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ECOHYDROLOGY

DOI:
10.1002/eco.1928

Published: 01/03/2018

Peer reviewed version

Dyfyniad o'r fersiwn a gyhoeddwyd / Citation for published version (APA):
de Sosa, L. L., Glanville, H. C., Marshall, M. R., Abood, S. A., Williams, A. P., & Jones, D. L. (2018). Delineating and mapping riparian areas for ecosystem service assessment. *ECOHYDROLOGY*, *11*(2), [e1928]. https://doi.org/10.1002/eco.1928

Delineating and mapping riparian areas for ecosystem service assessment

Laura L. de sosa[1], Helen C. Glanville[12], Miles R. Marshall[3], Sinan A. Abood[4], A. Prysor Williams[1], Davey L. Jones[1]

[1] School of Environment, Natural Resources & Geography, Bangor University, Environment Centre Wales, Deiniol Rd, Bangor, Gwynedd, LL57 2UW, UK

[2] School of Geography, Geology and the Environment, Keele University, Keele, Staffordshire, ST5 5BG, United Kingdom

[3] Centre for Ecology and Hydrology, Environment Centre Wales, Deiniol Rd, Bangor, Gwynedd, LL57 2UW, UK

[4] School of Forest Resources & Environmental Science, Michigan Technological University, Houghton, MI, USA

Correspondence

Laura L. de sosa, School of Environment, Natural Resources & Geography, Bangor University, Environment Centre Wales, Deiniol Rd, Bangor, Gwynedd, LL57 2UW, UK

E-mail: afs411@bangor.ac.uk.

Funding information

This research was supported by the UK Natural Environment Research Council under the Macronutrients Programme from a NERC grant: NE/J011967/1: The Multi-Scale Response of Water Quality, Biodiversity and Carbon Sequestration to Coupled Macronutrient Cycling from Source to Sea'. This research was also supported by a Knowledge Economy Skills Scholarship

(KESS 2) awarded to LDS funded via the European Social Fund (ESF) through the European Union's Convergence program administered by the Welsh Government.

Abstract

Riparian buffers, the interface between terrestrial and freshwater ecosystems, have the potential to protect water bodies from land-based pollution, and also for enhancing the delivery of a range of ecosystem services. The UK currently has no defined optimal width or maximum extent of riparian buffers for specific ecosystem services. Here, we present the first study which attempts to 1) compare and critique different riparian buffer delineation methods, 2) investigate how ecological processes e.g. pollutant removal, nutrient cycling and water temperature regulation are affected spatially by proximity to the river and also within a riparian buffer zone. Our results have led to the development of new concepts for riparian delineation based on ecosystem service-specific scenarios. Results from our study suggest that choice of delineation method will influence not only the total area of potential riparian buffers, but also the proportion of land cover types included, which in turn will determine their main ecosystem provision. Thus, for some ecological processes (e.g. pollutant removal), a fixed–distance approach will preserve and protect its ecosystem function whereas for processes such as denitrification, a variable width buffer will reflect better riparian spatial variability maximizing its ecological value. In summary, riparian delineation within UK habitats should be specific to the particular ecosystem service(s) of interest (e.g. uptake of nutrients, shading, etc.) and the effectiveness of the buffer should be ground-truthed to ensure the greatest level of protection.

KEYWORDS

Ecosystem services, Freshwater corridors, GIS, Land use mapping, Riparian zone modelling, Riverbanks, Wetlands

1 | INTRODUCTION

Riparian areas are defined as the interface between land and freshwater ecosystems and are characterized by distinctive soil, hydrology and biotic conditions (Naiman et al., 2005). Riparian areas have been widely recognised for decades as having great potential to accomplish specific ecological functions such as alleviating agricultural runoff, promoting nutrient cycling and retention, flooding control or stream shading (Malanson, 1993; Wenger, 1999; Zaimes et al., 2007; Vigiak et al., 2016). However, due to the lack of a universal definition of ‘riparian’ and development of holistic classification systems (Verry et al., 2004; Naiman et al., 2010), their spatial complexity within the landscape as transitional zones and their sensitivity to disturbance have made their integration for management and delineation challenging.

Despite their importance, there is little guidance on how to reliably integrate the main riparian features such as vegetation or floodplain extension when delineating their boundaries (Salo et al., 2016). Delineating riparian areas may assist in improving our understanding of how these areas might benefit ecosystem service provision by: 1) identifying patterns in land use and their importance in the landscape, 2) characterising soil types and habitat distributions within the riparian areas, 3) reducing the anthropogenic pressures to which they are subject, 4) preserving their intrinsic value, and 5) establishing a common framework for their classification. Numerous approaches to delineate riparian areas have been undertaken ranging from simplistic models in which a fixed width buffer is implemented (Hawes & Smith, 2005; Stoffyn-Egli & Duinker, 2013), to more complex holistic approaches where the most relevant riparian characteristics such as soil properties, associated floodplain extent, vegetation type or hydrologic parameters are integrated into delineation models of varying complexity. These are subsequently used to generate a variable width riparian buffer (Lyons et al., 1998; Baker et al., 2006; Abood & Maclean, 2011; Momm & Bingner, 2014; Belletti et al., 2017). However, recent approaches are more inclined to disregard fixed width buffers as they can be grossly inaccurate due to the poor and inconsistent relationship between riparian width and its ecological functionality (Aunan et al., 2005; Abood & Maclean, 2011; Abood et al., 2012). Furthermore, the use of geographic information systems (GIS) for conducting riparian estimations and the recent availability of high resolution data and imagery have resulted in the variable width buffer gaining more popularity over the past ten years (Xiang, 1993; Goetz et al., 2003). This allows the integration of a large amount of variables to characterise the potential riparian area. Hence, different GIS-based methods are already available which attempt to integrate multiple physical riparian attributes such as land cover (Baker et al., 2006), soil characteristics (Palik et al., 2004) and flood height (Mason, 2007) for riparian delineation. Approaches including biological attributes (e.g. amphibian habitat or vegetation type) have also been applied (Perkins & Hunter, 2006; Mac Nally et al., 2008). It is worth noting that the number of variables incorporated into the riparian area modelling process greatly affect its data-intensiveness and computational complexity by increasing data pre- and post-processing and increasing the number of interactions into the model. Thus, the delineation process should only incorporate spatial data at appropriate resolutions which allows capture of riparian versatility while maintaining the effectiveness and efficiency of the modelling process.

Ultimately, the spatial delineation of riparian areas remains critically dependent upon the ecosystem service being studied. For example, this could involve mapping of services directly adjacent to the river (e.g. shading, habitat), while other services may extend for considerable distances away from the watercourse (e.g. nutrient attenuation, flood risk management). Legal or policy adoption of a specific riparian buffer methodology could therefore potentially lead to the inclusion or exclusion of a particular area as being “riparian”. This could in turn determine the implementation and success of future management activities designed to optimise riparian functioning or in the assessment of riparian performance. Fundamental to this, will be to understand the relationship between land cover strongly influenced by physical attributes such as soil type or hydrology, and ecosystem service provision, as studies have indicated a link between land cover and its capacity to provide specific ecosystem services (Burkhard et al., 2009; Sheldon et al., 2012; Clerici et al., 2014).

The aim of this study was to critically evaluate the relative accuracy of different riparian delineation approaches and explore the impact of data quality and data types on predictions of riparian typologies. Specifically, our objectives are; 1) to evaluate to what extent fixed-width riparian buffers provide a different outcome than functionally-targeted variable-width riparian buffers, and 2) to determine how the quality of nationally-available digital information influences the prediction of functional variable-width riparian buffers?

2 | MATERIALS AND METHODS

2.1 | Study area

The study was conducted in the Conwy catchment, North Wales, UK (3°50’W, 53°00’N; Figure 1). The catchment comprises a total land area of 580 km^2 and its main river (River Conwy) runs for 43 km from its southern source to its subsequent estuarine discharge point into the Irish Sea (Emmett et al., 2016). The river rises in the Snowdonia National Park and the upper reaches of the river cross a wide range of habitats including upland bog, improved and unimproved grazed grasslands and coniferous and deciduous woodlands. Within this catchment, five sub-catchments were selected representing the dominant land-use types and riparian typologies in the catchment. A detailed description of the catchment is provided in Emmett et al. (2016). Main features of the sub-catchments are provided in Table 1 and in the On-line Supplementary Information (Figures S1-S5).

2.2 | Riparian delineation methodology

All riparian modelling and data manipulation were undertaken using ArcGIS Desktop 10.2 (ESRI Inc., Redlands, CA). A schematic representation of the three different methodological approaches undertaken in this study can be seen in Figure 2. The different riparian delineation approaches were evaluated as follows:

Method 1. Fixed-width riparian buffer approach: Two buffer strips contiguous to the watercourse, 10 m and 50 m width respectively, were defined to assess the influence of proximal and distal riparian buffer delineation. There is no consensus on the most appropriate fixed buffer width for riparian area delineation (Wenger, 1999), however, as a broad recommendation, studies have indicated that efficient buffer widths should range between 3 m to >100 m depending on what resource they are trying to preserve (Hawes & Smith, 2005). For this study we chose a distance of 10 m following the absolute minimum buffer width suggested by Wenger (1999), and 50 m based on the recommendation of Peterjohn & Correll (1984) for agricultural catchments.

Method 2. Variable-width riparian buffer approach: Variable-width riparian buffer strips were spatially quantified using a modified version of Riparian Buffer Delineation Model v2.3 (Abood et al., 2012; *https://www.riparian.solutions/*) to work with the data available for this study. The model was implemented as an ArcGIS toolbox connected to ArcMap. The model generates riparian ecotone boundaries based on four critical inputs: stream and lake locations, digital elevation model (DEM) and the 50-year flood height. The specific sources and data inputs are listed in Table 2. The locations of streams and lakes are critical inputs into the model as they represent the drainage network associated with the riparian areas. In addition, the DEM provides the height information of the floodplain. Alongside the river network and DEM, the model also establishes the 50-year flood height as a required input on the assumption that this parameter represents the optimal hydrologic descriptor of a riparian area throughout the watercourse based on the research of Ilhardt et al. (2000). The 50-year recurrence interval was also indicated as the most likely elevation to intersect the first terrace or other upward sloping surface and in most cases, present the same microclimate and geomorphology as the stream channel (Ilhardt et al., 2000). Previous studies have addressed this task by performing regression equations between periodic measurements of flow rate, velocity and channel width obtained from river gauging stations (Mason, 2007; Abood et al., 2012). In this study, due to the lack of river gauge data for all sub-catchments, an alternative approach was used. Briefly, river hydraulic modelling was performed using HEC-GeoRAS (US-ACE, 2005) with a high resolution DEM to obtain required cross-sectional data and then the HEC-RAS (US-ACE, 2014) software used to generate surface water elevation (Figure 3). The model utilized several input parameters that influence flow behaviour: Manning's values (data based on the recommended design values of the Manning Roughness coefficients of McCuen (1998)) and boundary conditions (the channel bed slope of the first two cross-sections at the upstream boundary and the last two cross-sections at the downstream boundary as a starting value for a mixed flow regime). Once the river cross-sections were defined, the Network-wide Flood Estimation Handbook (Q(T) grid flood estimates; Robson and Reed, 1999) was used to derive the 50-year flood discharge (flow data in the HEC-RAS) (Table 1) for the major rivers in each sub-catchment.

As an estimate of flood extent, the Flood Zone 3 map for a 100-year event provided by the UK Environment Agency was used to compare the resultant floodplain area in each sub-catchment. Results from the HEC-RAS simulations, which include the locations of the cross-sectional cut lines together with water surface profile data, were processed in the HEC-RAS Mapper utility where the profile data is outputted as water surface elevations (depth grid). A detailed description of the process can be found in Ackerman (2011). Flood height results for the main rivers in all sub-catchments ranged between 1.4 and 2.2. However, in order to implement the same flood height for all study sites and to facilitate model development, a single average flood height of 1.6 m was used for all sub-catchments.

Once all the inputs were introduced into the model, sample points along streams and transects around those sample points were built. For the study area, a maximum transect length of 250 m was imposed to improve the processing efficiency and to account for the spatial variation in height within our study (Abood et al., 2012). The model detected the change in elevation between the sample and the transect points and determined if the point should be included inside the riparian buffer. A detailed description of model performance can be found in Abood et al. (2012). As the DEM is one of the crucial model inputs, we also tested the influence of different DEM spatial resolutions on model output (2, 5, 10, 30 and 50 m). As optional data we include wetlands (according to New Phase 1 classification (Lucas et al., 2011) and soil data from the National Soil Map of England and Wales (National Soil Resources Institute, Cranfield, UK; NATMAP; http://www.landis.org.uk/data/natmap.cfm).

Method 3. Fixed-width legislative riparian buffer approach: One fixed-width buffer of 2 m was defined along minor rivers and the same distance was manually digitalized along the main rivers. As the buffer automation was created from the centre line of the river, manual digitalization was necessary in order to prevent the buffer from ending in the middle of major rivers considering the small size of the buffer. The digitization was accomplished using orthophotos and satellite imagery. The distance was chosen following the main requirements found in national and European-level policies in which a minimal buffer of 2 m is established for riparian areas (i.e. SMR 1; GAEC 1, 2016). This is also in agreement with common riparian fencing practices in the catchment, most of which are undertaken under the auspices of Welsh Government agri-environment schemes (e.g. Tir Gofal, Glastir).

2.3 | Datasets

The datasets used in the study are presented in Table 1. Where possible, the best nationally available datasets were used. For lakes and open water bodies (>2 ha in area), a 30.5 m fixed buffer was used according to Ilhardt et al. (2000). Typically, these riparian areas only constituted <1% of the total riparian area within each sub-catchment. Lastly, the riparian buffers in each of the sub-catchments were overlain onto soil type and two independent land cover datasets (LCM2007 and New Phase 1; Table 1). This was used to evaluate and characterize the percentage of land use and soil type within the riparian areas delineated using each of the three methods. For ease of comparison, different habitat types were aggregated into common land cover categories. These included: (1) broadleaved woodland, (2) coniferous woodland, (3) arable and horticulture, (4) improved grassland, (5) semi-natural grassland, (6) mountain, heath and bog, (7) freshwater, and (8) other, including built-up areas and gardens. A summary of how they were grouped is presented in the On-line supplementary information (Table S1).

3 | RESULTS

3.1 | Estimate of riparian area using different delineation methodologies

The different approaches used to delineate stream riparian boundaries differed substantially in terms of their ability to predict the spatial distribution of riparian areas (Figure 4) and the total land area they covered in the sub-catchment (Figure 5). Of all the study areas, sub-catchment 1 showed the largest differences in terms of the total riparian area delineated by the different methods. For example, the fixed buffer approach (50 m) mapped the largest land area, encompassing 5.5 km^2 (26.6% of the total area), while the variable buffer approach only predicted a total area of 4.1 km^2 (19.7%). In contrast, the fixed (10 m) and the legal (2 m) approaches gave much lower estimates of 1.2 km^2 (5.6%) and 0.26 km^2 (1.2%), respectively. In the case of sub-catchment 2, no major difference was apparent between the fixed buffer (50

m) method (0.50 km^2, 34.3% of the area) and the variable buffer approach (0.52 km^2, 35.8%). Within the same sub-catchment, the legal based approach produced a very small riparian area, probably as it consisted predominantly of minor rivers. Similar to sub-catchment 2, the riparian predictions for the fixed buffer (50 m) method (3.0 km^2, 25.0%) and variable buffer (3.4 km^2, 28.1%) were close for sub-catchment 3. Sub-catchments 4 and 5 were intermediate, giving a discrepancy between the fixed buffer (50 m) and variable buffer of 0.99 km^2 and 0.27 km^2 respectively.

3.2 | Agreement between the areas delineated with the fixed and variable width buffer approach

Due to the similarity of the results, in terms of total area delineated, shown by the fixed (50 m) and variable width buffer approaches, we compared whether they actually mapped the same areas. This was achieved by analysing the spatial agreement of pixels identified by both methods. The fixed width buffer (50 m) displayed clear differences when compared with variable width buffer predictions with nearly 30% of the digital pixels in spatial disagreement for sub-catchment 1, 21% for sub-catchment 2, 24% for sub-catchment 3, 27% for sub-catchment 4 and 17% for sub-catchment 5 (Figure 4).

3.3 | Effect of digital elevation model (DEM) resolution on variable width riparian area predictions

Resolution of the DEM (i.e. sources and creation method of the DEM) was tested as it indicates the level of elevation details that are captured within the floodplain topography. A comparison of the impact of DEM resolution (2, 5, 10, 30 or 50 m) on the spatial mapping/distribution of riparian zones is shown in Figure 6, while its effect on the total riparian area delineated is shown in Figure 7. The results showed that the variable riparian buffer model calculated from the 2 m DEM produced a range of significantly smaller riparian areas than those calculated with the 5 and 10 m DEMs (Figure 6a). The spatial pixel disagreement between the variable width buffer from the 2 m resolution DEM versus the variable width buffer from 5 and 10 m resolution DEM was also noticeable with 24% and 45% disagreement, respectively. In contrast, comparison of the variable width buffer from a 2 m resolution DEM versus the results obtained from 30 and 50 m resolution DEMs showed a decreasing trend in terms of total surface area (Figure 6b, Figure 7). Both the 30 and 50 m model outputs displayed discontinuous and dispersed riparian area boundaries. The spatial pixel disagreement between riparian area from 2 m resolution and the two coarser DEMs resulted in 67% of disagreement for the 30 m resolution DEM and 74% for the 50 m resolution DEM. The changes observed in riparian surface area according to the different DEM spatial resolutions in sub-catchment 1 are shown in Figure 7. The results obtained using the 10 m DEM produced the greatest surface area with an area of 8.05 km^2. A similar trend was found for the other sub-catchments (data not presented).

3.4 | Effect of delineation method on riparian land cover predictions

Differences in delineation methodology might not only influence the total riparian area, but also the prediction of soil distribution and the proportion of land cover types included within them. We overlaid the different riparian boundaries obtained with the different delineation methodologies onto the most detailed national soil map and the two most widely used national land cover maps (LCM2007 and New Phase 1). It should be noted that the comparison of soil distribution was only undertaken for sub-catchment 1, as it was the only area mapped at sufficient accuracy (1:63,000).

Overall, the Denbigh and Sannan soil series comprised the greatest land area regardless of the delineation approach (Figure 8). A description of the different soil series and their equivalent in the FAO World Reference Base (WRB) is shown in Table S2. In general, the total amount of each soil series predicted within the riparian zone was relatively similar for all four delineation methods. Only the variable width buffer showed a >5% discrepancy in the main soil categories compared to the rest of the methodological approaches.

Land cover datasets (LCM2007 and New Phase 1) were intersected with all riparian delineations separately and are presented in Figs. 9-13. It should be noted that some of the least abundant categories (those comprising <1% of the total riparian area) are not presented. In general, both land use datasets gave good agreement with 'improved grassland' and 'mountain, heath and bog' being the dominant habitats within the riparian buffer zones. However, strong contradictions in terms of habitat classification are noticeable in some sub-catchments (e.g. sub-catchment 2 and 3). For instance, while 'improved grassland' and 'mountain, heath and bog' were the dominant habitat types according to the New Phase 1 classification, 'semi-natural grassland' comprised the most abundant habitat type for the LCM2007 classification in sub-catchment 2 (Figure 10). It is worth noting that some of the habitat types present in some of the sub-catchments (e.g. sub-catchment 3 and 4) according to the New Phase 1 map are missing for the LCM2007 results (Fig 11 and 12). Our results suggest that the New Phase 1 land cover map tended to provide the information at a finer resolution than the LCM2007 as it identified a higher number of habitats types within riparian zones with the different modelling approaches (e.g. fixed or variable width buffer).

Sub-catchments 1 and 2 displayed the strongest discrepancy in terms of the proportion of different riparian habitat types identified using the different methodologies with the New Phase 1 habitat map. For example, in sub-catchment 1, 'broadleaved woodland' only compromised 26% of the total variable width buffer area while it accounted for 51% when using the legal approach. Similarly, in the same sub-catchment, 'improved grassland' represented approximately 56% of the total variable buffer approach in contrast with only 18%

obtained with the legal buffer approach. In addition, sub-catchment 2 showed the percentage of ‘improved grassland’ was over 50% for the total variable width buffer, while for the legal buffer this decreased to 35% of the total riparian area. In contrast, sub-catchment 3 gave a similar distribution for the riparian plant communities for both methods of classification. Both datasets indicated that ‘mountain, heath and bog’ and ‘semi-natural grassland’ were the dominant land cover classes. However, the LCM2007 dataset estimated that ‘mountain, heath and bog’ constituted 90% of the total riparian area, whereas the New Phase 1 dataset predicted a coverage range of only 65-72% for the same habitat category. For ‘semi-natural grassland’ in sub-catchment 3, the LCM2007 predicted that it only covered 5% of the total riparian area compared with 13-20% for the New Phase 1 map. Sub-catchment 4 showed a similar distribution of habitat types across both land cover datasets and all buffer delineations. However, ‘freshwater’ and ‘broadleaved woodland’ exhibited the greatest discrepancies in percentage riparian area cover when selecting more restrictive buffer strips (e.g. fixed width 10 m buffer and legal fixed buffer). It is also worth noticing that the New Phase dataset included ‘freshwater’ and ‘other’ in its habitat categories while these are not present in LCM2007. Sub-catchment 5 displayed a discrepancy between both land cover datasets of 5-10% between the main habitat types.

4 | DISCUSSION

4.1 | Critical evaluation of the differing riparian delineation approaches

Previous studies have attempted to determine the most efficient way to identify riparian areas and the multiple ecosystem services they provide (Hawes & Smith, 2005; Holmes & Goebel, 2011; Fernández et al., 2012). In this work, we show that different delineation approaches greatly influence the total predicted riparian area within a sub-catchment, their spatial land patterning and the subsequent distribution of habitats present within these areas. In reality, however, riparian boundaries are rarely discrete and no single approach can be expected to adequately capture all the features of riparian areas, particularly as our mechanistic and quantitative understanding of some riparian functions is still lacking (e.g. hyporheic filtering of nutrients, groundwater flow and recharge rate, riparian biodiversity; Hanula et al., 2016; Hathaway et al., 2016; Doble & Crosbie, 2017; Swanson et al., 2017). Further, riparian zones are typically both spatially heterogeneous (vertically and horizontally) and temporally dynamic with strong interactions between the aquatic and terrestrial component (Broder et al., 2017). This frequently results in diffuse and continuously changing riparian limits (Lindenmayer and Hobbs, 2008), in contrast to our riparian boundaries which are both static in time and spatially discrete. Moving forward, it would be useful to agree on a universal definition for riparian areas and the identification for reference values for riparian functions, similar to those which exist for agriculture (Gregory et al., 1991; Fischer et al., 2001; Hawes & Smith, 2005; Naiman et al., 2010; Xiang et al., 2016). Until this is established, and as evidenced here, estimating the spatial extent of riparian areas will be subject to considerable uncertainty and user bias. Establishing a common riparian framework is not impossible. McVittie et al. (2015) proposed a model applied to riparian areas that integrated physical attributes (land cover, soil type, rainfall), terrestrial and aquatic process (e.g. erosion, river flow) and management intervention using Bayesian Belief Networks (BBN). Thus, the parameters introduced will ultimately aim to outline the fundamental ecological processes that deliver ecosystem services within riparian areas.

In achieving an effective riparian delineation, some theoretical and practical limitations in favour of, or against the fixed-width versus variable-width option were considered. The fixed-width riparian approach has been suggested by some authors to be inadequate for delineating riparian areas as it fails to take into account crucial factors such as geomorphology or stream order (Skally & Sagor, 2001; Holmes & Goebel, 2011). Consequently, some land areas might be incorrectly included or excluded in the buffer delineation. Additionally, this approach does not reflect the magnitude of the river and its associated floodplain (i.e. major and minor rivers). In this sense, some studies such as Peterson et al. (2011) have shown how stream order could be relatively easyily incorporated into riparian models by using the strength of a decay functions to weight the important of vegetation from close to the stream to further away. However, the results from this study arguably showed a close similarity in terms of surface area and patterns of land cover distribution between the fixed 50 m width approach and the variable-width riparian buffer, even though the latter was constructed more robustly by including digital elevation data, soil and hydrologic descriptors of riparian areas (Abood et al., 2012). Moreover, the digital spatial comparison of the above-mentioned buffers revealed a spatial agreement of ca. 70-83% between the two methods. Whether this percentage is acceptable or sufficient depends on the goals of the study undertaken in terms of ecosystem service provision and the potential value that a particular riparian area can achieve. For instance, this percentage disagreement could be pivotal for those areas designated as being at risk from agricultural pollution (i.e. Nitrate Vulnerable Zones, NVZ) which might require a higher level of protection and precision in their delineation. Moreover, from a management perspective, riparian areas often constitute zones excluded from productivity which greatly affect stakeholders (e.g. farmers) considering the profound impact on the costs associated with the buffer width chosen (Ahnström et al., 2009; Roberts et al., 2009). Additionally, it is worth noting that some riparian areas responsible for important ecosystem services within agricultural catchments such as nutrient cycling or water regulation, might require a more thorough assessment than those with recreational and aesthetic values as the main ecosystem service outcome.

Few riparian delineation studies have highlighted drawbacks associated with the variable-width buffer approach. These may include, however, the heavy dependency of these methodologies on accurate and precise digital information (e.g. DEM, soil data), the need for up-to-date datasets and some technical expertise to reality check the predictions (Phillips et al., 2000; Aunan et al., 2005). In our study, the determination of the 50-yr flood height as a crucial parameter for the model led to additional time-consuming tasks due to the lack of available hydrological data (e.g. flow rate, velocity or channel width) for our sub-catchments. As we were unable to get this hydrological parameter from existing methodologies (Mason, 2007; Abood et al., 2012), manual tracing of the cross-sections along the main rivers and a computation of the 50-yr flood discharge to generate the water surface elevation was required. This additional, component greatly increased the time required to successfully define the riparian boundary by comparison with the fixed-width approach. However, as better digital data (e.g. high-resolution soils and land cover datasets or real-time water quality and flow data) become available, variable-width approaches will become much more efficient and precise than the fixed-width approach.

4.2 | Influence of DEM on model outcome

The clear need for using a precise digital elevation dataset in the variable-width model was demonstrated here. Abood et al. (2012) observed an increase in the riparian land included in the delineation process when using a coarser spatial resolution of the DEM. A similar finding was also reported by Papaioannou et al. (2016) when flood risk mapping. The difficulty arises in detecting incremental changes in elevation, especially in steep areas where the elevation usually changes abruptly. Our study also supports these conclusions for the 5 and 10 m spatial resolution DEMs. However, in our case, the results from the 30 and 50 m spatial resolution DEMs encompassed between 2 and 5 times smaller total riparian surface (km^2) respectively than obtained at a 2 m spatial resolution. Analysis of the 2 m resolution DEM compared to the 30 m resolution DEM revealed a discordance in elevation of up to 290 m in some cases. As a result, the stream network obtained from much higher resolution data failed to match the coarser resolution DEM. Consequently the 50 year flood height estimation was probably underestimated, directly impacting upon the final riparian delineation. In addition, the maximum transect length of 250 m was clearly insufficient for such a coarse resolution. The same was also true for the 50 m resolution DEM.

4.3 | Limitations of riparian soil mapping

The National Soil Map at 1:250,000 scale was the only available dataset with full coverage in our study area (SSEW, 1983). During characterisation of the sub-catchments and on assessment of model performance, it became clear that its resolution was inadequate for small-scale applications, such as riparian delineation. The best-available soil maps for the UK are at 1:63,000 scale, however, these only have limited coverage and may still contain significant errors, particularly for soil types of limited spatial extent, as exemplified by riparian soils (Mayr et al., 2008). Of these national 1:63,000 maps, most were completed over 50 years ago and have never been updated. Over time, it can be expected that some soil features may also have changed due to changes in policy and land management regime (e.g. afforestation, fencing, drainage, riverbank stabilization). Further, climate change may also have altered their properties (e.g. changes in soil C content or hydrological regime; Keay et al., 2014). The impact of these factors on riparian soil classification remains unknown, but it adds extra uncertainty to the model outputs. Based on the cost of undertaking ground-based soil surveys, however, it is unlikely that the poor availability of soil data will improve in the near future. The recent availability of high-spatial-resolution satellite and high-spectral-resolution aircraft imagery has significantly improved the capacity for mapping riparian buffers, wetlands, and other ecosystems and potentially the soils contained within them (Makkeasorn et al., 2009; Forzieri et al., 2010). However, satellite sensors still do not have the combined spatial and spectral resolution to reliably identify buffer vegetation types and conditions, let alone soils (Klemas, 2014).

4.4 | Riparian habitat mapping

Comparison of the two national land cover datasets raised some interesting issues. Firstly, we noted that regardless of riparian delineation method, both datasets produced noticeable differences in the coverage of different habitat types within riparian areas. For instance, there is evidence that in the sub-catchment 2, the criteria used for the classification of the habitat type is different for both datasets (e.g. Mountain, heath and bog versus Semi-natural grassland). This variability is most likely due to the much finer scale resolution of the Phase 1 map in which habitat surveying is both ground- and digital-based (nominal resolution 5 m), compared to LCM2007 that is based largely on remote sensing and digital processing. This fact reveals that comparison of outputs from models run using different underpinning datasets may be problematic and could have severe implications. It should also be noted that small areas of vegetation (<0.01 ha) will also be missed by most land cover maps. In this sense, ecosystem services may be incorrectly assigned due to strong correlation between land cover type and ecosystem service provision (Burkhard et al., 2009; Peterson et al., 2011; Maes et al., 2011). For example, Sgouridis and Ullah (2014) established a link between land cover and land use management with denitrification potential. The importance of accurate habitat identification is also endorsed by studies like Tscharntke et al. (2005) which showed that local habitats might be essential to improve the delivery of ecosystem services, enhancing local diversity and providing a natural corridor of special importance in simple landscapes dominated by arable fields. On the other hand, Fisher et al. (2009) stressed that ecosystem services were not homogeneous across landscapes. Therefore, if riparian models rely on accurate datasets, able to capture the landscape heterogenity, we could better predict the way that services can be managed, protected and monitored across spatial and temporal scales. From this point of view, De Groot et al. (2010) also added that furthering our understanding of the threats and underlying mechanisms at the landscape scale will help better target our resources where the enhancement of the service is needed most.

Differences in the precision and accuracy of digital data could lead to a misinterpretation of the relative position and structure of a particular habitat within riparian zones. This may be particularly problematic for very narrow riparian areas whose habitat type will not be captured (Scholefield et al., 2016). Previous studies have reported that minimal changes in land use might affect ecosystem service provision (Bennett et al., 2009; Raudsepp-Hearne et al., 2010). Brenner et al. (2010) identified that small boundary habitat adjustment could heavily influence the estimation of ecosystem services. Therefore, the over- or under-estimation of the habitats included within riparian areas might influence the ecological and economic value and could lead to an improper use as well as its need for protection.

It is also worth mentioning that although it is important to include riparian physical features into models (i.e. 50-year flood height optimal hydrologic descriptor of a riparian ecotone) that help us to predict their location, a thorough assessment of the resource to be addressed and the particular ecosystem provision being targeting should also be incorporated. The majority of the models follow the trend described in Verry et al. (2004) where it is suggested that the functional riparian delineation (named here as the variable-width approach) is a probabilistic approach based on a most likely predicted extent of riparian areas which are connected with physical patterns (e.g. stream valley geomorphology to predict flood-prone areas). However, apart from physical patterns, we strongly believe that there is a need to link riparian buffers with the ecosystem services they provide and ensure that the width selected is adequate to undertake the function. Results from different studies support this statement. For example, Peterjohn & Correll (1984) established that sediment removal rates by riparian buffers in agricultural catchments only increased by 4% despite more than doubling the buffer width. This suggests that approaches such as a fixed-width buffer (10 m) or the legal approach (2 m), might be sufficient to accomplish certain ecological functions. On the contrary, other studies have showed that a 10% increase in phosphorus removal could be accomplished by extending the buffer width by a factor of 2.5 (Wenger, 1999). Therefore, the implementation of a more restrictive buffer might not preserve the habitat requirements. Consequently, using functional models which detect physical attributes in riparian areas in addition to the incorporation of the spatial supply of ecosystem services, that is its functionality, would greatly strengthen not only riparian delineation but also its understanding.

5 | CONCLUSIONS

The results of this study revealed substantial differences in terms of spatial distribution, total riparian area delineated and land cover patterns depending on the delineation method employed and the spatial data available. Although simple, the single-width buffer approach lacked both consistency and any underpinning scientific rationale for mapping and classifying riparian areas. We conclude that this approach is likely to lead to gross inaccuracies and is therefore should not generally be used. The exception to this is where the buffer strip is made sufficiently wide to allow capture of some site-specific ecosystem services, at which point it could prove valuable for assessment and planning purposes without requiring much investment in money or time. In contrast, the variable-width buffer approach, despite being robust enough to recognise the multiple interactions that take place within riparian areas, relies heavily on accurate and up-to-date digital datasets and is more difficult to implement. Nevertheless, the possibility of incorporating a specific dataset into the model to predict riparian zones allows the opportunity to tailor a riparian area for every catchment according to its specific characteristics. The selection of a particular method to delineate riparian areas and the accuracy of the underpinning datasets heavily influences the predicted land cover distribution within the riparian area. This will in turn determine future management activities to target riparian ecosystem services. Our results have led to the development of new concepts for riparian delineation based on ecosystem service-specific scenarios. Outcomes from our study suggest that riparian delineation within UK habitats should be specific to the particular ecosystem service(s) of interest (e.g. uptake of nutrients, shading, etc.).

ACKNOWLEDGMENTS

We thank Prof Andrew Wade and members of the 'Turf2Surf' project funded by the UK Natural Environment Research Council Macronutrients Cycles Programme Grant No NE/J01533/1 for provision of data. We would also like to thank Dr David Cooper and Dr Sopan Patil for help and guidance provided during the study.

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TABLE 1. Main features of the sub-catchments selected in this study. More information is provided in the Online Supplementary Information.

	Sub-catchment 1	**Sub-catchment 2**	**Sub-catchment 3**	**Sub-catchment 4**	**Sub-catchment 5**
Area (km^2)	20.6	1.46	12.0	7.45	14.8
Stream network length (km)	60.0	6.05	34.5	32.1	60.8
Main channel length (km)	9.90	2.29	8.17	5.58	5.86
Average slope (%)	25.8	14.2	10.7	35.2	29.7
Dominant land use	Intensive livestock grazing	Intensive livestock grazing	Light livestock grazing	Light grazing and forestry	Light grazing
Dominant habitat type	Improved grassland	Improved grassland	Blanket bog	Coniferous woodland	Acid grassland

TABLE 2. Data inputs and sources used in the characterisation of the sub-catchments and delineation of the riparian areas.

Dataset	**Scale or resolution**	**Data type**	**Source**	**Description**
Digital Soil Data	1:250,000 1:63,000	Shapefile	National Soil Resources Institute (NSRI) LandIS soil classification http://www.landis.org.uk/index.cfm	Digital Soilscape based on the National Map Soil; 1:63,000 soil maps only available for sub-catchment 1.
Land Cover Map 2007 (LCM2007)	25 m	Raster	Centre for Ecology & Hydrology (LCM2007) http://www.ceh.ac.uk/services/land-cover-map-2007.html	LCM2007 includes 23 categories derived from satellite images and digital cartography.
New Phase 1 Land Cover	1:25,000	Shapefile	Natural Resources Wales (Lucas et al., 2011)	Updated Phase 1 Survey comprising 105 specific habitat types grouped into 10 broad habitat types.
Network-wide FEH flood peak estimates (Q (T) grids)	50 m	Raster	Centre for Ecology & Hydrology http://www.ceh.ac.uk/services/peak-river-flows-qt-grids (Robson and Reed, 1999; Morris, 2003)	Flood peak river flows estimated for different return periods at 50 m intervals along the UK river network. The flood peak estimates have been produced using a fully automated version of the Flood Estimation Handbook statistical procedures.
Detailed River Network (DRN)		Shapefile	UK Environment Agency (2008)	DRN derived from Ordnance Survey Mastermap features.
Inland lakes	1:10,000	Shapefile	Ordnance Survey (OS) Master Map https://www.ordnancesurvey.co.uk/business-and-government/products/mastermap-products.html	Lakes and open water bodies extracted from OS Master Map.
Catchment and sub-catchments		Shapefile	Centre for Ecology & Hydrology, D. Cooper	Catchment and sub-catchment boundaries.
Flood Zone 3	1:10,000	Shapefile	UK Environment Agency (2004) http://www.environment-agency.gov.uk/homeandleisure/37837.aspx	Shapefile with the Environment Agency best-estimate of the areas of land with a 1% or greater chance of flooding each year from rivers.
Annual rainfall (SAAR 61-90), mm	5 km	Raster	Natural Environment Research Council (NERC, 2012)	Annual rainfall 5 km x 5 km gridded datasets covering the UK based on Met Office Standard Average Annual Rainfall 1961-1990.
Digital Elevation Model (DEM)	2 m	Raster	Centre for Environmental Data Archival (Landmap Earth Observation collection); http://www.ceda.ac.uk/	DEM photogrammetrically derived from aerial photography by GetMapping and acquired by the Landmap project.
Digital Elevation Model	5, 10, 30 and 50 m	Raster	UK Environment Agency	Lidar composite DEM

1

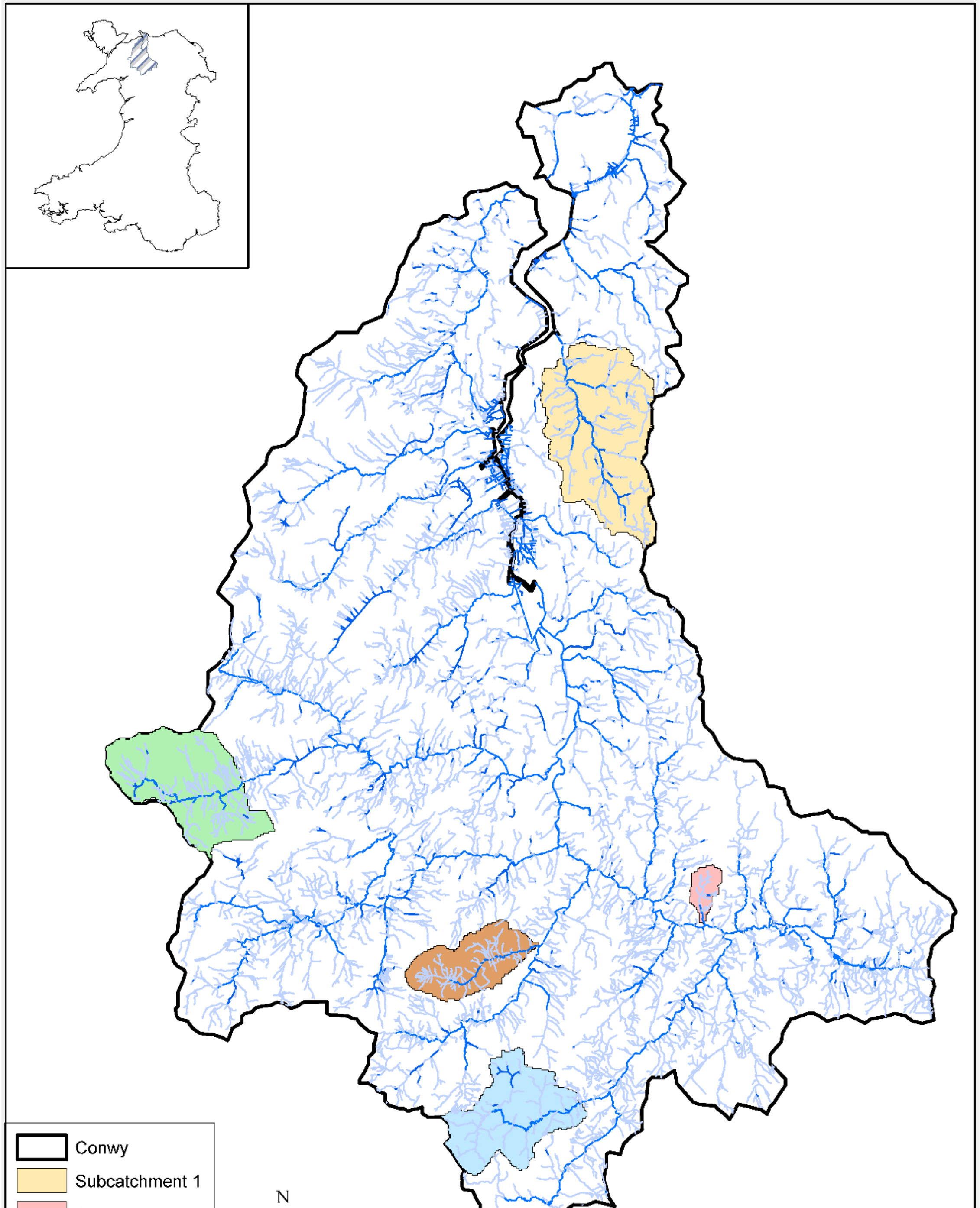

Conwy
Subcatchment 1
N

Fig. 1. Representation of the Conwy catchment and the five sub-catchments used in this study. Inset shows the location of the main catchment within Wales.

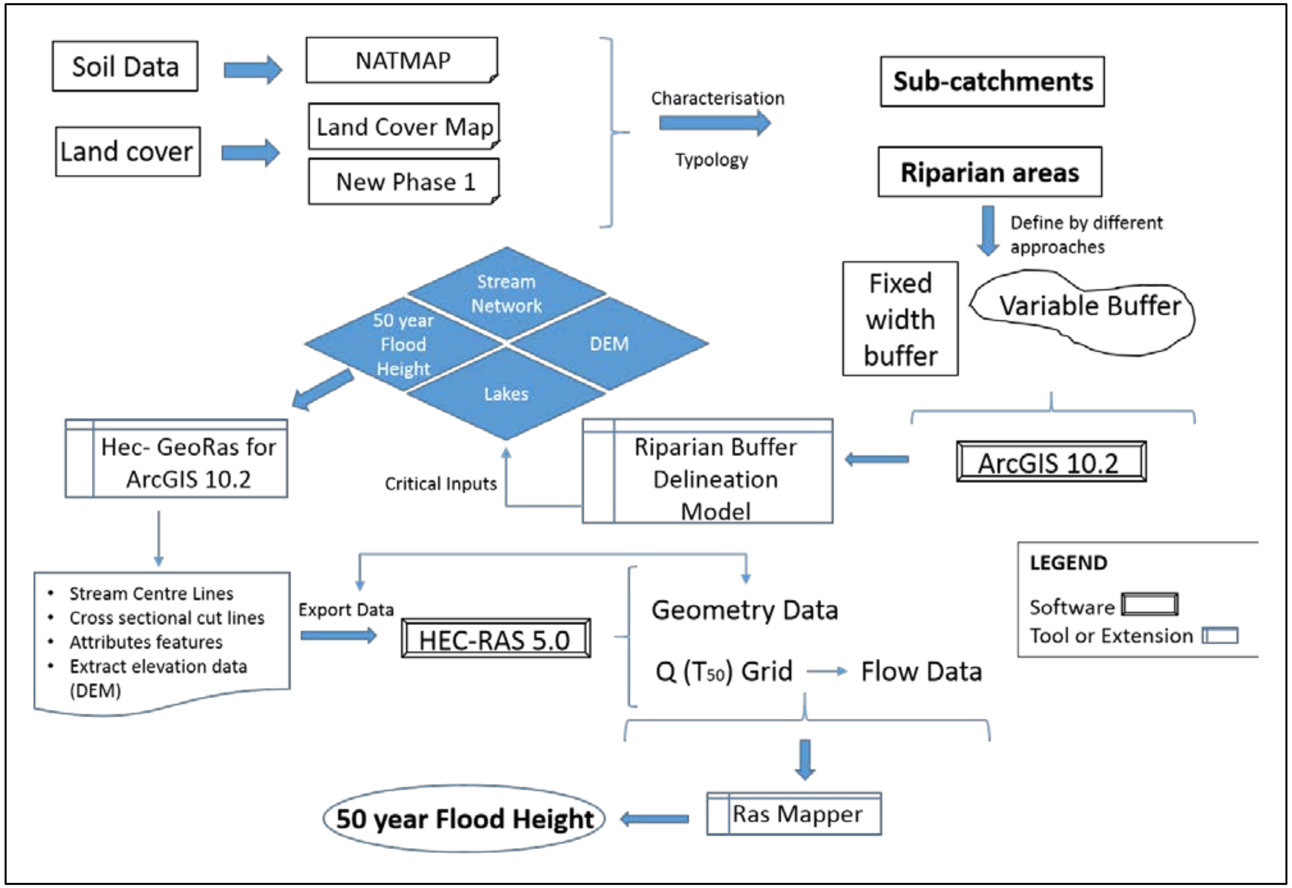


Fig. 2. Flowchart describing the methodology used to delineate riparian areas within this study.

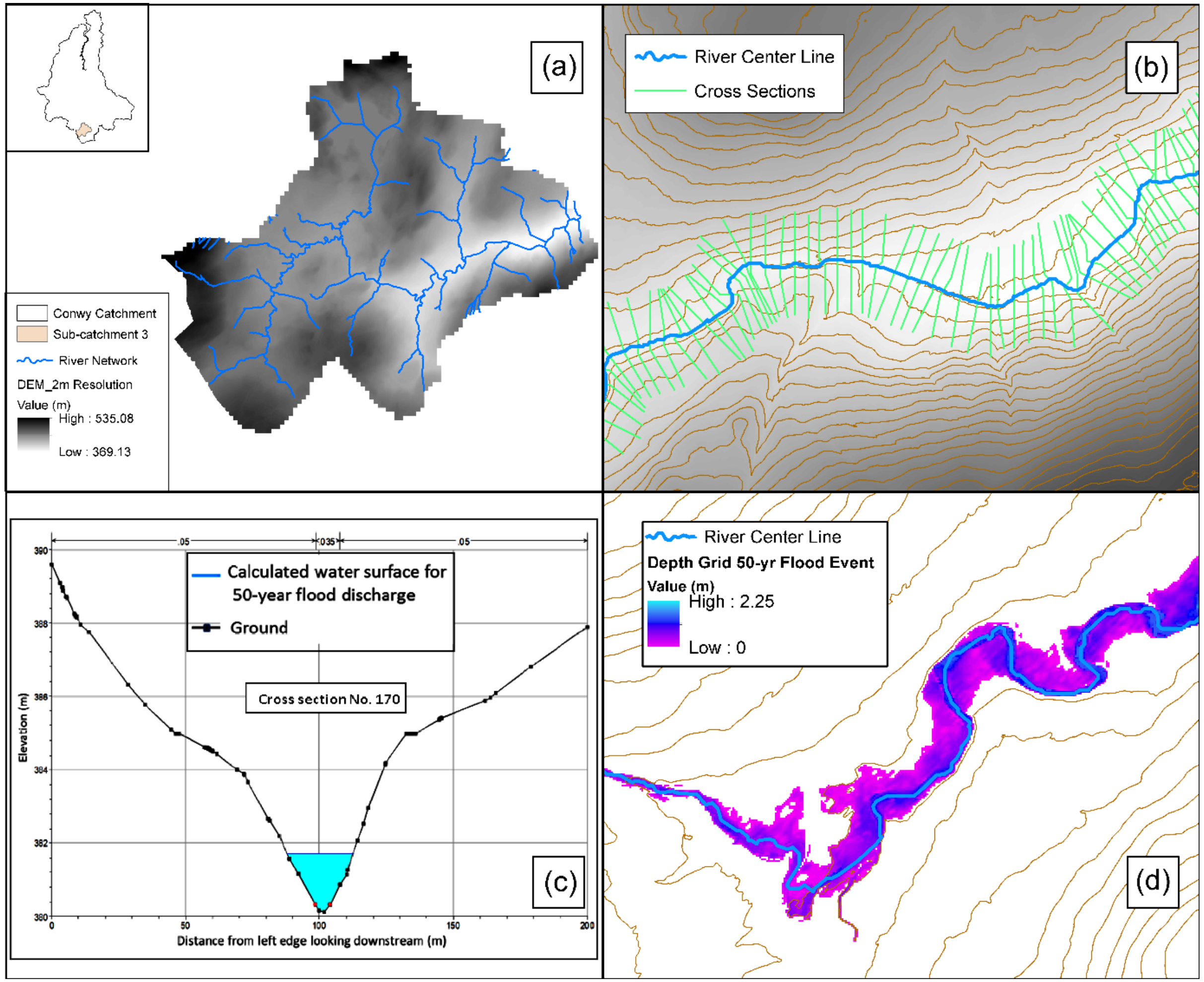


Fig. 3. Illustration of the river network over the digital elevation model (a) and cross sections along the river centre lines (b) at the same location. (c) An example of a HEC-RAS cross section, looking downstream, and (d) the RAS Mapper depth grid for the 50-year floodplain.

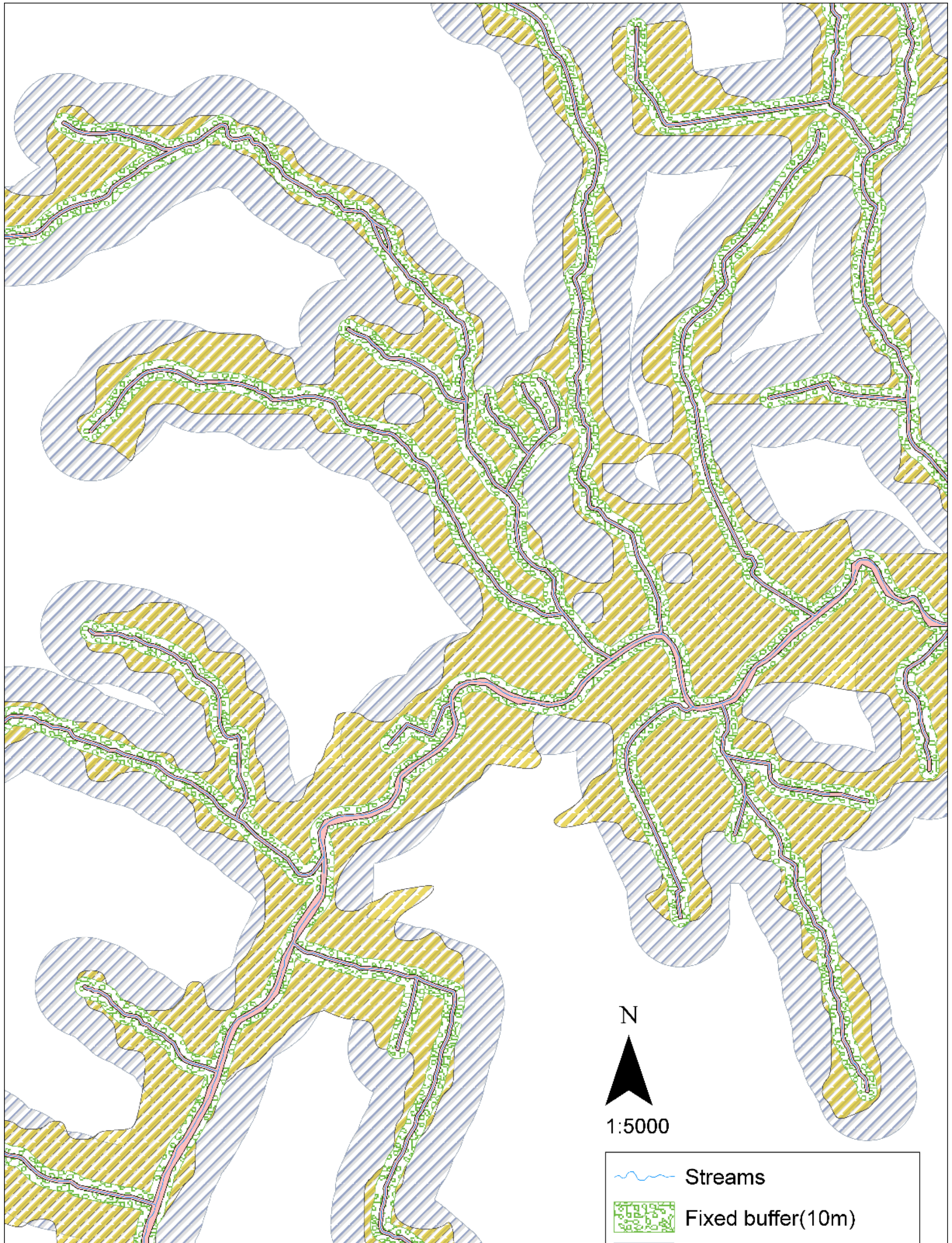

N
1:5000
Streams
Fixed buffer(10m)

Fig. 4. GIS comparison of all the different approaches for delineating riparian buffers within sub-catchment 5.

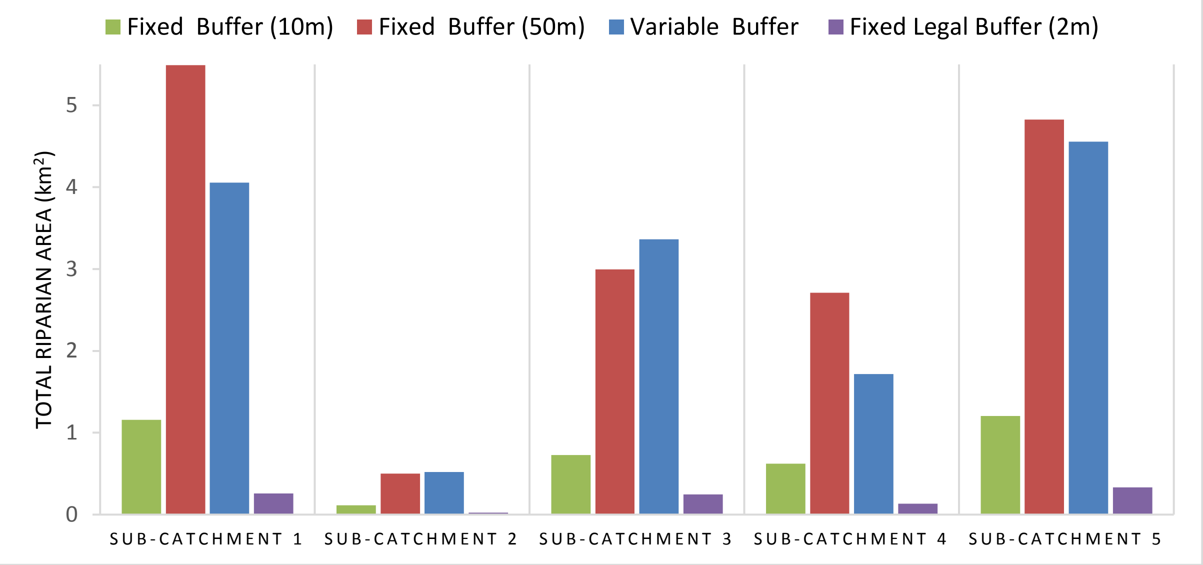
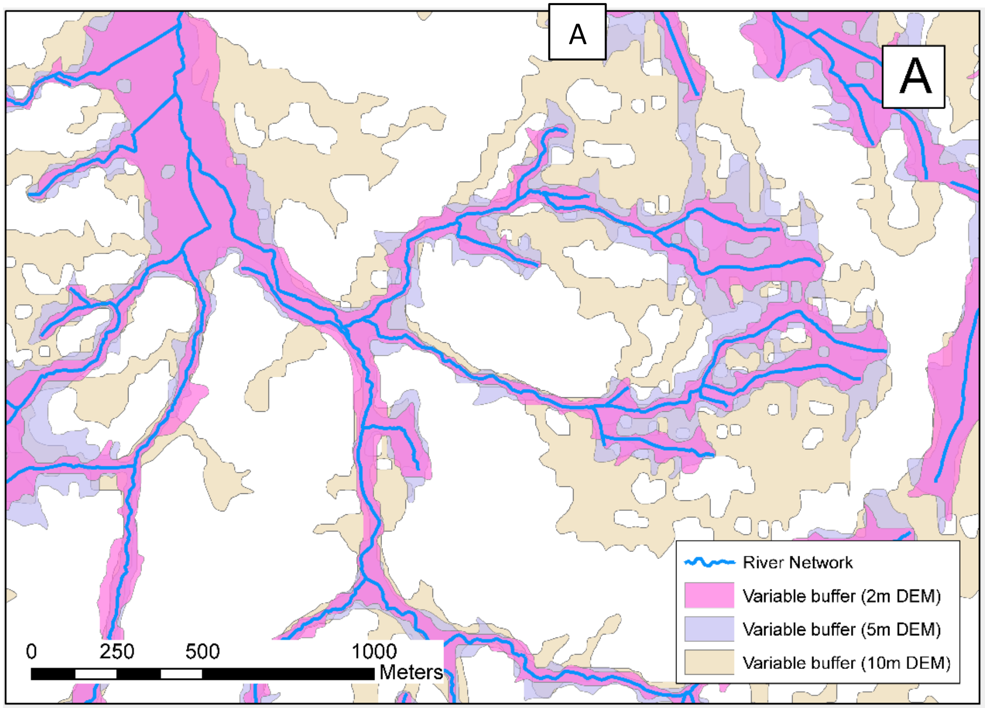


Fig. 5. Comparison of the four different GIS-based methods on the total amount of riparian area delineated within each of the five sub-catchments within the Conwy catchment.


A
A
0
250
500
1000
Meters
River Network
Variable buffer (2m DEM)
Variable buffer (5m DEM)
Variable buffer (10m DEM)

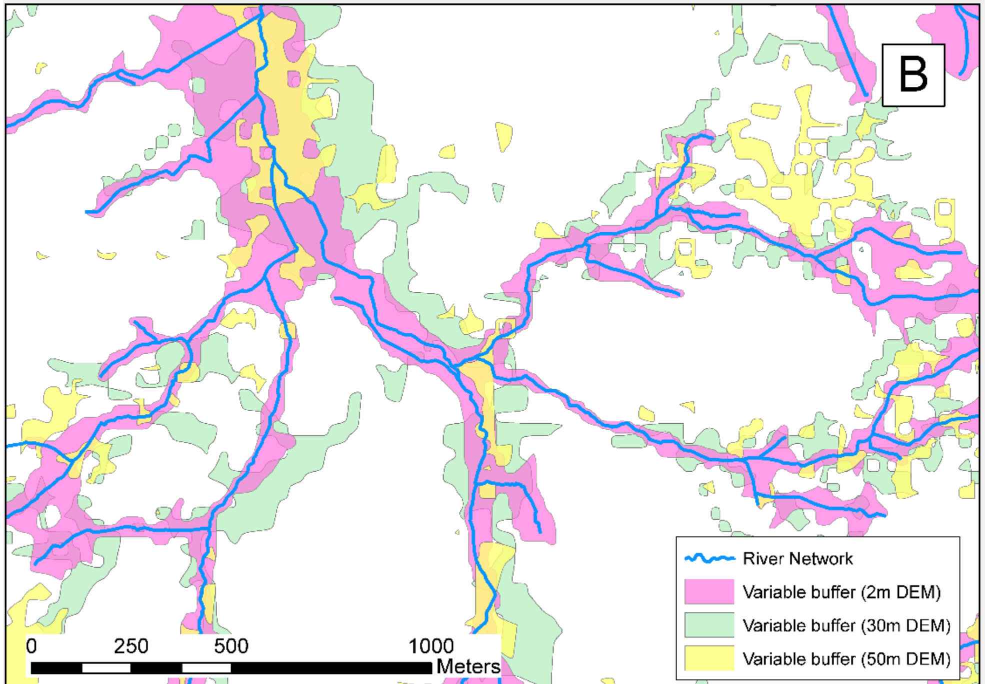

B
0
250
500
1000
Meters
River Network
Variable buffer (2m DEM)
Variable buffer (30m DEM)
Variable buffer (50m DEM)

Fig 6. Example area comparing the riparian variable width model result using 2 m resolution DEM with 5 and 10 m resolution DEM results (Panel A) and 30 and 50 m resolution DEM results (Panel B) in sub-catchment 1.

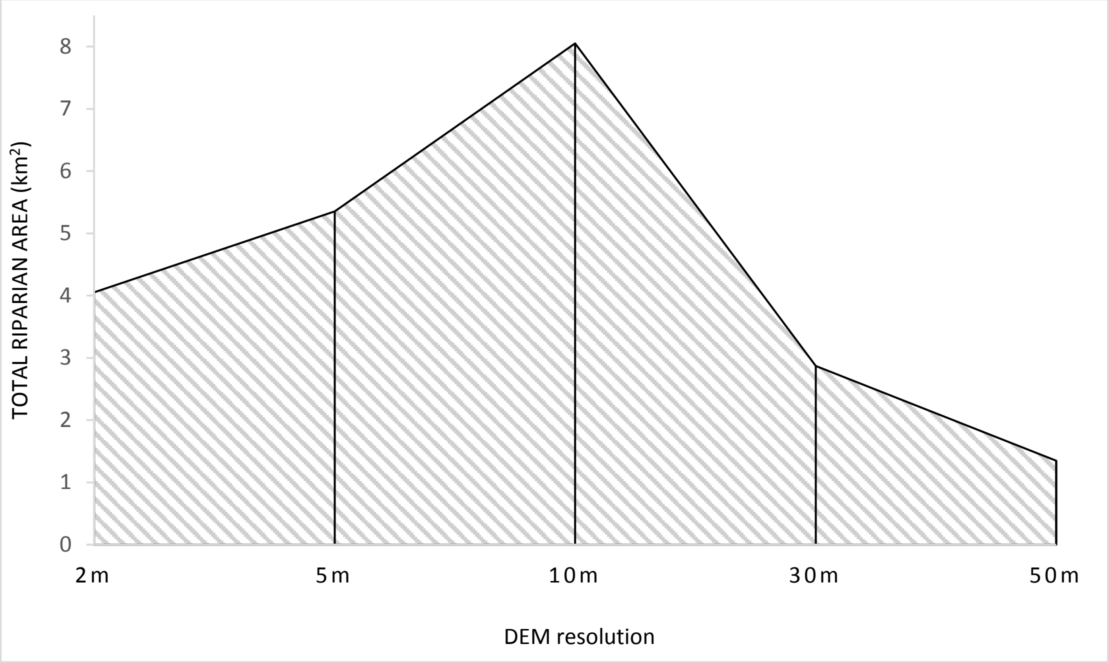


Fig 7. Comparison of the total amount of riparian area delineated when running the model with DEM resolutions ranging from 2 m to 50 m for sub-catchment 1.

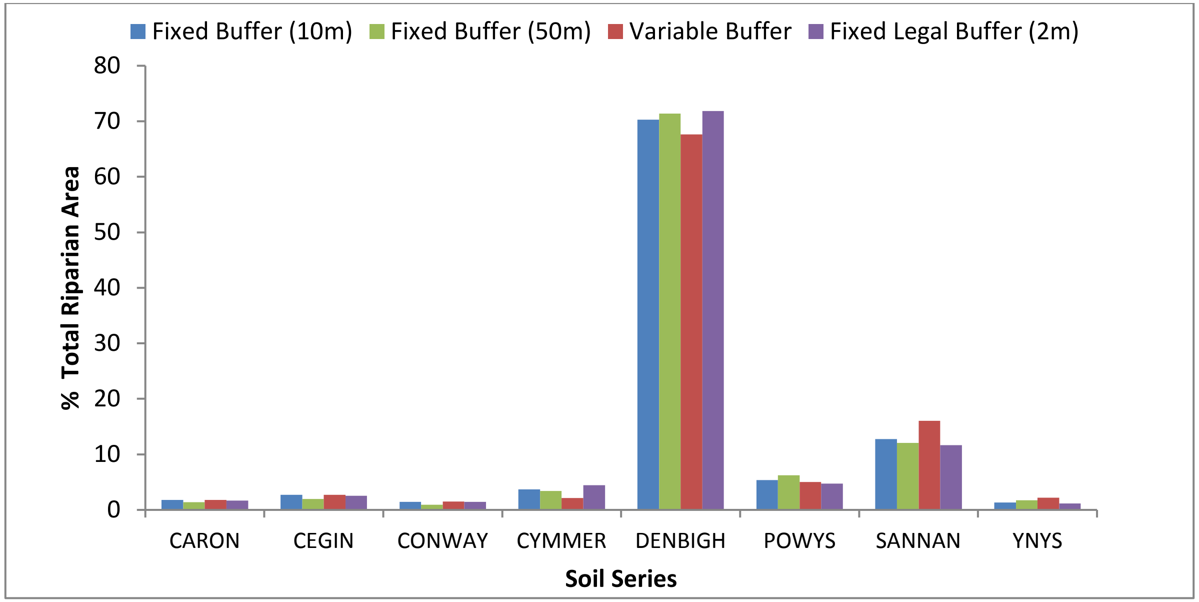
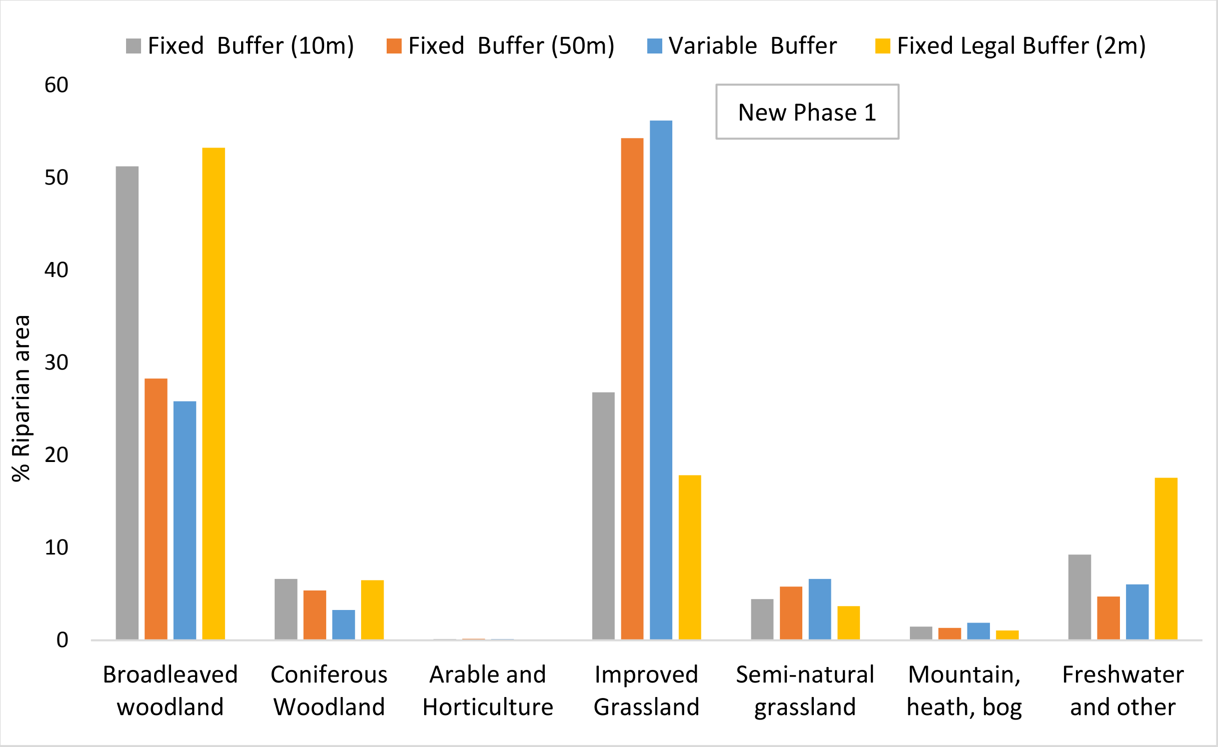


Fig 8. Distribution of different soil types (series) estimated by four different riparian delineation methods for sub-catchment 1. A description of the different soil series and their equivalent in the FAO World Reference Base (WRB) is shown in Table S2.


Fixed Buffer (10m)
Fixed Buffer (50m)
Variable Buffer
Fixed Legal Buffer (2m)
New Phase 1
% Riparian area
60
50
40
30
20
10
0
Broadleaved woodland
Coniferous Woodland
Arable and Horticulture
Improved Grassland
Semi-natural grassland
Mountain, heath, bog
Freshwater and other

99

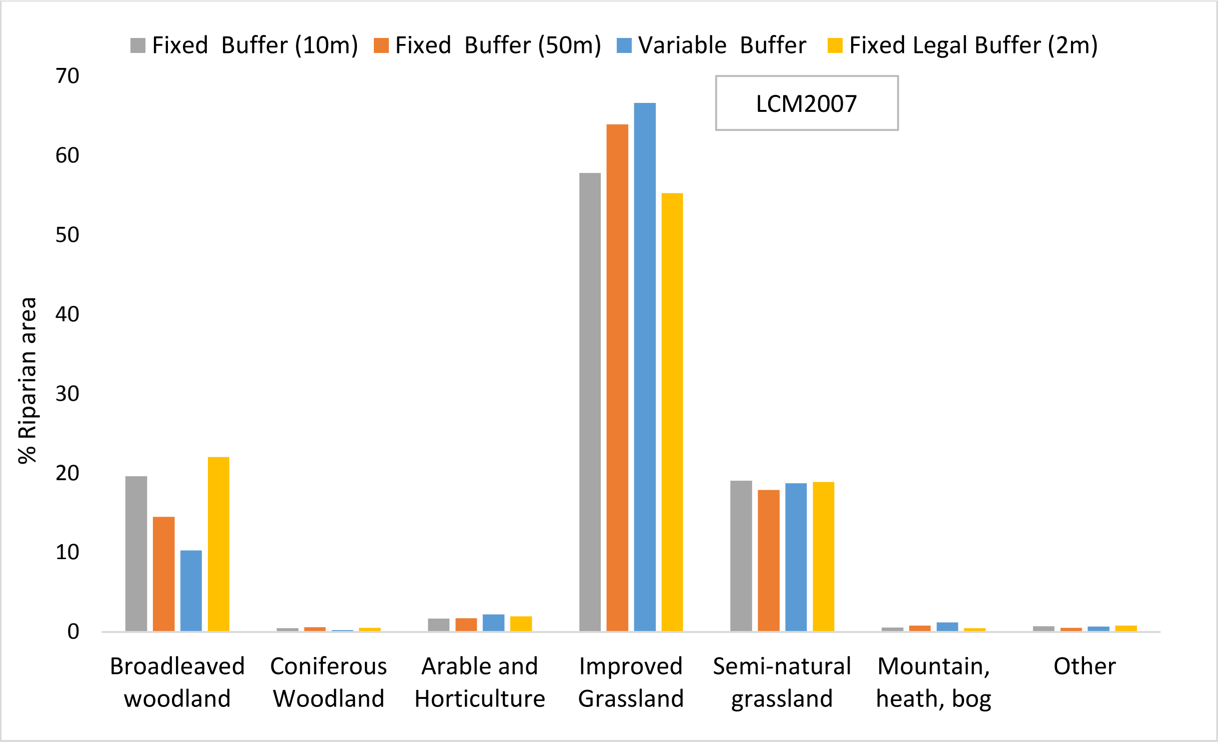
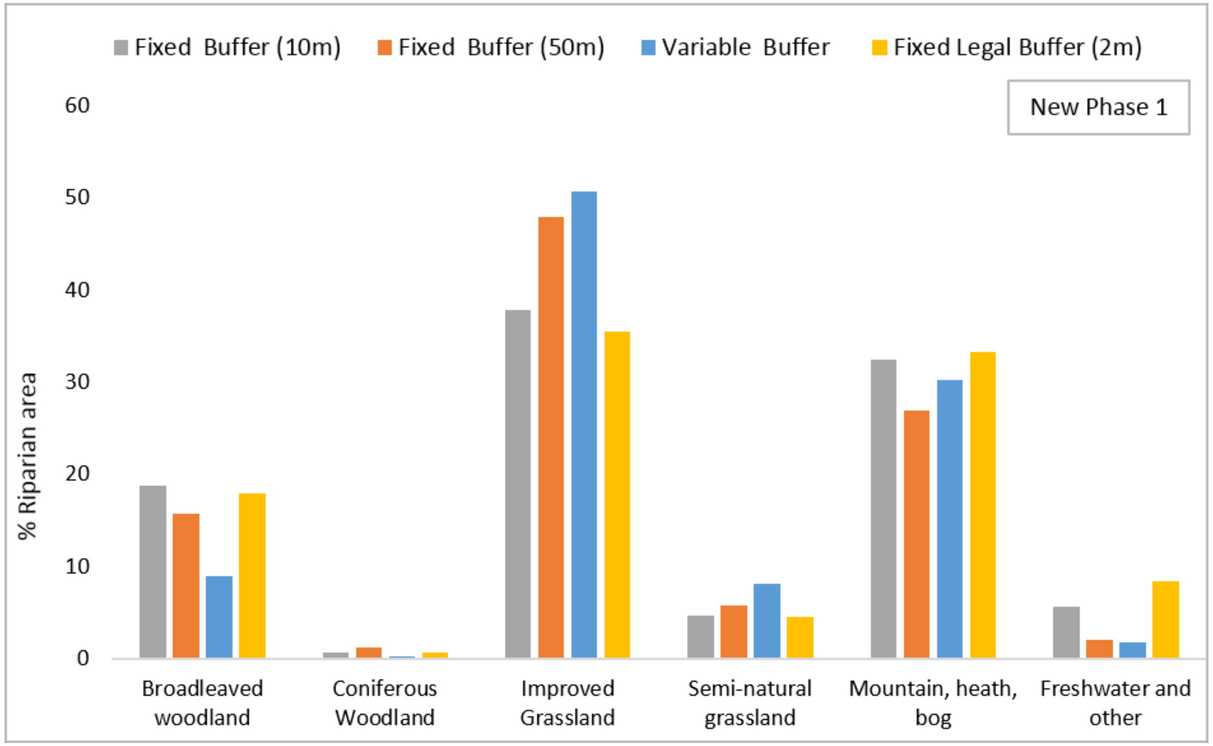


Fig. 9. Comparison of the area of riparian habitat types determined using either New Phase 1 (Panel A) or LCM2007 (Panel B) national vegetation mapping datasets using four different riparian delineation methods for sub-catchment 1.


Fixed Buffer (10m)
Fixed Buffer (50m)
Variable Buffer
Fixed Legal Buffer (2m)
New Phase 1
% Riparian area
60
50
40
30
20
10
0
Broadleaved woodland
Coniferous Woodland
Improved Grassland
Semi-natural grassland
Mountain, heath, bog
Freshwater and other

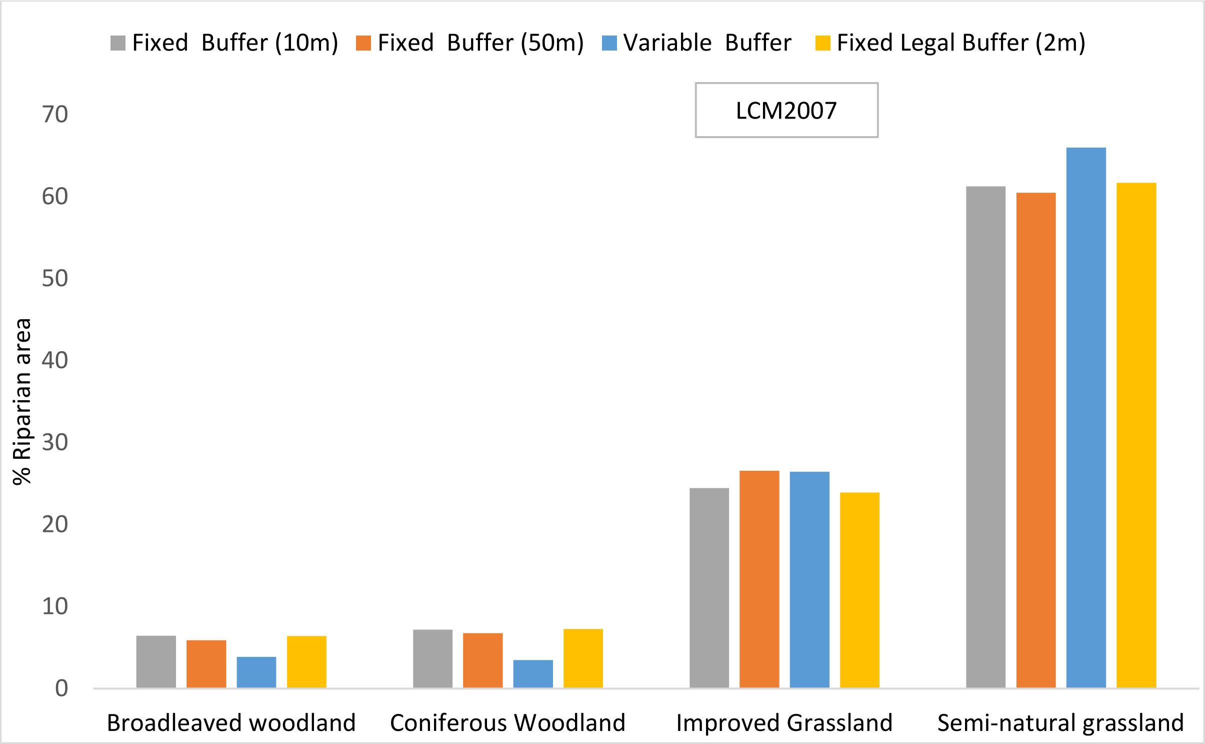
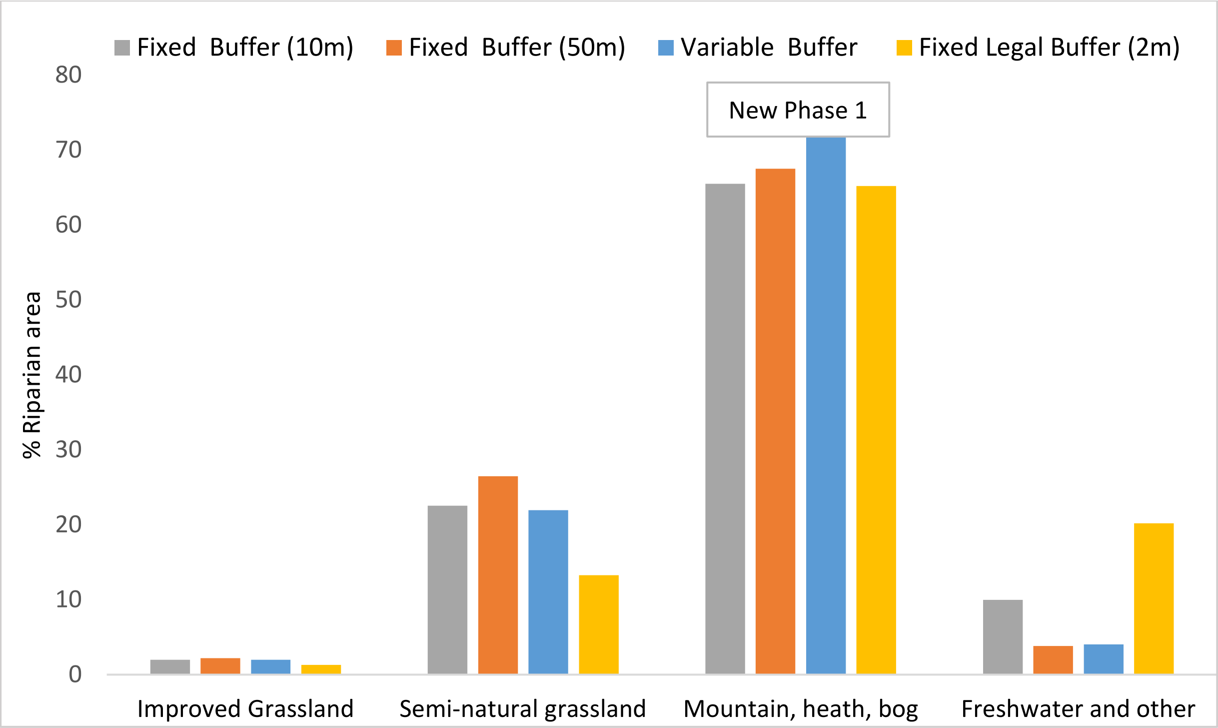


Fig. 10. Comparison of the area of riparian habitat types determined using either New Phase 1 (Panel A) or LCM2007 (Panel B) national vegetation mapping datasets using four different riparian delineation methods for sub-catchment 2.

117


Fixed Buffer (10m)
Fixed Buffer (50m)
Variable Buffer
Fixed Legal Buffer (2m)
New Phase 1
% Riparian area
80
70
60
50
40
30
20
10
0
Improved Grassland
Semi-natural grassland
Mountain, heath, bog
Freshwater and other

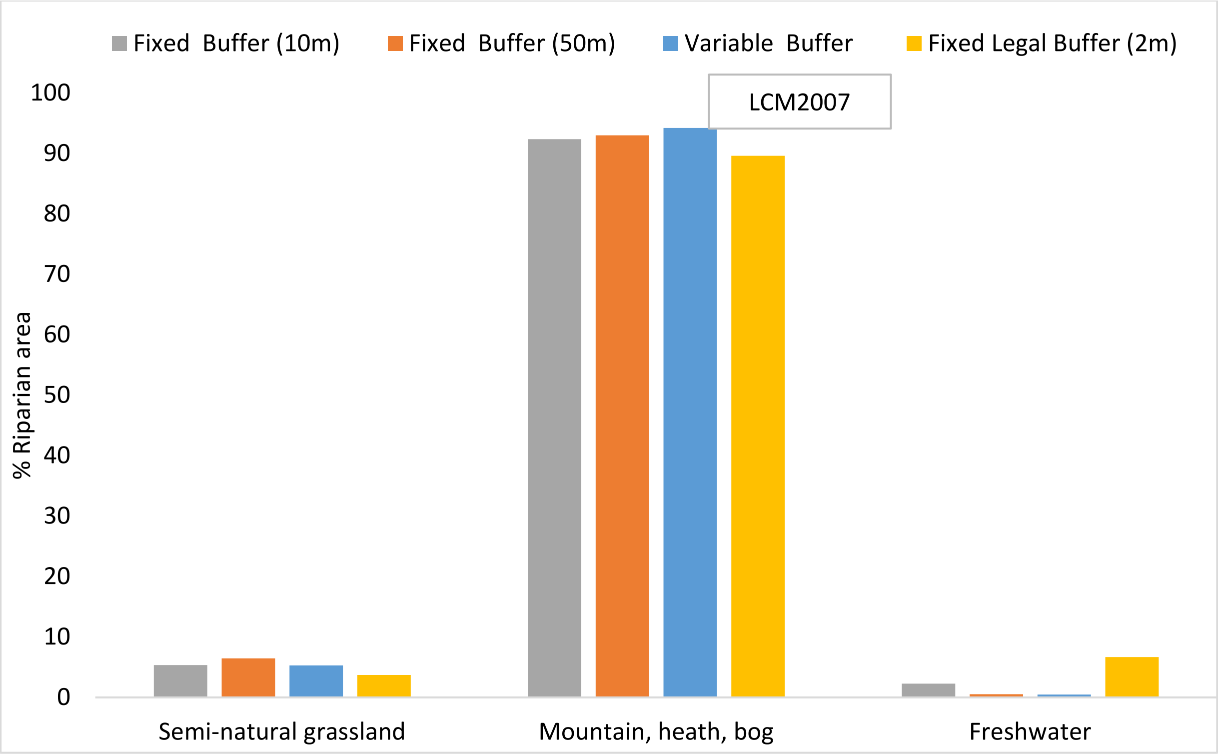
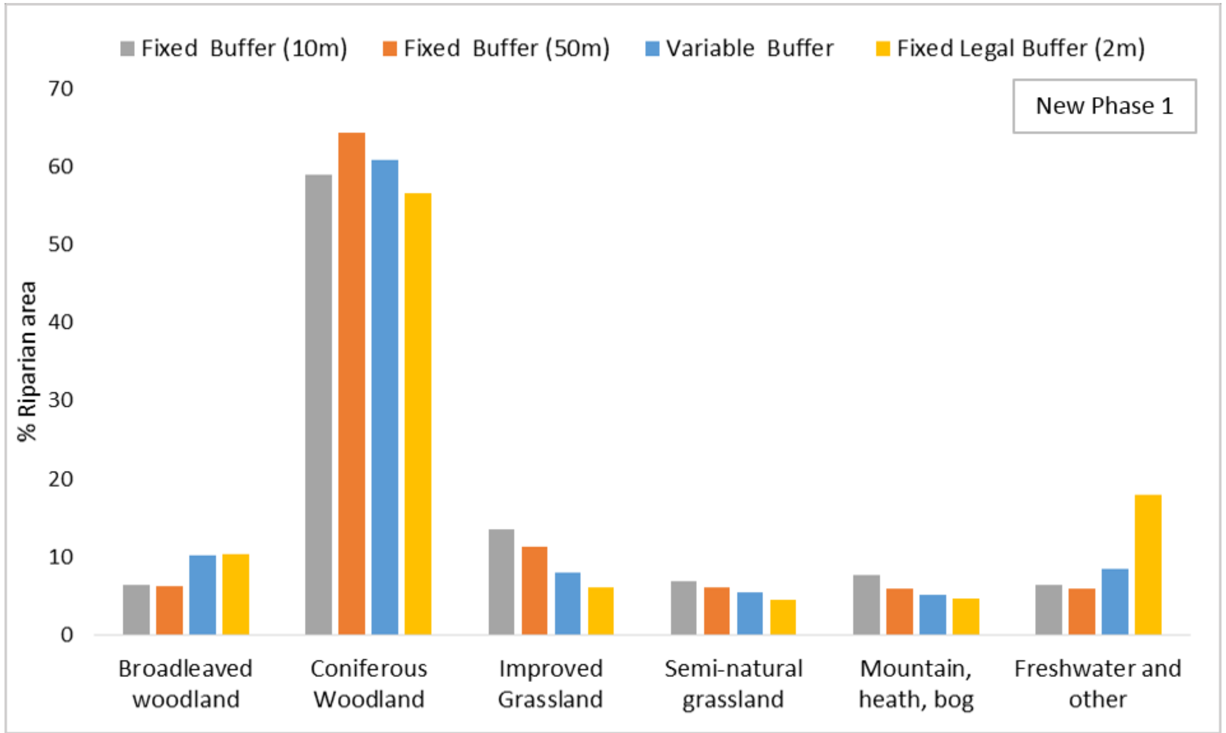


Fig. 11. Comparison of the area of riparian habitat types determined using either New Phase 1 (Panel A) or LCM2007 (Panel B) national vegetation mapping datasets using four different riparian delineation methods for sub-catchment 3.


Fixed Buffer (10m)
Fixed Buffer (50m)
Variable Buffer
Fixed Legal Buffer (2m)
New Phase 1
% Riparian area
70
60
50
40
30
20
10
0
Broadleaved woodland
Coniferous Woodland
Improved Grassland
Semi-natural grassland
Mountain, heath, bog
Freshwater and other

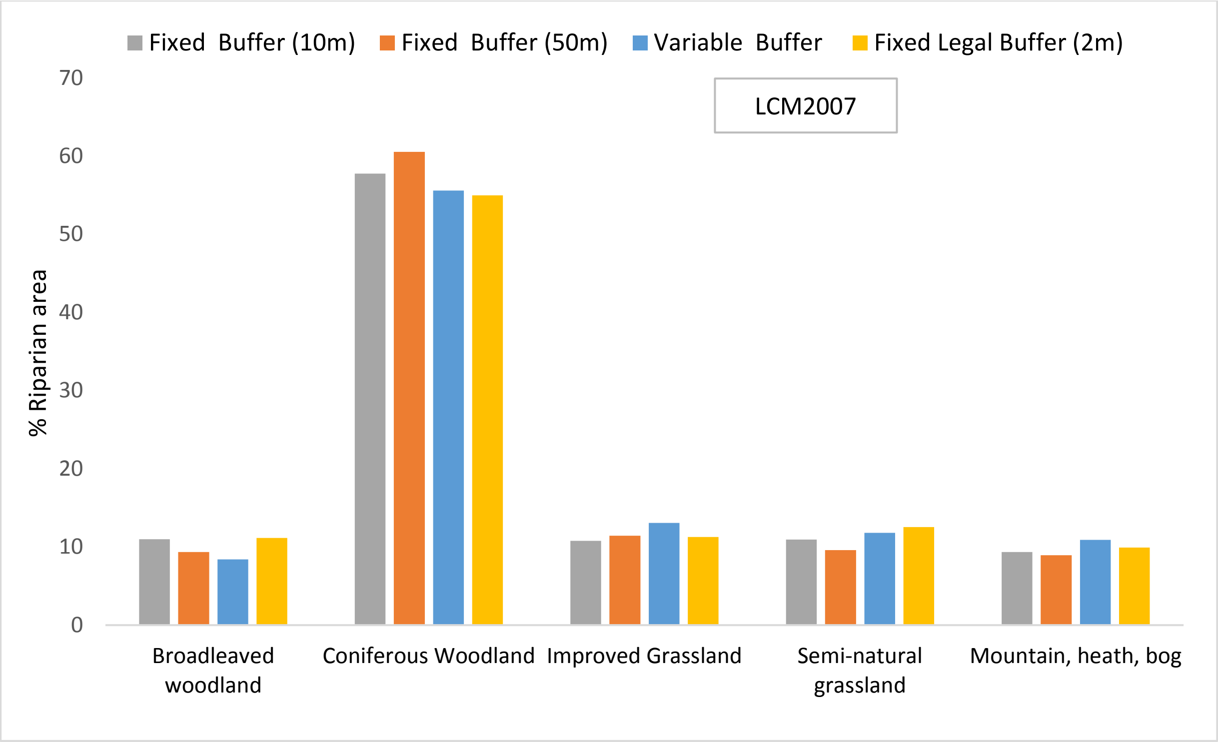
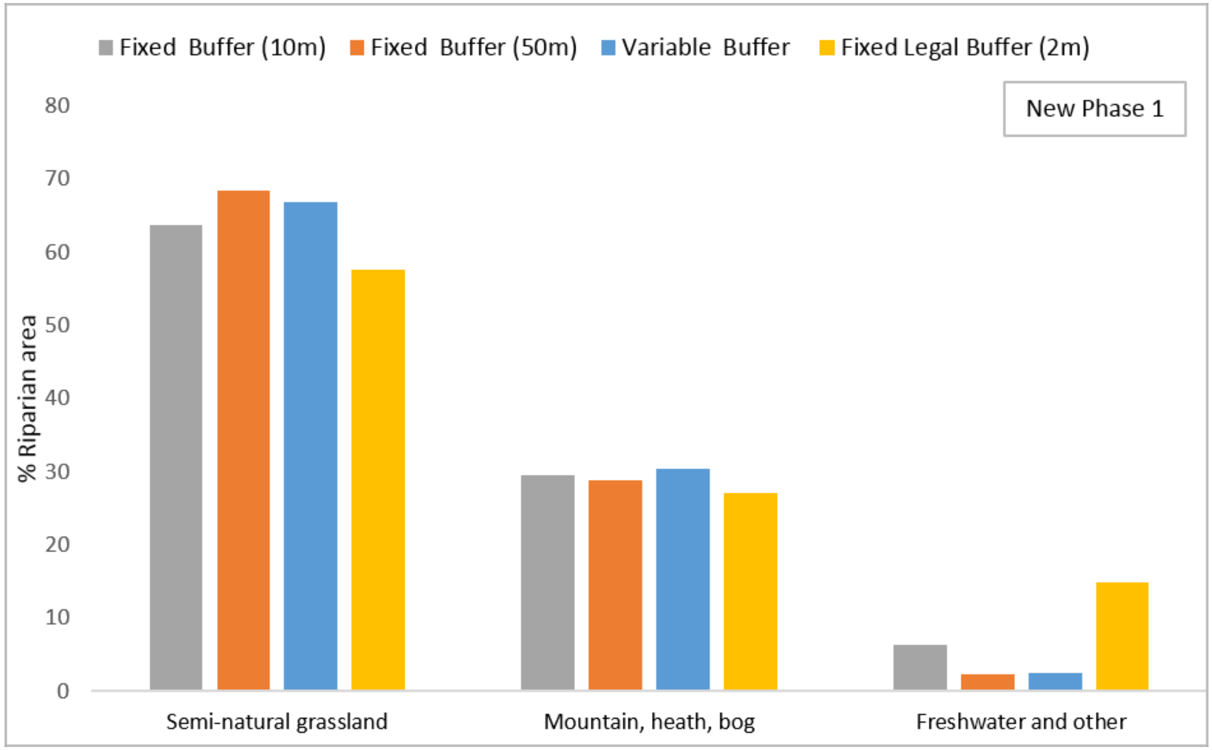


Fig. 12. Comparison of the area of riparian habitat types determined using either New Phase 1 (Panel A) or LCM2007 (Panel B) national vegetation mapping datasets using four different riparian delineation methods for sub-catchment 4.

New Phase 1


Fixed Buffer (10m)
Fixed Buffer (50m)
Variable Buffer
Fixed Legal Buffer (2m)
New Phase 1
% Riparian area
80
70
60
50
40
30
20
10
0
Semi-natural grassland
Mountain, heath, bog
Freshwater and other

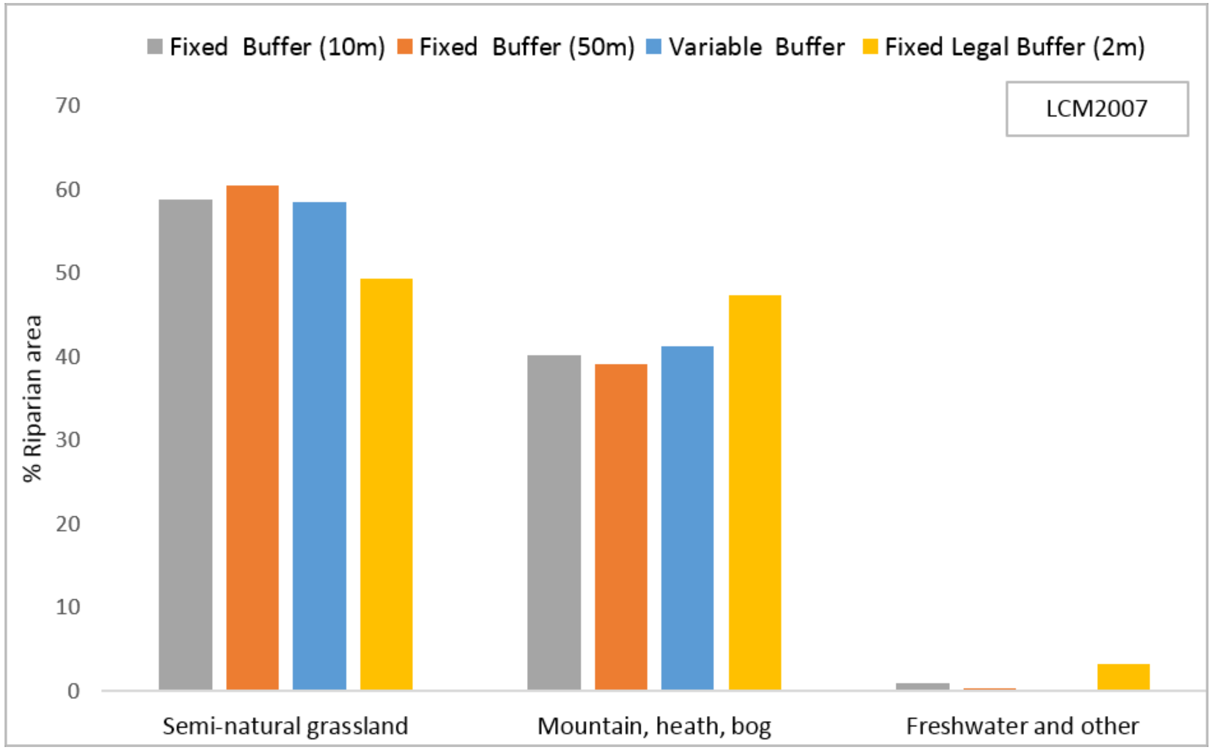


Fig. 13. Comparison of the area of riparian habitat types determined using either New Phase 1 (Panel A) or LCM2007 (Panel B) national vegetation mapping datasets using four different riparian delineation methods for sub-catchment 5.