An index of floodplain surface complexity

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Abstract

Floodplain surface topography is an important component of floodplain ecosystems. It is the primary physical template upon which ecosystem processes are acted out, and complexity in this template can contribute to the high biodiversity and productivity of floodplain ecosystems. There has been a limited appreciation of floodplain surface complexity because of the traditional focus on temporal variability in floodplains as well as limitations to quantifying spatial complexity. An index of floodplain surface complexity (*FSC*) is developed in this paper and applied to eight floodplains from different geographic settings. The index is based on two key indicators of complexity; variability in surface geometry (*VSG*) and the spatial organization of surface conditions (*SPO*) and was determined at three sampling scales. Relationships between these measures of spatial complexity and environmental drivers, namely; flow variability (mean daily discharge [Q], the coefficient of variation of daily discharge [Q_{CV}], the coefficient of variation of mean annual discharge [Q_{CVAnn}], the coefficient of variation of maximum annual discharge [Q_{CVMax}]), sediment yield (SY), valley slope (Vs), and floodplain width (Fpw) were examined. *FSC*, *VSG*, and *SPO* varied between the eight floodplains and these differences depended upon sampling scale. All complexity values declined with increasing Fpw in either a power, logarithmic, or exponential function. There was little change in surface complexity with floodplain widths greater than 10 km. *VSG* was significantly related to SY and no significant relationships were determined between any of the hydrological variables and floodplain surface complexity.

1 Introduction

The floodplain surface is an important component of floodplain ecosystems. It provides the primary physical template (sensu Southwood, 1977) upon which ecosystem and evolutionary processes are acted out (Salo, 1990). Complexity of floodplain surfaces contributes to the relative abundance of physical habitat (Hamilton et al., 2007), high biodiversity (Ward et al., 1999), and elevated levels of productivity (Thoms, 2003), as well as nonlinear ecosystem responses to inundation (Murray et al., 2006; Thapa et al., 2015). The majority of floodplain research has focused on temporal variations and in particular how hydrology drives floodplain structure and function (Junk et al., 1989; Hughes, 1990; Bayley, 1995; Whited et al., 2007). Such a focus has contributed to a limited appreciation of the spatial complexity of floodplain surfaces.

There are two main components to the spatial complexity of floodplain surfaces (Scown et al., 2015a). The first component relates to the presence/absence, abundance, and diversity of features or conditions present. This influences the number and range of distinct habitats and potential interactions between those habitats; both of which contribute to complexity (Levin, 1998; Phillips, 2003). The second component is concerned with the spatial organization of features or conditions present within a floodplain surface. Spatial organization controls local interactions and feedbacks between features and can emerge in the absence of any global control (Hallet, 1990). It also affects the flux of matter and energy throughout systems (Wiens, 2002). Any measurement of spatial complexity must incorporate both components; something that does not generally occur (Cadenasso et al., 2006). Studies of floodplain surface complexity have been limited because they tend to only measure one of the components of spatial complexity (Scown et al., 2015c). Moreover, many of the measures of spatial complexity that have been proposed are based on categorical ‘patch’ data (e.g., Papadimitriou, 2002). Such data have limitations because of the qualitative delineation of patch boundaries, loss of information within patches, and subsequent analyses of these data being restricted to the minimum scale at which patches were initially defined (McGarigal et al., 2009). Continuous numerical data have been used in some studies, and single metrics of surface complexity have been developed, such as rugosity or fractal dimension (see review by Kovalenko et al., 2012). These single-metric-based indices do not fully encompass the multivariate nature of spatial complexity; thus, multiple indicators are required to get the full measure of surface complexity (Dorner et al., 2002; Frost et al., 2005; Tokeshi and Arakaki, 2012). While frameworks encompassing the multiple dimensions of complexity have also been proposed (e.g., Cadenasso et al., 2006), they have not provided a quantitative measure of spatial complexity (Scown et al., 2015c). Quantitative measures of floodplain spatial complexity are required in order to advance our understanding of the influences of spatial complexity on these ecosystems and how it varies between floodplains.

New technologies are available for intensive data capture, such as light detection and ranging (LiDAR), and the analysis of these data using geographic information systems (GIS) overcomes many of the limitations that have inhibited the quantification of spatial complexity. LiDAR provides high resolution, quantitative topographic data over large areas for many landscapes including floodplains. These data are useful for measuring floodplain surface complexity. LiDAR-derived digital elevation models (DEMs) of floodplain surfaces can be used to measure the character and variability of surface features or conditions using a suite of surface metrics (McGarigal et al., 2009) and moving window analyses (Bar Massada and Radeloff, 2010; De Jager and Rohweder, 2012). The spatial organization of these features or conditions can then be measured using spatial correlograms and geostatistical models (Rossi et al., 1992). These quantitative measurements of the two components of spatial complexity can be incorporated into a single multivariate index. The advantages of using single indices that can be decomposed into sub-indices (e.g., for use in assessing ecosystem health [Norris et al., 2007]) have been widely favoured in ecosystem research.

A quantitative index of floodplain surface complexity is developed in this study and applied to eight floodplains from different geographic settings. The primary data source is a LiDAR-derived DEM for each floodplain. The character and variability of surface features and conditions and their spatial organization are incorporated into a single quantitative index to enable a comparison of surface complexity between floodplains. The different environmental settings of each floodplain provide an opportunity to determine the influence of environmental controls on floodplain surface complexity. In addition, the index is measured over three sampling scales (moving window sizes) to investigate the effects of scale on floodplain surface complexity. In this study we ask three questions: 1) Does the surface complexity of the eight floodplains differ and is this consistent among sampling scales? 2) Are the two components of spatial complexity related in floodplain surfaces? 3) What environmental factors influence floodplain surface complexity?

2 Study area

Eight floodplain surfaces from different geographic settings were examined in this study (Fig. 1, Table 1). The Bidgee, Gwydir, Macquarie, Narran, and Yanga floodplains are all located within the Murray-Darling Basin in S.E. Australia; whereas the floodplain of the Woodforde is located in central Australia approximately 150 km north of the town of Alice Springs. The floodplain of the Shingwedzi is located in N.E. South Africa, in the northern regions of Kruger National Park; and the floodplain of the Upper Mississippi is located within navigation Pool 9 and forms the boundary of the states of Minnesota, Wisconsin and Iowa in the USA. Details of the eight floodplains are provided in Table 1, and in summary, they differed in terms of their degree of valley confinement, climate, and position within the stream network. Four floodplains (the Bidgee, Mississippi, Shingwedzi, and Woodforde) are contained within relatively confined river valley troughs with floodplains width ranging between one and five kilometers. The other four floodplains (the Gwydir, Macquarie, Narran, and Yanga) are all contained within relatively unconfined river valleys with floodplain widths up to 60 kilometers. The eight floodplains also differ in their hydrology and geomorphology, exhibiting a variety of morphological features such as flood channels, oxbows, natural levees, crevasse splays, and back swamps. Detailed descriptions of each of the eight floodplains are provided by Scown et al. (2015a).

3 Methods

The Index of Floodplain Surface Complexity (*FSC*) developed for this study was calculated from data extracted from LiDAR-derived digital elevation models (DEMs) for each floodplain. Floodplain extents were delineated using multiple lines of evidence. This delineation was based on examination of breaks of slope in the DEM, contours, changes in vegetation from aerial photography, soil conditions from local soil conservation surveys, and floodwater extents derived from Landsat TM imagery. A buffer within this manually delineated extent was also removed to ensure nothing other than what was deemed to be part of the floodplain was included. Premanently inundated areas were also removed because attaining accurate subsurface land elevations using LiDAR is difficult. Each DEM was then detrended to remove the overall downstream slope. Details of the detrending procedures for each of the floodplains are provided by Scown et al. (2015a; 2015b). Each detrended DEM was subsequently resampled to a 5 × 5 m^2 grid size using the cubic method in ArcGIS 10.2 because this was the finest resolution available for one of the floodplains.

The *FSC* index is comprised of two sub-indices, which record the two components of spatial complexity; the variability in surface geometry (*VSG*) and the spatial organization of surface conditions (*SPO*). *VSG* is a composite of four surface metrics (Table 2), measured at 50 random sample locations throughout each of the floodplains, while *SPO* is calculated from spatial correlogram models of Moran's I over increasing lag distances for each of the four surface metrics from 1000 random sample locations (Table 2). Details of the procedures for calculating each indicator are provided by Scown et al. (2015a). In summary, the surface metrics are used to indicate increasing surface variability, while the spatial correlogram model parameters (range and nugget) are used to indicate increasing 'patchiness' or organization in the surface (Table 2). It is argued here, and elsewhere (Scown, 2015; Scown et al., 2015a), that increasing variability and spatial organization results in increasing spatial complexity. All surface metrics were measured within sampling windows of 50 m, 200 m, and 1000 m radius. These window sizes were chosen based on the identification of scale thresholds between them by Scown et al. (2015b). This enabled us to determine whether any effect of sampling scale occurred.

The individual indicators were combined and weighted, using the standardized Euclidean distance procedure, to calculate the overall *FSC* index. This index was used for an overall assessment of floodplain surface complexity and the sub-indices of *VSG* and *SPO* were derived to provide specific interpretations of the two components of spatial complexity for each floodplain surface. An example of *FSC* calculation is given in Equation (1), where I is the overall index and *A, B, C, …* , *N* are the n individual indicators of surface complexity, the details of which are provided in Table 2.

$$I = 1 - \frac{\sqrt{(1-A)^2 + (1-B)^2 + (1-C)^2 + \ldots + (1-N)^2}}{\sqrt{n}} \quad . \qquad (1)$$

Calculating the *FSC* index required the *SPO* indicators to have an additional weighting of 0.5, as there were twice as many indicators of *SPO* compared to *VSG*. All indicators were range-standardized and scaled between 0 and 1, hence this index provides a relative measure among those floodplains studied. An index value approaching one indicates the floodplain surface is among the most spatially complex of all floodplains observed, while an index value approaching zero indicates the floodplain surface is among the least spatially complex. The approach used has been applied successfully in developing a large scale index of River Condition (Norris et al., 2007).

Relationships between the two components of spatial complexity were also investigated *VSG* and *SPO* at each sampling scale. In addition, relationships between *VSG*, *SPO*, and *FSC* and seven environmental variables were also investigated. The environmental variables were mean daily discharge in ML/day (Q), CV daily discharge (Q_{CV}), CV mean annual discharge (Q_{CVAnn}), CV maximum annual discharge (Q_{CVMax}), sediment yield in t/km^2/y (SY), average valley slope in m/m (Vs), and average floodplain width in km (Fpw). Detailed calculations of environmental variables are provided by Scown et al. (2015a). Each of these environmental variables reflect an aspect of the flow, sediment, energy, and valley conditions, which have previously been shown to influence floodplain surface morphology (Nanson and Croke, 1992; Warner, 1992). Curve estimation between *VSG*, *SPO*, and *FSC* and each environmental variable at each sampling scale was conducted in SPSS. Q, SY, and Vs were normalized using a logarithmic transformation before analysis.

4 Results

4.1 Floodplain surface complexity (*FSC*)

Floodplain surface complexity, as measured by the *FSC* index, was highly variable among the eight floodplains and across sampling scales. The Gwydir floodplain had the least complex of surfaces across all sampling scales (mean *FSC* of 0.17), while the Shingwedzi floodplain had the most complex surface (mean *FSC* of 0.69) across all scales (Fig. 2). This presumably reflects differences in the geomorphology of these two floodplains. The Shingwedzi floodplain is dissected by numerous channels and gullies, which create highly organized patches of increased topographic relief, whereas the Gwydir floodplain has a relatively flat, featureless surface over larger continuous areas and limited organization around any of the significant surface features. The effect of sampling scale on *FSC* was not consistent across the eight floodplains (Fig. 2), indicating that comparisons among floodplains are scale-dependent. For example, the Gwydir and Narran floodplain surfaces became more complex with increasing window size, whereas the Shingwedzi, Macquarie, and Mississippi floodplains became less complex.

4.2 Variability in surface geometry (*VSG*)

The *VSG* index was also highly variable among the eight floodplains and across sampling scales (Fig. 3). Again, the Gwydir floodplain consistently had the lowest values for this index over all window sizes (mean *VSG* of 0.06), while the Shingwedzi floodplain consistently had the highest (mean *VSG* of 0.65). This reflects the large differences in topographic relief and variability between these two floodplains. The *VSG* score of 0.00 for the Gwydir floodplain at the 50 m window size indicates that this floodplain had the lowest scores for all four indicators of variability in surface geometry of the eight floodplains studied at this scale. Similar to *FSC*, the effect of sampling scale on *VSG* was not consistent across floodplains (Fig. 3). *VSG* increased with sampling scale for the Narran floodplain, but decreased for the Shingwedzi, Bidgee, Macquarie, and Woodforde floodplains. *VSG* was highest at the 50 m window size and lowest at 200 m for the Mississippi and Yanga floodplains, while it was highest at 200 m and lowest at 50 m for the Gwydir. This indicates that the scale at which surface geometry is most variable depends on the floodplain.

4.3 Spatial organisation of surface conditions (*SPO*)

The *SPO* index was also highly variable among the eight floodplains and across sampling scales (Fig. 4). Unlike *FSC* and *VSG*, there was no consistency as to which floodplain had the highest and lowest *SPO* across sampling scales. This indicates that no floodplain has consistently the highest or lowest degree of spatial organization of surface conditions among the eight floodplains studied. The effect of sampling scale on *SPO* was also inconsistent across floodplains (Fig. 4). For five of the eight floodplains, *SPO* was lowest at the 200 m window size and highest at 1000 m. For the Mississippi and Woodforde floodplains, the opposite was observed, with *SPO* being highest at 200 m and lowest at 1000 m. The Bidgee floodplain was the only floodplain for which *SPO* increased consistently across all sampling scales. This indicates that the degree of spatial organization of surface conditions is highest at large sampling scales for most floodplains, but at intermediate scales for some. *SPO* was highly variable across window sizes for the Yanga, Woodforde, and Gwydir floodplains. *SPO* was 178 % higher at the 1000 m window size than at 200 m for the Gwydir floodplain and 138 % higher for the Yanga floodplain, while for the Woodforde floodplain it was 61 % lower. This indicates a significant change in the spatial organization of these floodplain surfaces between these two sampling scales. The results also showed that floodplain and window size have a greater combined effect on *SPO* among the eight floodplains than on relative *FSC* and *VSG* (Figs. 2, 3, and 4).

4.4 Relationship between *VSG* and *SPO*

SPO values were, on average, 17 % higher than the *VSG* values. The greatest difference between *SPO* and *VSG* was 0.51 for the Woodforde floodplain, at the 200 m window size, followed by 0.47 for the Bidgee and Yanga floodplains at the 1000 m window size (Figs. 3 and 4). The Mississippi floodplain was the only floodplain where *SPO* was lower than the *VSG*, with an average difference of -0.03. This comparison between *SPO* and *VSG* values, suggests surface conditions across the eight floodplains are generally more highly spatially organized than they are geometrically variable.

Average variance of *SPO* across sampling scales within a floodplain (0.0212) was almost six times higher than that of *VSG* (0.0037). However, the average *SPO* variance was dominated by a limited number of floodplains; notably the Gwydir, Woodforde, and Yanga floodplains (Fig. 4). Four of the five other floodplains had a less variable *SPO* across sampling scales compared to their *VSG*; with the exception being the Bidgee floodplain. These results of *SPO* variance across sampling scales indicates that, on average, the spatial organization of surface conditions is much more sensitive to sampling scale than the variability of surface geometry.

Significant linear relationships between *VSG* and *SPO* were recorded at the 50 m and 200 m window sizes only (Table 3). Overall, *SPO* increased with *VSG* (Fig. 5) and this positive relationship was strongest at the 50 m window size, with more than 61 % of the variance in *SPO* explained by *VSG*, reducing to 56 % at the 200 m window size, and less than 8 % at 1000 m window size. The *y*-intercept of each regression line was greater than 0.1 at all window sizes, while the slope was less than one at 50 m and 1000 m, but greater than one at 200 m (Table 3). This provides further indication that *SPO* is generally higher than *VSG* in these eight floodplains.

4.5 Relationships between floodplain surface complexity and environmental variables

Floodplain width (Fpw) was the only environmental variable statistically related to any of the three indices of spatial complexity ($p < 0.05$). This variable was significantly related to *FSC* and *VSG* over all window sizes, and to *SPO* over all but the 1000 m window size (Table 4).

The decrease in all three complexity indices with increasing Fpw was best explained by either a power, logarithmic, or exponential function (Table 4). In terms of the decrease in *FSC* with increasing Fpw, this was best explained by a power function at all window sizes (Fig. 6a), indicating *FSC* undergoes rapid decline with increases in Fpw, approaching an asymptote at approximately 10 km in Fpw. The modelled change in *FSC* with increasing Fpw was almost identical between the 50 m and 200 m window sizes. At the 1000 m window size, *FSC* was generally lower compared to that at 50 m and 200 m windows sizes in narrow floodplains, before approaching a higher asymptote at larger Fpw. This indicates that broad floodplains generally have higher *FSC* when measured at larger sampling scales, whereas narrow floodplains generally have higher *FSC* when measured at smaller sampling scales.

Decreases in *VSG* with increasing Fpw was best explained by a logarithmic function at the 50 m window size, a power function at the 200 m window size, and an exponential function at 1000 m (Fig. 6b). These models indicate a more rapid initial decline in *VSG* with increasing Fpw at the 200 m window size than at the 50m and 1000 m window sizes. This is followed by approach to a higher asymptote at the 200 m window size above Fpw of approximately 10 km, whereas modelled *VSG* continues to decline between Fpw of 10 km and 25 km at the 50 m and 1000 m window sizes. This indicates that Fpw has a greater effect on *VSG* in wider floodplains when measured at small and large sampling scales than it does at intermediate scales. The relationship was strongest at the 200 m window size, with more than 80 % of the variance in *VSG* being explained by Fpw.

The decrease in *SPO* with increasing Fpw was best explained by a logarithmic function at the 50 m and 200 m window sizes (Fig. 6c). The modelled decline in *SPO* was initially more rapid at the 50 m window size than at 200 m, before approaching a higher asymptote at narrower Fpw. This indicates that Fpw has more of an effect on *SPO* in wider floodplains when measured at the 200 m window size than at 50 m. The relationship was strongest at the 200 m window size, with more than 77 % of the variance in *SPO* being explained by Fpw. This was reduced to 71 % at the 50 m window size. There was no significant relationship between Fpw and *SPO* at the 1000 m window size (Fig. 6c). This suggests that Fpw exerts little or no control over the spatial organization of surface conditions when measured at large sampling scales.

A weak statistical relationship was recorded between *SY* and *VSG*. An increase in *VSG* with increasing SY was observed at the 200 m window size (r^2 = 0.44; p = 0.07). The relatively lower level of significance of this result was attributable to the Gwydir having a high SY but a very low *VSG*. When the Gwydir floodplain was removed from the analysis, there was a significant and strong linear relationship between log-transformed SY and *VSG* across all window sizes for the remaining seven floodplains (Table 5, Fig. 7). This relationship was almost identical across all window sizes.

5 Discussion

The Euclidean Index of floodplain surface complexity (FSC) used in this study is comprised of the two key components of spatial complexity; the character and variability of features or conditions, and their spatial organization. This index appears to discriminate between floodplains with distinctly different geomorphological features. The multivariate nature of the index, comprised of 12 indicators of surface complexity (Table 2), has advantages over univariate indices that have been applied to measure floodplain surface complexity. Univariate indices fail to incorporate both aspects of surface structure, which contribute to surface complexity (Dorner et al., 2002; Frost et al., 2005; Tokeshi and Arakaki, 2012). Having a single, multivariate-based index is also favorable rather than multiple individual indicators of floodplain surface complexity, as it allows a quantitative measure that can be compared for multiple riverine landscapes. Norris et al. (2007) provide a comparable example of such an application in their assessment of river condition. It is important to note that, the standardization of indicator scores from 0 to 1 is necessary for the Euclidean Index equation (Norris et al., 2007), as the FSC index is a relative index of floodplain surface complexity across a group of floodplains all of which were included in the standardization of the indicators. This is appropriate for examining relationships between floodplain surface complexity and environmental controls, given adequate replication over a range of floodplain settings is achieved. However, it should not be used to compare against indices of other studies, unless all floodplains being compared are included in the calculation of the index.

The results of this research demonstrate: floodplain surface complexity to be highly variable among the eight floodplains studied, and floodplain width to exert a significant 'top-down' control (sensu Thorp et al., 2008) on differences in floodplain surface complexity. These results clearly support geomorphological and ecological thinking that *"…the valley rules the stream…"*, as argued first by Hynes (1975) and strongly supported since (e.g., Schumm, 1977; Miller, 1995; Panin et al., 1999; Thoms et al., 2000). In this case, the valley rules the floodplain surface complexity, at least in terms of the ‘top-down’ influences investigated here. The influence of floodplain width on floodplain surface complexity decreases significantly once widths are greater than 10 km. Above 10 km, little change in the index of floodplain surface complexity was recorded. This is likely due to the dissipation of flood energy in wide floodplains, limiting the construction of large topographic features, which contribute to surface complexity. However, subtle topographic features in wide floodplains are also importance surface features (Fagan and Nanson, 2004), which may have been overlooked in this index. In narrower, confined settings, where widths are less than 10 km, floodplain construction may be the result primarily of vertical processes (e.g., accretion/incision) leading to more prominent topographic features that exhibit a higher degree of spatial organization and thus increased surface complexity (Nanson and Croke, 1992). Such complexity can lead to the concentration of flood energies in particular areas, promoting episodic catastrophic stripping (Nanson, 1986). The narrowest floodplain examined in this study was, on average, 1.5 km in width and the results presented in this study may not be consistent in floodplains narrower than this. In particular, there is a loss of surface complexity when floodplains are contained between artificial levees or embankments (Florsheim and Mount, 2002; Gurnell and Petts, 2002), so floodplain surface complexity should not be considered to increase indefinitely in floodplains approaching a width of 0 km.

Valley trough or floodplain width has been identified as a primary controller of floodplain pattern and process in several previous studies. Spatial patterns of flow depth, velocity, and shear stress in overbank flows were found by Miller (1995) to all be influenced by valley width and this influence was particularly noticeable at locations of valley widening or narrowing. Similarly, Thoms et al. (2000) found that valley width had a significant effect on sediment textural character and associated heavy metal concentrations within different morphological units of the Hawkesbury River Valley, New South Wales. In particular, they found higher proportions of silt and clay, and lower proportions of sand and gravel, in wide floodplain sections compared to narrow floodplains. The results of this present research support the findings that floodplain width is an important controller of floodplain pattern and process.

The effect of floodplain width was relatively consistent across all three indices examined. This suggests that floodplain width has a similar effect on the variability of floodplain surface geometry, the degree of spatial organization, and overall floodplain surface complexity. This likely explains the significant positive linear relationship between the variability of surface geometry and the spatial organization of surface conditions sub-indices. This relationship likely occurs because environmental conditions, particularly related to floodplain width, which promote higher variability in floodplain surfaces, also cause a high degree of spatial organization. Reinforcing feedbacks between these two components of spatial complexity may also exist. That is, high variability of surface geometry promotes a high degree of spatial organization, and vice versa. Positive feedback is common in complex systems (Levin, 1998; Phillips, 2003), and feedbacks between hydrology, geomorphology, and biology in floodplains may play a part in this (Hughes, 1997).

The textural character of floodplain sediments and local energy conditions during inundation has been postulated as important controls of floodplain morphology (Nanson and Croke, 1992). These two drivers would also be expected to influence floodplain surface complexity. In this study, sediment yield was found to have a weak effect on the variability in surface geometry, although relationships were not significant. This may be because estimates of contemporary sediment yield were used in this study, whereas historical sediment yields are relatively more important (Panin et al., 1999). Substantial anthropogenic increases in sediment loads have been reported for the Gwydir floodplain (De Rose et al., 2003). Removal of this floodplain from our analyses, resulted in a significant increase in variability in surface geometry with increasing sediment yield across the seven remaining floodplains. This result suggests that sediment yield may exert ‘top-down’ control on the variability of floodplain surface geometry, although recent anthropogenic changes in sediment yields (Prosser et al., 2001), particularly increased erosion in the catchment due to land use changes, may have delayed ‘lag’ effects on floodplain surfaces which have not yet been observed. Valley slope was used in this study as a surrogate for stream energy, and this was not found to have any effect on overall floodplain surface complexity. More accurate measures of energy conditions such as specific stream power (Nanson and Croke, 1992) may reveal any effects of energy conditions on floodplain surface complexity, if they exist, more clearly. It is also likely that variable flood energy conditions within each floodplain have an effect on localized surface complexity. For example, Fagan and Nanson (2004) found distinct differences in floodplain surface channel patterns among high, intermediate, and low energy areas of the semi-arid Cooper Creek in Australia. They also found the energy of flood flows to be largely controlled by floodplain width.

Hydrology has been widely considered the main determinant of floodplain ecosystem pattern and process (Junk et al., 1989; Hughes, 1990; Bayley, 1995; Whited et al., 2007). However, the research presented in this paper indicates that this may not be the case for floodplain surface complexity. None of the four hydrological variables measured here had a significant effect on floodplain surface complexity. This suggests that, although hydrology is largely important in driving floodplain ecosystem processes, floodplain width and sediment conditions appear to exert more control over the complexity of floodplain surfaces. This is important given that floodplain research and restoration is often focused on hydrology, particularly connectivity (e.g., Thoms, 2003; Thoms et al., 2005); whereas valley trough, sediment, and energy conditions may be more important in structuring and maintaining the physical template upon which hydrology acts as an ecosystem driver (Salo, 1990). Loss of floodplain surface complexity due to changes in sediment yield or calibre, or confinement between artificial levees, may be as ecologically important as changes to hydrology and should not be overlooked (Thoms, 2003). It is important to note, however, that some of the eight floodplains studied have experienced anthropogenic alterations to their hydrology. Thus, hydrological parameters based on contemporary data may not reflect the nature of the flow regime that was influential in establishing current surface conditions; lagged effects of altered hydrology on surface complexity may occur in the future (sensu Thoms, 2006).

Riverine landscapes and their floodplains are hierarchically organized ecosystems (Dollar et al., 2007; Thorp et al., 2008), being composed of discrete levels of organization distinguished by different process rates (O'Neill et al., 1989). Each level of organization, or holon, has a spatial and temporal scale over which processes occur and patterns emerge (Holling, 1992). The different sampling scales used in this research indicate that the scale at which patterns in floodplain surfaces are most complex depends on the floodplain setting. In particular, wide, unconfined floodplains appear to have higher floodplain surface complexity when measured at larger sampling scales, whereas narrow, confined floodplains have so at smaller sampling scales. Thus, the scale at which floodplain surface complexity is maximized likely relates to the width of the floodplain. Selecting different window sizes tailored to each floodplain individually relative to floodplain width should be the focus of future research. This may reveal consistent effects of scale on floodplain surfaces.

These results suggest that the scale of processes that maximize complexity, and potentially biodiversity and productivity (Tockner and Ward, 1999), in floodplains differ between different valley settings. This has implications for understanding and managing the complexity of floodplain ecosystems. Floodplain processes, which operate over certain temporal scales, elicit a response over relative spatial scales (Salo, 1990; Hughes, 1997). Consequently, managing processes at the appropriate scale to achieve desired outcomes is important (Parsons and Thoms, 2007). This has already been recognized for managing floodplain hydrology to maintain biodiversity (Amoros and Bornette, 2002) and these results indicate it is also important for managing the processes that maintain floodplain surface complexity.

Recent approaches to examining and understanding ecosystem complexity and the emergent properties that arise from interactions within systems emphasise the importance of heterogeneity, connectivity, and contingency within the landscape (Loreau et al., 2003; Cadenasso et al., 2006). We have presented an index of floodplain surface complexity within such a framework that incorporates measures of variability and spatial organization. These two components of spatial complexity are directly associated with heterogeneity and connectivity (Wiens, 2002), although no direct measure of historical contingency is given in this spatial approach. Metrics and indicators used to measure properties of landscape and ecosystem complexity in the past have largely been based on discrete units and the familiar concept of 'patches' (Forman and Godron, 1981). The surface metrics employed in this study are conceptually equivalent to certain patch metrics and a comprehensive comparison of surface and patch metrics is provided by McGarigal et al. (2009). Thus, the approach presented in this study should be considered complimentary to other ecosystem complexity frameworks, such as the meta-ecosystem approach (Loreau et al., 2003), which are based on patches.

In terms of the origin and implications of floodplain surface complexity, this research focuses on 'top-down' environmental drivers of floodplain surface complexity. 'Bottom-up' feedbacks from the floodplain ecosystem are also likely to affect surface complexity. For example, vegetation establishment on deposited floodplain sediments is known to produce a positive feedback loop in which more sediment is trapped and semi-permanent morphological features such as islands develop (Nanson and Beach, 1977; Hupp and Osterkamp, 1996). Such feedbacks are likely to influence floodplain surface complexity, particularly in floodplains dominated by such features (Gurnell and Petts, 2002; Stanford et al., 2005). 'Bottom-up' influences on floodplain surface complexity are difficult to quantify and were not examined in this study. Future research into the influence of vegetation type and density on floodplain surface complexity, particularly in relation to its hydraulic roughness, may provide valuable insights into 'bottom-up' controls on floodplain surface complexity. Such data are also available through LiDAR (Straatsma and Baptist, 2008). Effects of floodplain surface complexity on biodiversity and productivity should also be examined in future research. The floodplain surface provides the primary geomorphic template upon which ecosystem and evolutionary processes are acted out (Salo, 1990) and it would be expected that increased surface complexity would promote the range of physical habitats required to maintain floodplain biodiversity (Hamilton et al., 2007).

The inclusion of other floodplains, from different regions, in future studies of this nature, would further determine whether the trends observed in this study extend beyond the floodplains investigated here. This study was limited to eight floodplains because of data availability. As high-resolution LiDAR data across many more floodplains are made available to researchers, other analyses such as multiple regression will be possible in studies such as this. Multiple regression would enable the interactive effects of environmental variables to be elucidated, whereas this study was limited to relatively simple linear regression because of the sample size of only eight floodplains.

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Table 1. Summary of the geographical and climatic settings of the eight study floodplains.

Floodplain name	Valley setting	Climate	Stream network setting
Bidgee	Confined	Semi-arid/temperate	Lowland continuous
Gwydir	Unconfined	Semi-arid/temperate	Lowland terminal
Macquarie	Unconfined	Semi-arid/temperate	Lowland continuous
Mississippi	Confined	Continental	Upland continuous
Narran	Unconfined	Semi-arid	Lowland terminal
Shingwedzi	Confined	Sub-tropical	Upland continuous
Woodforde	Confined	Arid	Headwaters continuous
Yanga	Unconfined	Semi-arid/temperate	Lowland continuous

Table 2. Summary of the indicators used to calculate the index of Floodplain Surface Complexity (*FSC*). Averages and standard deviations of the surface metrics (left columns) are calculated from 50 random sample locations throughout each floodplain. The nugget and range from the Moran's I spatial correlograms (right columns) are extracted from the exponential isotropic models fit to these. See Scown et al. (2015a) for detailed calculation procedures.

Indicators of variability in surface geometry		Indicators of spatial organisation of surface conditions	
Average standard deviation of surface heights	Indicates variability in surface elevation within an area	Spatial correlogram exponential isotropic model nugget (×4 metrics)	Indicates strength of spatial organisation
Average coefficient of variation of surface heights	Indicates variability in surface elevation relative to the mean elevation within an area	Inverse of the spatial correlogram exponential isotropic model range (×4 metrics)	Indicates patchiness or fragmentation in spatial organisation
Standard deviation of skewness of surface heights	Indicates variability in erosional and depositional features within an area		
Average standard deviation of surface curvature	Indicates how convoluted the surface is		

Table 3. Results from regression analyses of *SPO* against *VSG* at each of the three window sizes.

	Best model	F	*d.f.*	p	r^2
50 m	$y = 0.703x + 0.223$	9.676	1, 7	0.02	0.61
200 m	$y = 1.135x + 0.120$	7.627	1, 7	0.03	0.56
1000 m	$y = 0.329x + 0.429$	0.472	1, 7	0.52	0.07

Table 4. Results from regression analyses of *FSC*, *VSG*, and *SPO* against Fpw at each of the three window sizes.

		Best model	F	*d.f.*	p	r^2
FSC	50 m	$y = 0.765x^{-0.414}$	10.344	1, 7	0.02	0.63
	200 m	$y = 0.762x^{-0.420}$	25.523	1, 7	0.00	0.81
	1000 m	$y = 0.549x^{-0.213}$	5.871	1, 7	0.05	0.50
VSG	50 m	$y = -0.151 \ln x + 0.630$	9.642	1, 7	0.02	0.62
	200 m	$y = 0.627x^{-0.418}$	26.319	1, 7	0.00	0.81
	1000 m	$y = 0.472e^{-0.064x}$	13.574	1, 7	0.01	0.69
SPO	50 m	$y = -0.145 \ln x + 0.737$	14.515	1, 7	0.01	0.71
	200 m	$y = -0.204 \ln x + 0.866$	20.586	1, 7	0.00	0.77
	1000 m		*0.570*	*1, 7*	*0.48**	*0.09*

Table 5. Results from regression analyses of *VSG* against $\log_{10}(SY) + 1$ at each of the three window sizes with Gwydir removed.

	Best model	F	*d.f.*	p	r^2
50 m	$y = 0.183x + 0.088$	50.497	1, 6	0.00	0.91
200 m	$y = 0.158x + 0.084$	18.179	1, 6	0.00	0.78
1000 m	$y = 0.142x + 0.088$	36.076	1, 6	0.00	0.88

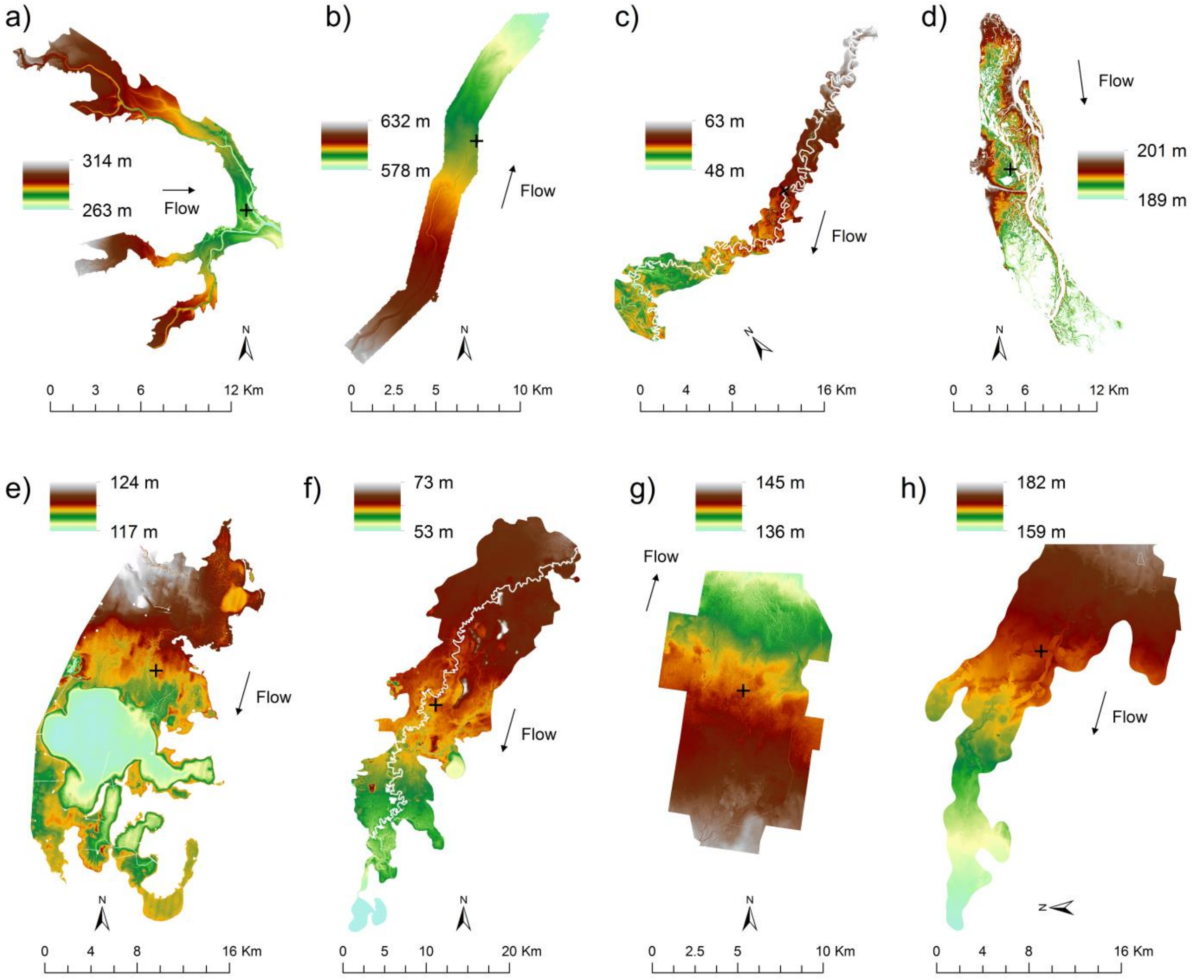

Figure 1. Digital elevation models displaying the floodplain surface in meters above sea level for each study site (crosses indicate coordinates listed): a) Shingwedzi (31°24’E, 23°05’S); b) Woodforde (133°20’E, 22°21’S); c) Bidgee (143°24’E, 34°42’S); d) Mississippi (91°15’W, 43°29’N); e) Narran (147°23’E, 29°48’S); f) Yanga (143°42’E, 34°30’S); g) Macquarie (147°33’E, 30°41’S); h) Gwydir (149°20’E, 29°16’S).

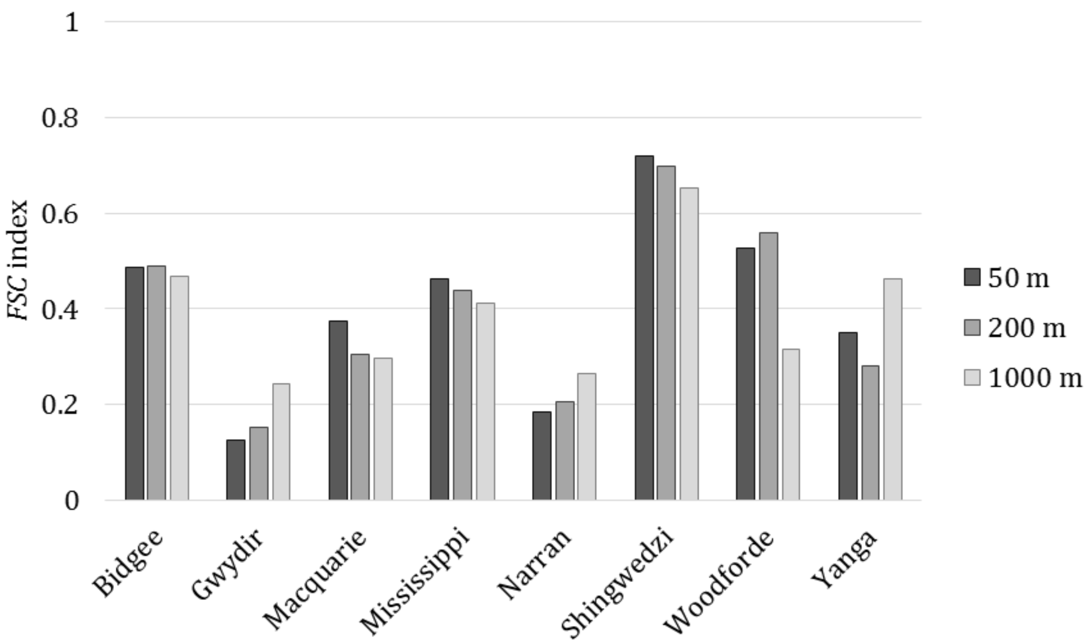

Figure 2. Index of floodplain surface complexity (*FSC*) for the eight floodplains at each of the three window sizes.

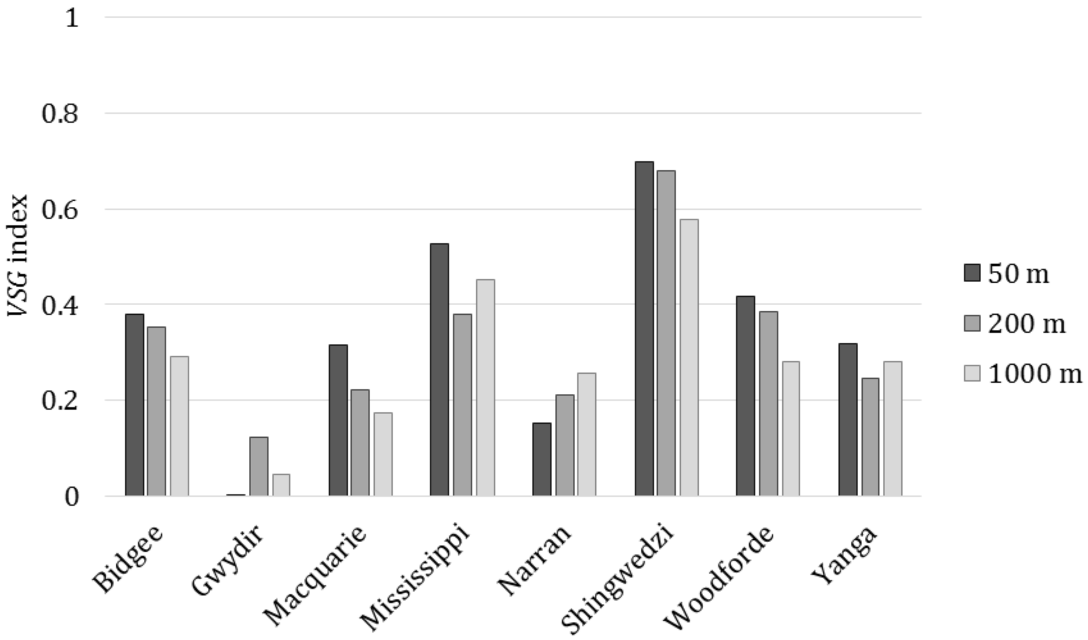

Figure 3. Index of variability in surface geometry (*VSG*) for the eight floodplains at each of the three window sizes.

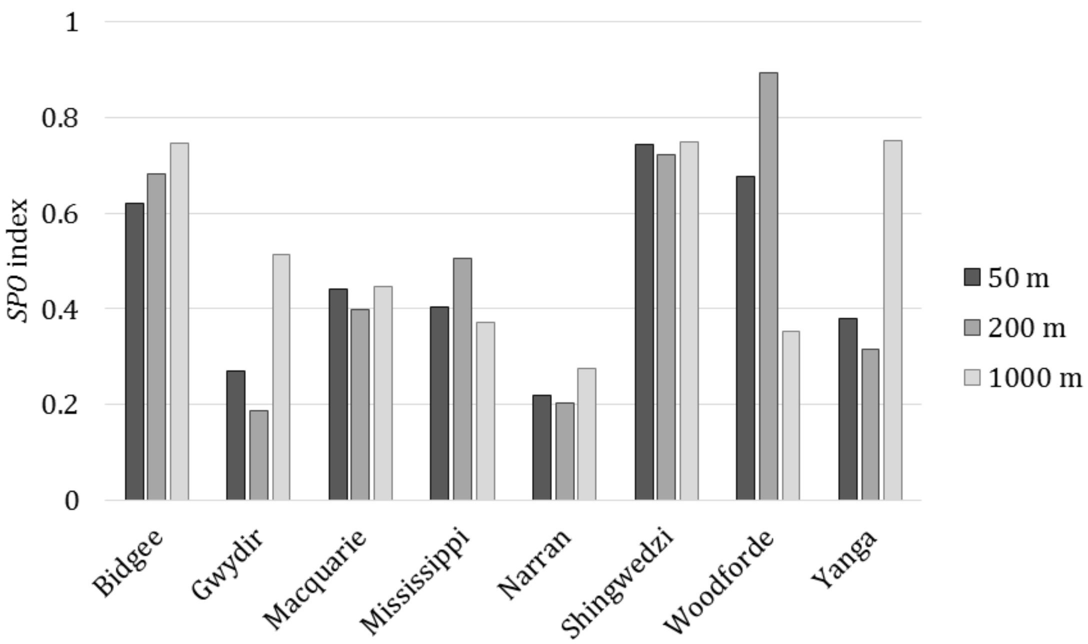

Figure 4. Index of spatial organisation of surface conditions (*SPO*) for the eight floodplains at each of the three window sizes.

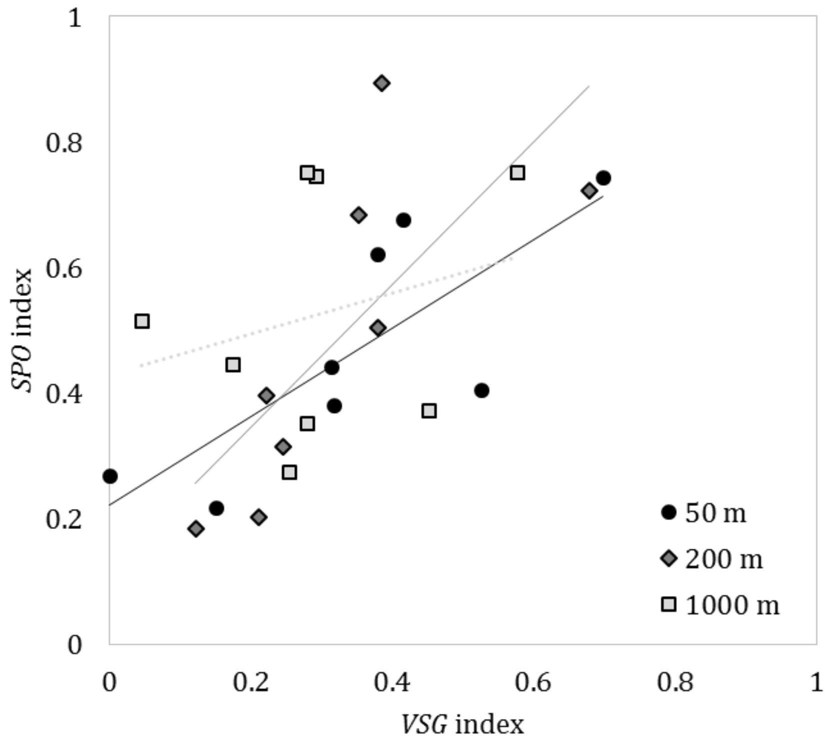

Figure 5. Linear relationships between variability in surface geometry (*VSG*) and spatial organisation of surface conditions (*SPO*) at each of the three window sizes.

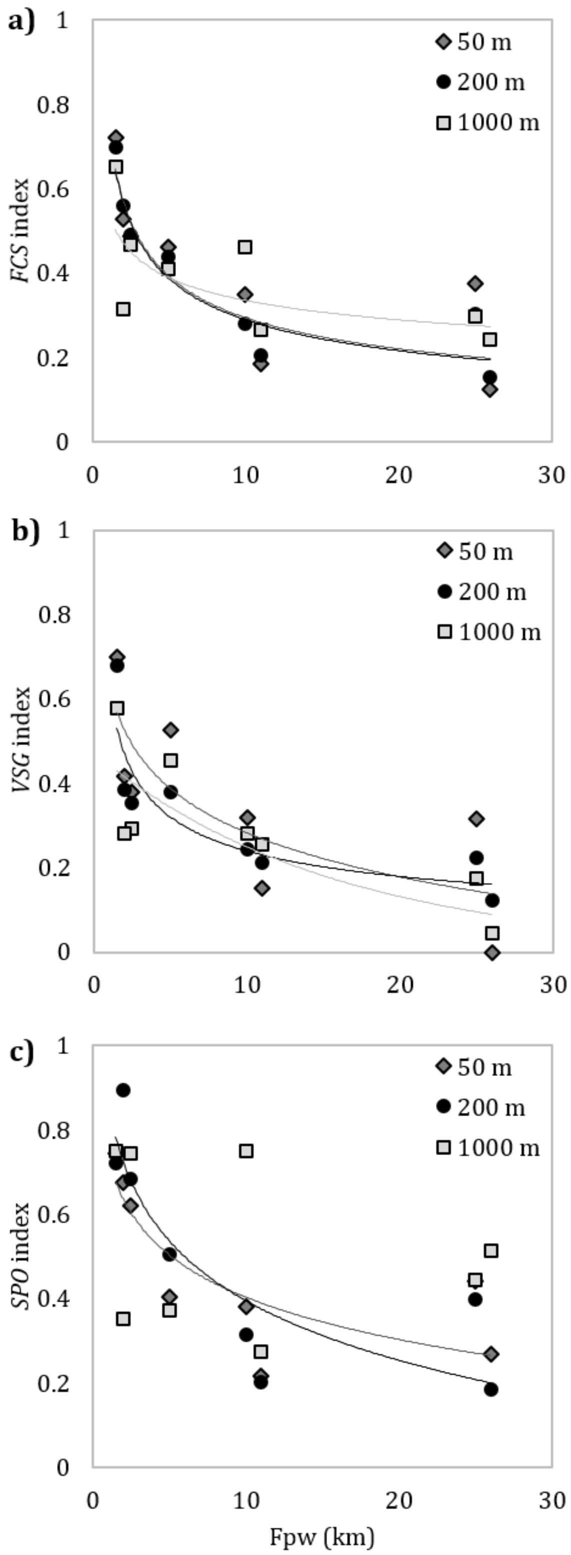

Figure 6. Power relationships between floodplain width (Fpw) and a) floodplain surface complexity (*FSC*), b) variability of surface geometry (*VSG*), and c) spatial organisation of surface conditions (*SPO*) at each of the three window sizes.

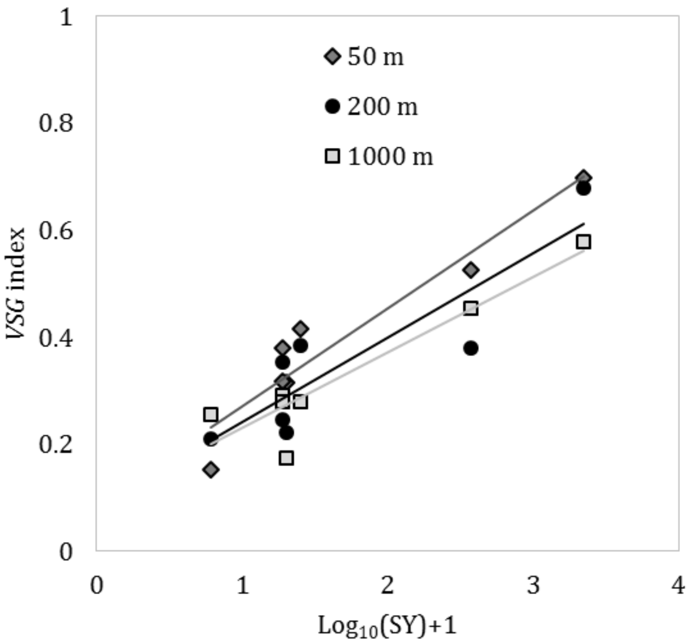

Figure 7. Linear relationships between log-transformed SY and variability of surface geometry (*VSG*) at each of the three window sizes with Gwydir removed.