanisms: 1. Resprouting from woody aerial remains, 2. Growth of seedlings, mostly in bare ground. The data indicate that the timescale of response varied, with immediate signs of regrowth in some quadrats but others only recovering after a delay of some years. The sprouting tended to be more immediate than the growth of seedlings. The growth and effects of subsequent flows in the period 2012–2020 can be compared with those of the 1997–2010 period (Figure 12). It can be seen that the decade prior to 2012 was very dry, with very few flows and no high peaks (Figure 2). Nevertheless, the Retama (measured on the same quadrat) did still grow to a height of 3–4 m, its characteristic mature state in these sites, after some set-back in the 1997 flood (Mant 2002; Hooke and Mant 2015) and stasis during the drought. The evidence for the nearly 10-year period 2012–2020 is that the perennial shrubs take a long time to come back. A few perennials proved resilient, notably Juncus, and also Anthyllis where

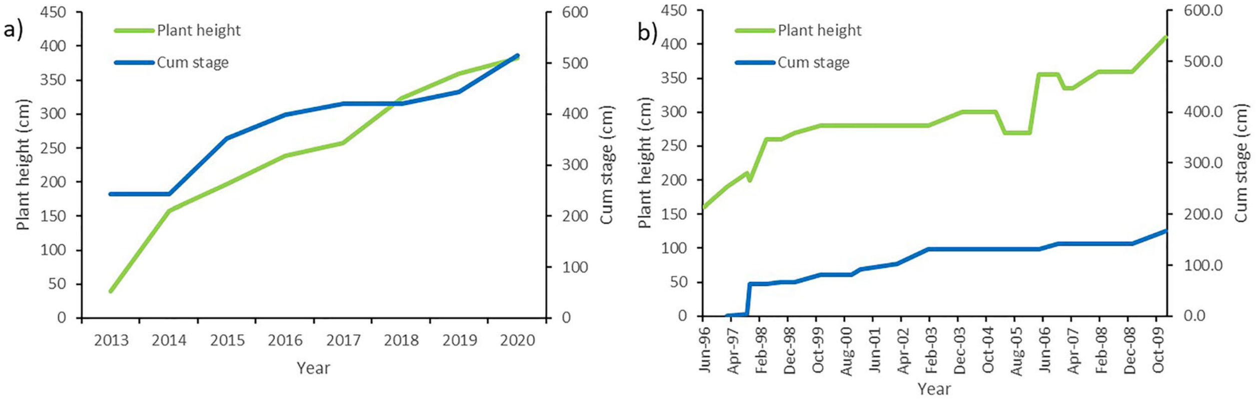


Figure 12. Growth in a Retama plant on one vegetation quadrat at site NogMon in relation to cumulative amounts of flow as measured by peak stage recorder at the site, a) 2012–2020, b) June 1996–January 2010 (after Hooke and Mant 2015).

sheltered by Retama bushes. The extent and rate of regrowth has mainly been influenced by occurrence of flow events preventing or constraining regeneration in the inner channels but available moisture promoting regrowth on bars. The regrowth was not influenced so much by the presence of gaps as found by Gurnell and Bertoldi (2020), as clearance was massive in the lower sites and vegetation cover is sparse anyway in this region, but remaining branches of some Retama plants have sustained increased growth of an understorey of herbs and shrubs in some cases. Of course, regeneration and rates of regrowth are influenced by other factors as well as flow. Although the consistent timing of the observations of vegetation should take out the seasonal factors, the time since actual flows as well as actual temperature and patterns of rainfall can have an influence. Extremes of temperature did occur, with snow in 2017. The effect of very high temperatures in summer 2022 have not yet been measured.

Overall, it is notable that the most vigorous recovery is in the bar areas (Table 2), less affected by the frequent low flows that have occurred quite frequently since 2013 and yet having enough moisture to nurture growth. Many of the channel areas have remained very sparsely vegetated. An enhanced differentiation of zones is particularly apparent at NogMon (Figure 6). Water is a limiting factor in this environment and therefore the greatest rates of growth and recovery are in the channel edges where the plants can obtain more water than the high floodplain but are rarely affected directly by the flows. This is similar to results produced by Ablat et al. (2021) from NDVI analysis of MODIS images in an arid area. It fits with much other research that has demonstrated the close relation of plant type and abundance to elevation across channels (Bendix 1999; Parsons et al. 2006; Bywater-Reyes et al. 2017) and also that colonisation, growth and disturbance are closely related to flow disturbance. The evidence, especially from the prior composition and extent of growth of shrubs in the channel at Nog2, is that, with long periods of low or absence of flows, vegetation will colonise into the inner channels, as found in much analysis of channel narrowing in response to changed flow regime (e.g. Dean and Topping 2019). Overall, it is possible that channels and bars are diverging in trajectories at these sites, perhaps in a similar way to that proposed by Bertoldi et al. (2014). However, the sequences of phases of wetter and drier periods and differing frequencies of high flows will have a major influence on the future morphological and vegetation evolution and their mutual feedbacks, as elsewhere (van Rooijen et al. 2022).

The mechanisms of destruction and “removal” or disappearance of plants, particularly the Retama are difficult to discern in some cases. The high amounts of deposition, sufficient at NogMon to bury flattened Retama plants, makes it difficult to detect where the decrease in number of plants was due to removal or to burial. The evidence is that the gravel layer was mobilised to at least 20 cm depth and possibly much more during the event and thus large-scale “scour” would have taken place in the early phase of the event. Bywater-Reyes et al. (2015) found that scour significantly decreases the forces needed to remove plants. However, the Retama plants can survive with some depth of exposure of roots (personal observation). The Retama remains were *in situ*; they are not broken branches and plants that have been transported, unlike at other sites, such as the Tagliamento (Corenblit et al. 2007, 2015) where deposition of transported large woody debris then forms the core of “islands” for regeneration. Woody debris and flotsam deposits were remarkably rare in these reaches, and, if large plants were removed and transported, they must have been deposited far downstream because there was little sign of major accumulation as far as Puerto Lumbreras. Another factor commonly considered in discussion of the impacts of flows is the duration of flow (Hooke 2015), but the fact that this event, which was of such a short duration and had a remarkably rapid rise of the hydrograph, produced the observed effects on the plants demonstrates that here it was not the effect of long-continued submergence of the plants that caused mortality but of direct forces of short duration. In some of the Retama remains, large cobble-sized particles were found (Figure 3b) and this may have contributed to damage and mortality. However, the sediment accumulation within the plants was evidence of the slowing and trapping effect of vegetation. Lateral bank erosion was not a major mechanism in the unconfined, braided study reaches of the Nogalte because the banks were mostly very low and ill-defined, except at Nog1 VQ5, where there was a more defined and deeper main channel in the downstream part of the reach (Figure 7).

Vegetation has been shown to increase sedimentation rates in all kinds of fluvial environments (e.g. Lightbody et al. 2019) and it is likely that the presence of even the damaged remains of plants did increase the rate. The slowing and trapping effect is demonstrated by the material trapped in Retama remains (Figure 3). However, there was little sign of vegetation wakes created in the event, unlike in previous events and more commonly in channels composed of marl-derived sediment (Sandercock and Hooke 2010, 2011). Prominent vegetation wakes are often a major element of channel topography in vegetated channels (Bywater-Reyes et al. 2017) and are major features in the neighbouring marl channels (Sandercock and Hooke 2011). The surface was generally flattened in the flood except at the upper site. This is probably due to the extreme characteristics of this event in terms of forces, Froude number and very high sediment load (Hooke 2019), combined with the nature of the gravels, the lack of fine sediment at these sites and the sparsity of the remaining vegetation. More generally, biogeomorphic feedbacks of vegetation on morphology are widely recognised (e.g. Corenblit et al. 2011), though feedbacks and even presence of riparian vegetation are still rarely integrated adequately into models or into hydromorphic assessments (del Tanago et al. 2021). The modelling by Brookes et al. (2000) attempted to incorporate feedbacks but the longer-term data analysed here provide more substantial quantification of impacts.

The hydraulic analysis of the possible effects of the state of vegetation on the forces in the channel indicate that these forces could have been 2–3 times greater if the channel had been free of vegetation compared with the state when the flood occurred. Likewise, the channel capacity would have been of the order of 50–30% less than in the post -flood low vegetation state. Of course, much uncertainty surrounds use of Manning's n values, especially for vegetated channels. It is possible that the figure for resistance in the vegetated state should be much greater (Antonarakis et al. 2009) and therefore the differences even more. The much reduced velocities and discharge mean that vegetation can be very effective in slowing flow and therefore reducing some forces, even if, at extremes, it does destroy the vegetation. It means that more water is held at these locations and it may prevent rapid transmission of floods downstream, as advocated in many strategies of natural flood management nowadays (Rowinski et al. 2018). It also means that the stage will be higher for particular flows and therefore the floodplain will be more frequently laterally connected to the channel, again a strategy that is encouraged now (Diaz-Redondo et al. 2018). This also has possible implications for the traditional type of rain-fed farming and use of canals and channels constructed to lead water into fields (Hooke and Mant 2002b), practices which have largely fallen into disuse.

The profound influence of flow regime on vegetation type, abundance and distribution has important implications for assessing the impacts of climate change from global warming. Martinez-Fernandez et al. (2018) have modelled this for Mediterranean streams but mostly in relation to Salicaceae species in perennial streams of NW Spain. Others have shown riparian communities to be likely to respond to changes in climate, with a trend to greater aridity (Stromberg et al. 2010; Reynolds and Shafroth 2017). Skoulikidis et al. (2017) regard that the ecosystems of the non-perennial streams of southern Europe are threatened by climate and other issues, which presents research challenges to support management and conservation. Over the decade since the 2012 event, these channels have experienced a much greater incidence of moderate–high peak flows than in the very dry period of 2000–2012 (Figure 2, Figure 12). Scenarios predict increased desertification in southern Europe (Martinez-Fernandez et al. 2018) but incidence of flash floods could still be greater. However, in such climates wetter and drier phases of a few years are common and land use changes also contribute to changes in regime (e.g. del Tanago et al. 2021). The recent high flows are in spite of some very large check dams being constructed in the Upper Nogalte. Resurvey has not taken place since January 2020 but observations in September 2022 indicate that, in spite of very high temperatures during summer 2020, vegetation growth was abundant, probably due to the very wet spring, illustrating the importance of event and phase sequences.

Conclusions

The effects of flows on vegetation have been analysed from field measurements and observations at a series of quadrats and cross-sections resurveyed at least annually since 1996 within three sites on an ephemeral dryland river. The measurement period included the occurrence of a very high flood event in September 2012, which was extreme in its magnitude, hydrograph characteristics and sediment load, allowing detailed data of the effects on, and of, vegetation and the hydraulic conditions of such an event to be generated. The flood event destroyed much of the vegetation and flattened the largest components, including plants of the phreatophyte *Retama* of up to 4 m in height and it produced an overall resetting of the vegetation in many parts of the wide, braided channel. This was an event that had a recurrence interval probably of the order of 50 years.

Calculated threshold values of peak flow shear stresses that produced mortality (with some aerial parts remaining) or removal/burial of the Retama plants are of the order of 300–400 N m^{-2}. This confirms the very high resilience of such plants to stream flow and their adaptation within dryland channels. The sparse shrubs only survived under remains of Retama and herbs were completely removed, with subsequent lower flows demonstrating their very low thresholds for destruction. Evidence of the mechanisms of damage and destruction of the Retama as well as other plants is that it was mainly by the force of the water, but with the bed mobilised during the event, though some plants may have been buried by extensive deposition on the upper bars.

Monitoring of quadrats in the subsequent years since the 2012 flood has allowed regrowth and rates of increase to be measured. A majority, but not all of the Retama remains have resprouted and new seedlings have colonised the bar surfaces. Rates of growth of the Retama have been rapid on the bars but the inner channels have remained low in vegetation cover, mainly because of subsequent flows. None of the quadrats had reached pre-flood vegetation density by 2020. Growth is greatest on channel edges and lower bars, probably mainly due to the moisture availability in the relatively frequent flows since 2012 but lack of direct effects. The patterns of flow and growth have led to increased differentiation between the bars and inner channels over the last decade.

Calculation of the hydraulics of the flood flow and the possible effects of the varying resistance offered by the different states of the vegetation indicate that the velocities and forces in the channel in an unvegetated state could be 2–3 times greater than in the vegetated state. Likewise, discharge capacity is decreased by 30–50% between the two states. However, this demonstrates how effective vegetation cover is in slowing flow and decreasing discharge and sediment flux downstream. The results here provide data that are needed for modelling vegetation dynamics and response to floods, droughts and sequences of flows and to climate changes, and to inform restoration and management and conservation of valuable habitats and biodiversity, in these dryland channels environments where data are still sparse.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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