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TerEx Toolbox for semi-automated selection of fluvial terrace and floodplain features from lidar

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ABSTRACT: Terraces and floodplains are important indicators of near-channel sediment dynamics, serving as potential sediment sources and sinks. Increasing availability of high resolution topography data over large areas calls for development of semi-automated techniques for identification and measurement of these features. In this study we introduce a novel tool that accommodates user-defined parameters including, a local-relief threshold selected by a variable-size moving window, minimum area threshold, and maximum distance from the channel to identify and map discrete terrace and floodplain surfaces. Each of the parameters can easily be calibrated for a given watershed or reach. Subsequently, the tool automatically measures planform area, absolute elevation, and height relative to the local river channel for each terrace polygon. We validate the tool in two locations where terrace maps were previously developed via manual digitization from lidar and extensive field mapping campaigns. The tool is also tested on six different types of rivers to provide examples of starting selection parameters, and to test effectiveness of the tool across a wide range of landscapes. Generally, the tool provides a high quality draft map of terrace and floodplain surfaces across the wide range of environmental conditions for which it has been tested. We find that the tool functions best in catchments where the terraces are spatially extensive, with distinct differences between the terrace and floodplain. The most challenging environments for semi-automated terrace and floodplain mapping include steep catchments with dense riparian vegetation, and very small terraces (~10 m^2 in areal extent). We then apply the tool to map terraces and floodplains in the Root River watershed, southeastern Minnesota and generate exceedance plots for terrace heights. These plots provide a first pass analysis to indicate the tributaries and reaches of the river where terraces constitute a significant source of sediment. Copyright © 2013 John Wiley & Sons, Ltd.

KEYWORDS: sediment sources; terrace selection; Digital Elevation Models; floodplains; Root River

Introduction

Floodplains and fluvial terraces are useful indicators of past and present geomorphic processes. Through analysis of terrace sequences and stratigraphy these landforms can be used to quantify source–sink dynamics, channel migration and planform changes, and channel response to changes in water and sediment flux or base level (Mackin, 1948; Bull, 1990; Pazzaglia, 2013). Understanding the regional pattern of terrace development and preservation can aid in development of sediment budgets (Smith *et al.*, 2011; Pazzaglia, 2013; Gran *et al.*, 2011) and provide insight into historic and contemporary sediment routing through channel–floodplain networks. Thus mapping of terraces and floodplains can be useful to inform land and water management decisions (Benda and Sias, 2003; Belmont *et al.*, 2011a, 2011b).

Terraces are relatively flat, abandoned floodplains that can form from autogenic processes in incising rivers (Finnegan and Dietrich, 2011), or in response to unique environmental conditions that influence sediment and water fluxes (Anderson and Anderson, 2010; Pazzaglia, 2013). Many external variables might lead to a shift in sediment and water flux, including changes in climate (Bull, 1991; Warner, 1992; Ritter *et al.*, 2002; Fuller *et al.*, 2009; Finnegan and Dietrich, 2011), tectonics (Riebe and Kirchner, 2001; Wegmann and Pazzaglia, 2002, 2009), a shift in base level (Pazzaglia *et al.*, 1998; Gran *et al.*, 2009; Belmont, 2011; Finnegan and Dietrich, 2011) or anthropogenic effects (DeLong *et al.*, 2011).

Two main types of alluvial terraces exist, based on their morphology and thickness of the alluvial deposits (Pazzaglia, 2013). A strath terrace can be formed in actively incising rivers and is characterized by a thin mantel of alluvium capping a planed bedrock surface (Bucher, 1932; Hancock and Anderson, 2002). In contrast, a fill terrace is typically formed in response to a local downstream rise in base level and is characterized by a thick alluvial deposit that buries the river valley bottom. If the river incises back through the deposit, the alluvium is highly susceptible to erosion by lateral migration and bank collapse. Therefore these features can serve as important near-channel sediment sources in watershed sediment budgets and stream restoration projects (Walter and Merritts, 2008).

Mapping terraces and floodplain features can be expensive and extremely time consuming. Until recently, mapping these features over large areas has required extensive field campaigns in combination with analysis of aerial imagery and topographic maps. In the late 1970s the development of Digital Terrain Models (DTMs) and computer algorithms was used to analyse terrain properties of watersheds (Collins, 1973). Over the last two decades, availability of coarse resolution (90, 30, 10 m grid spacing) Digital Elevation Models (DEMs) provided only modest gains for mapping terraces because the horizontal and vertical accuracy of these DEMs was typically insufficient to resolve these features. However, increasing availability of high resolution topography data (1–3 m grid spacing) derived from light detection and ranging (lidar) provides sufficient detail to resolve these and many other landscape features.

Many new tools are emerging that take advantage of high resolution DEMs developed from ground-based and/or airborne lidar (MacMillan *et al.*, 2003; Wheaton *et al.*, 2010; Belmont, 2011; Gangodagamage *et al.*, 2011; Passalacqua *et al.*, 2012). However, even with high resolution topography data, manually delineating terrace and floodplain features can be challenging, due to difficulties in visually identifying subtle transitions in slope and planform of features on the landscape. Manual techniques are often time intensive, as large areas of the landscape must be studied, often iteratively. Additionally, manual mapping can be subjective, vulnerable to mapper fatigue and limited by time constraints. An automated process provides an objective initial analysis of potential surfaces that can be subjectively edited to develop a final output map.

Several other researchers have developed automated or semi-automated techniques to delineate landforms and landscape units (van Asselen and Seijmonsbergen, 2006; Demoulin *et al.*, 2007; Iwahashi and Pike, 2007). Demoulin *et al.* (2007) developed a technique that semi-autonomously recognizes fluvial terraces from a DEM. From those terraces, they reconstructed paleo-profiles of the river. Their work demonstrates that autonomous detection of fluvial terraces is possible, even for relatively small remnants of terraces. Their work also inspired the formulation of two semi-automated methods to select fluvial terraces. Both of these works can be found on the website: http://gis4geomorphology.com/ (Cooley, 2012). These two methods use a series of existing tools in ArcGIS used in conjunction with the open source statistical package R to identify fluvial surfaces. However these methods and the work by Demoulin *et al.* (2007) were not designed to produce an actual map of the spatial extent of terraces, nor are terrace heights relative to the channel calculated for individual surfaces. Here we introduce a tool that utilizes a high resolution DEM to select, map and measure discrete, near-channel flat surfaces based on local relief and several other user-specified inputs. The tool, named TerEx, is sufficiently flexible (based on user-inputs) to be used for delineation of both strath and fill terraces at either the watershed or reach scale. It can either be run in a PYTHON environment or as a Toolbox in ArcDesktop (ESRI, 2011).

Due to the natural variability in form expressed by these features, a fully automated technique for mapping floodplains and terraces is not feasible. Thus, we chose to strike a balance between manual and automated approaches and develop a semi-automated procedure wherein simple criteria are used to initially delineate terrace and floodplain boundaries and the user is provided with facile means to modify those boundaries.

The purpose of this paper is to describe a method (and related toolbox) by which flat surfaces can be semi-automatically delineated from a DEM, mapped in planform, and measured for surface area and height above the local channel. Our methods are based on the fundamental observation that floodplains and terraces are discrete, flat areas near the river that are separated by sharp, steep features, referred to as risers. While elevation difference thresholds and slope thresholds are commonly used for manual mapping our integration of the local relief threshold within a semi-automated and user-adaptable tool will greatly simplify and expedite terrace mapping over large areas. Input data sets are a DEM and a stream polyline that represents the channel centerline. While this tool automates mapping, it is important to consider that the tool provides only a thorough first-pass at terrace and floodplain delineation. It cannot replace the field work that is required for robust validation and finalization of a surficial geologic map. However, with appropriate use, it is expected that geomorphologists can save both time and money in mapping efforts.

We first provide a brief explanation of the functionality of the tool, and discuss techniques for validation of automatically extracted terrace features in two highly contrasting landscapes where extensive terrace mapping campaigns have previously been conducted. We then describe tests performed on four additional rivers that represent a wide range of environments, listing relevant characteristics and optimal selection parameters for each river. Finally we demonstrate an application of semi-automated terrace extraction in the Root River watershed, southeastern Minnesota as part of a larger effort to develop a sediment budget to inform watershed management.

TerEx Toolbox for ArcGIS

Based on typical physical attributes of terraces and floodplains, we have defined a set of rules that (a) select probable floodplain/terrace cells from a DEM, (b) eliminate selected areas that are not of interest, (c) generalize the shape of the selected areas, and (d) ultimately produce a shapefile consisting of terrace and floodplain features. By offering multiple, easily-adjustable parameters to select and ultimately define floodplain/terrace features from a DEM, the TerEx tool enables users to employ geomorphic intuition when delineating features. In the first step the tool analyzes topography to identify flat surfaces based on three attributes: (1) local relief of the surface; which cannot exceed a user-defined value (e.g. 0.5 m) within a user-defined focal area (e.g. a 100 m^2 moving window); (2) the area of the surface, once identified, must be greater than the user-specified minimum area; and (3) the selected surface must fall partly within the user-defined valley width. A flow chart of the tool (Figure 1) illustrates how inputs, processes, and outputs are related. At the end of step one, the tool pauses to allow the user to edit the initial delineation of surfaces, which is an essential step to produce a satisfactory output.

Often in flat landscapes large tracts of upland (non-alluvial) terrain are selected due to the low relief. It is advisable to delete these and any other areas that the user deems as inappropriate surfaces to retain as a terrace or floodplain (i.e. roads, water surfaces, upland area, alluvial fans, etc.). Another potential problem encountered is that multiple surfaces of slightly different elevations, which should be mapped as distinct surfaces, are occasionally amalgamated by the tool as one single surface (Figure 2(b) outline polygon). Individual terraces may be inappropriately connected because the scarp between them is very subtle or obscured by erosion, vegetation-related errors in the DEM, and/or human modifications. Removal of these joining segments allows the single surface to be split into multiple surfaces that correctly represent the terraces on the landscape (Figure 2(c)). In contrast, roads, buildings, ditches and other human structures can have the opposite effect, splitting what should be a continuous surface into separate surfaces. For these reasons, TerEx contains an editing tool for easy modification to the automatically delineated surfaces.

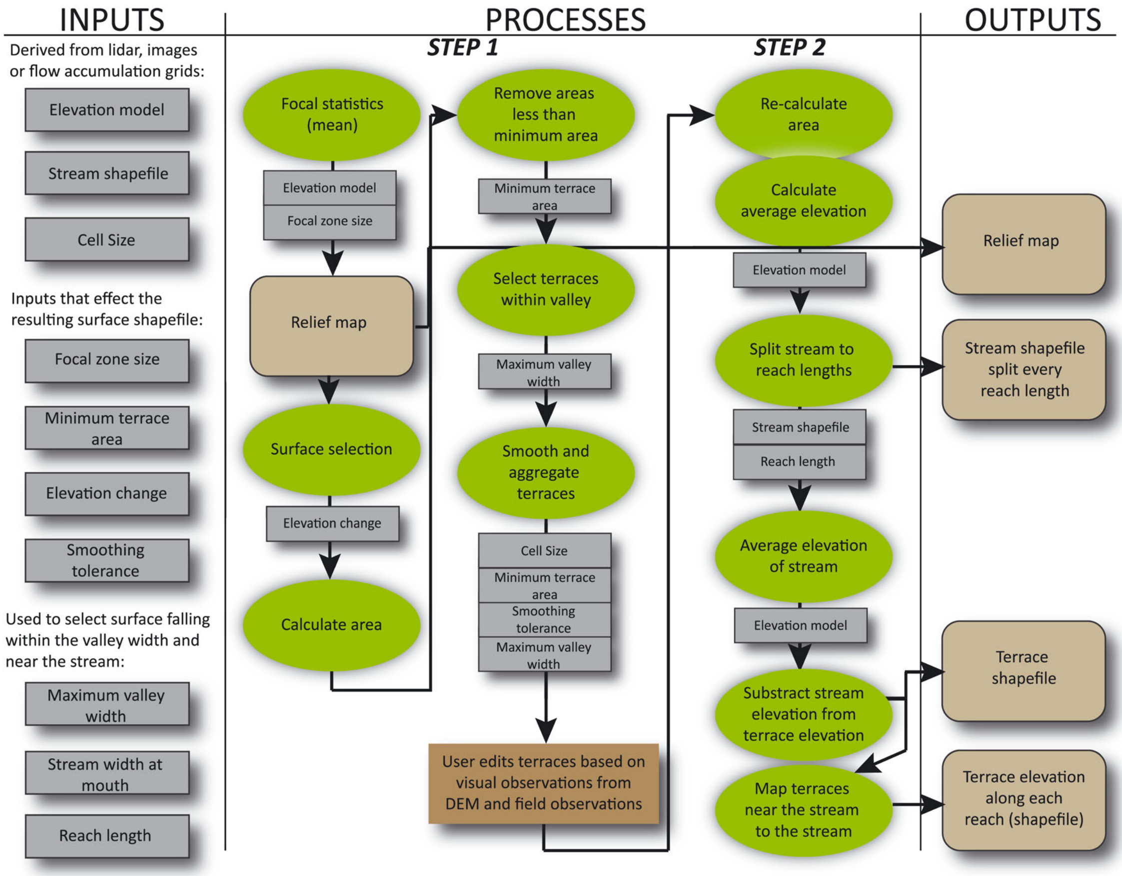

Figure 1. Flow chart for TerEx tool. The chart illustrates how inputs (smaller blue rectangles), processes (orange ovals), and outputs (larger green rectangles), are related and where each is relevant in the process. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

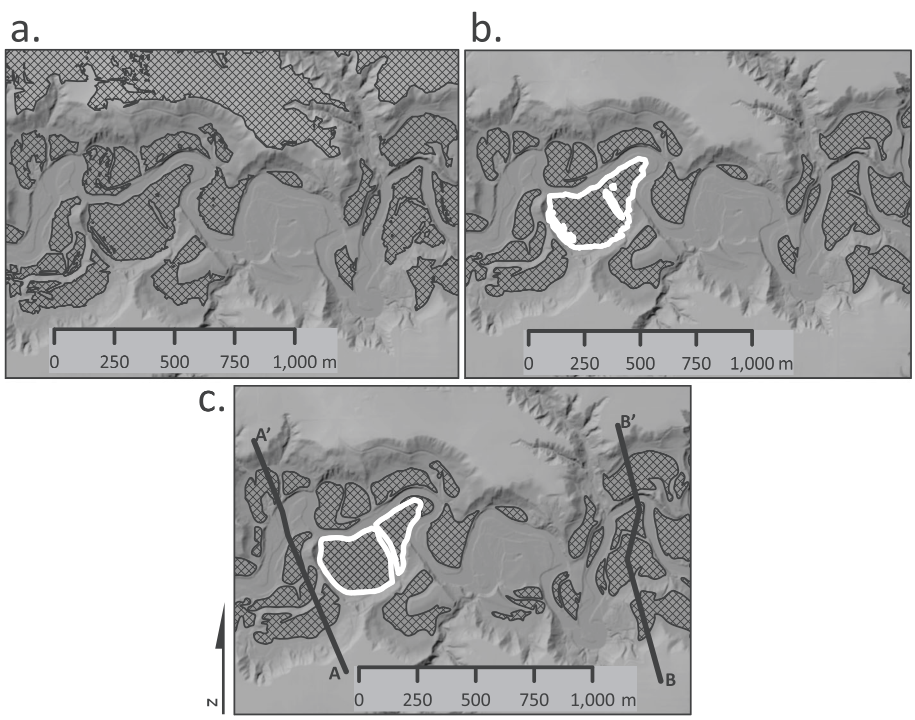

Figure 2. Examples of step 1 and step 2 from TerEx: (a) illustrating terraces prior to editing; (b) terraces that need to be edited; and (c) the final, edited, feature. Cross section locations are also presented.

TerEx divides the stream channel centerline at a user specified interval (step 2 in Figure 1). Once the stream polyline is split, the average elevation of each reach is automatically extracted from the DEM. The terrace and floodplain feature attribute table is then joined with the stream layer attribute table based on proximity (a given river reach is joined to the nearest terrace), and the average elevation of the stream is subtracted from the average elevation of the terrace/floodplain, providing an average elevation of the landform above the river. Note that in steep-gradient channels, this could cause significant errors in the estimated height above the channel. Shorter reach lengths and manual edits to the polygons will minimize this error. After calculation of terrace/floodplain elevation above the river, the heights of all terraces/floodplains near the river (within one channel width) are copied to the attribute table of the stream polyline. This is useful for visually mapping the height of terraces along the entire river longitudinal profile.

The resulting data sets from the tool (Figure 1) include a local relief DEM, a stream polyline split into reach lengths, a second stream polyline which lists the elevation of the nearest terrace in the attribute table, and a polygon shapefile of the mapped terraces. The attribute table of the terrace shapefile is comprised of the average absolute elevation of the terrace (m above sea level), the area of each polygon and the average elevation of each terrace above the nearest reach of the river (m).

Validation

The TerEx tool was designed to be used for analysis on entire river networks and long (10^1–10^3 km) river reaches. The tool was field-validated in two watersheds for which terrace maps have been independently developed. Validation watersheds include the Le Sueur River, a tributary to the Minnesota River in southern Minnesota, and Bridge Creek, a tributary to the John Day River in northern Oregon.

Le Sueur, MN, USA

The Le Sueur River, south-central Minnesota (Figure 3) provides a unique natural laboratory in which to apply the tool. The landscape evolution processes that characterize the modern morphology of the Le Sueur began roughly 13 400 years ago when Glacial Lake Agassiz catastrophically drained through the Minnesota River Valley, to which the Le Sueur is a tributary (Clayton and Moran, 1982; Belmont *et al.*, 2011a, 2011b). The knickpoint that formed in response to the 70 m drop in base level has propagated 40 km up through the Le Sueur River network resulting in the formation of hundreds of unpaired strath terrace surfaces. This record of incision has been documented by terraces that were mapped by Gran *et al.* (2009; in press).

We validated the TerEx tool against the Gran *et al.* (2009) terraces, which had been manually digitized from 3 m lidar and field checked for accuracy. We focused on a 32 km reach on the mainstem Le Sueur where terraces are particularly abundant. Information regarding the vegetation cover, height, minimum terrace area and DEM errors are summarized in Table II. Two metrics were used to validate the tool on the Le Sueur; observed versus predicted terrace areas and plots of the valley cross-section to determine how well the tool detected the edge of the terrace.

Observed versus predicted terrace areas

Areas of manually mapped (observed) terraces were individually plotted against the areas of terraces that were automatically mapped by the TerEx tool (predicted). Figure 4 illustrates the relationship between the observed and predicted areas. Points that fall above the 1:1 line were over-predicted by TerEx. Although there is some scatter in the data set, the grouping around the 1:1 line demonstrates that the terraces extracted by TerEx are broadly consistent with manually digitized features, and secondly, that variance between observed and predicted terraces is homoscedastic (equivalent across a broad range of spatial scales). A similar amount of scatter might be expected if two different people were to manually map the same

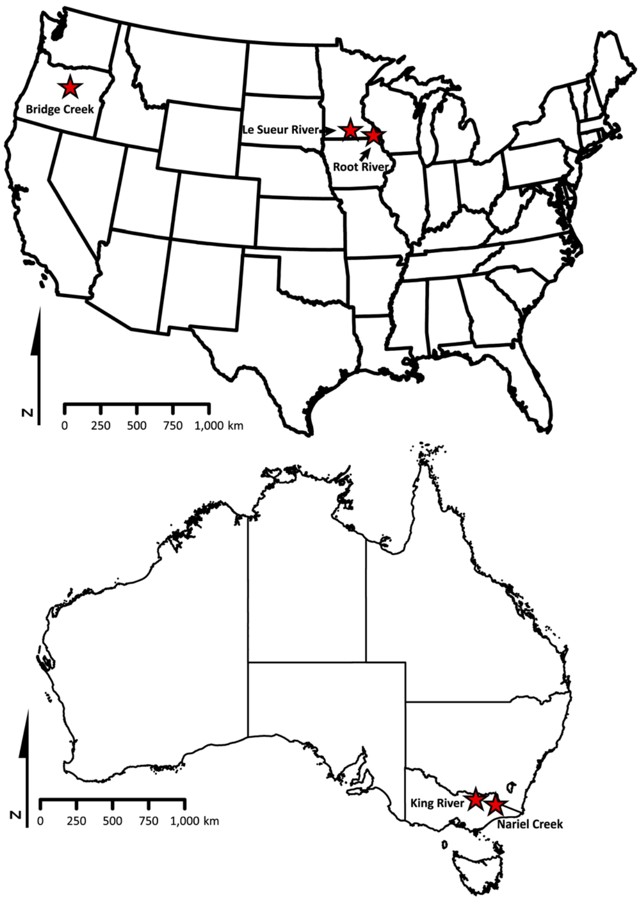

Figure 3. Map showing locations where the tool was validated (Bridge Creek and Le Sueur River), tested (Minnesota River, Gordon Gulch, King River and Nariel Creek), and applied (Root River). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

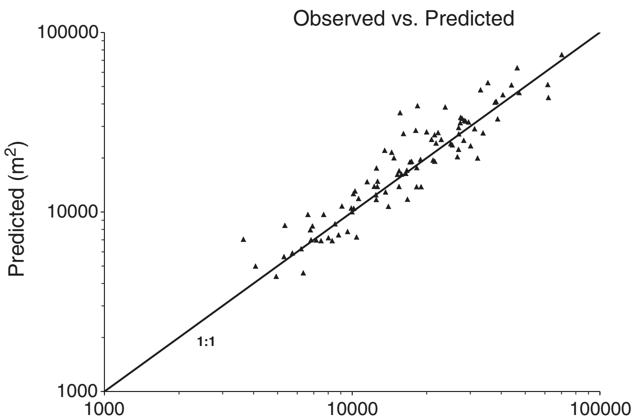

Figure 4. Observed (manually digitized) versus predicted (TerEx extracted) terrace surface areas in the Le Sueur River watershed. Terrace sizes were broadly consistent between observed and predicted and variance was scale-independent.

area. Close visual comparison of terrace boundaries mapped manually compared with those automatically extracted with TerEx indicates that in some locations the tool provided a smoother representation of terrace boundaries (Figure 5), but that the general shape and size are in fact very similar.

Validation of terrace edge detection

Two valley cross-sections (Figure 2(c)) were extracted from the DEM to demonstrate how well the tool delineates the edges of

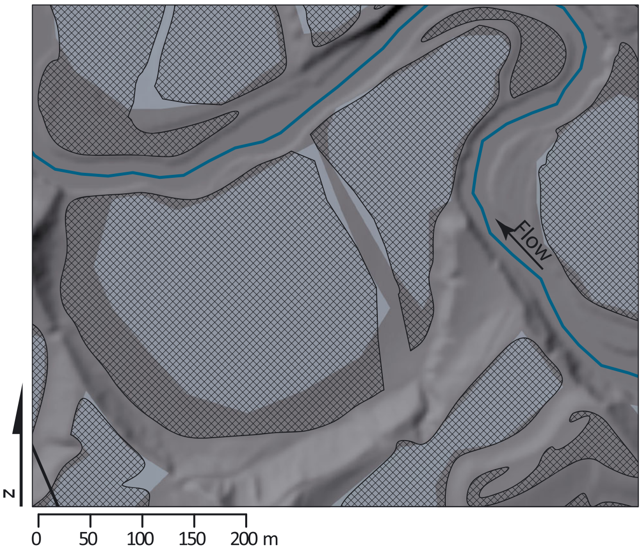

Figure 5. Close visual comparison of TerEx (black grid) versus manually digitized (solid blue) terraces in the Le Sueur River watershed. In many cases, TerEx polygons more precisely identified edges, and therefore the shape/area of terrace features. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

selected terraces. Figure 6 provides a visual comparison of manually mapped terraces versus those mapped by TerEx. Areas were accurately identified and the surface was mapped up to the junction of the scarp and tread, indicating that the method of using local relief to delineate these surfaces is effective. Using the comparison of the spatial extent of field mapped surfaces to the predicted terraces illustrates the ability of TerEx to select the edges of surfaces without needing another metric to mark edges of the terrace (e.g. convexity/concavity of the terrace surface as was used by Demoulin *et al.* (2007)).

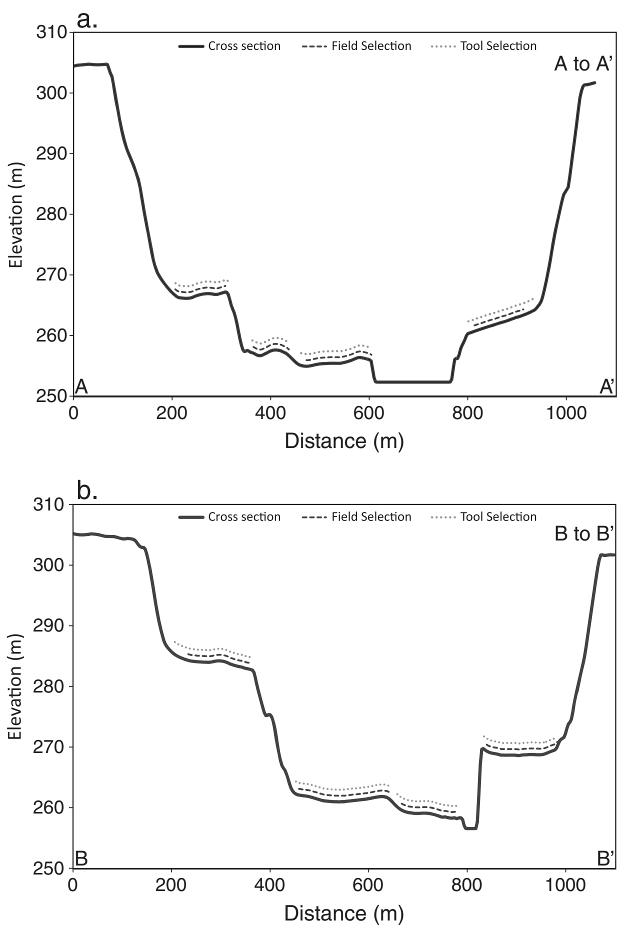

Figure 6. Cross-sections showing how well the tool mapped the edge of the terrace at two cross-sections. Cross-section locations are shown in Figure 2(c).

Bridge Creek, OR, USA

The tool was also used to select terraces on Bridge Creek, which is an incised (~ 4 m) tributary to the John Day River in eastern Oregon (Figure 3). Bridge Creek appears to have incurred pervasive anthropogenic disturbances (Pollock *et al.*, 2007) and experienced many cut-and-fill cycles. The lower valley of Bridge Creek is comprised of fine-grained alluvium, typically derived from alluvial fans issuing from tributaries. In sections of the valley, tributary inputs influence the planform of the stream as alluvial fans push the river to the opposite side of the valley. Field observations indicate that alluvial fans and fluvial terraces exhibit distinct grain size distributions with the latter being significantly coarser (Peacock, 1994). An ongoing (now in year 4) stream restoration experiment in Bridge Creek is implementing a soft-engineering approach to help the river develop heterogeneity in bed topography in an effort to re-establish beaver populations and increase complexity of fish habitat. Briefly, wooden posts are driven into the channel to control local hydraulics to promote scour or deposition of fine and/or coarse sediment. Thus, it is critical to identify locations along the 10 km restoration reach where coarse material (found in terraces) or fine-grained material (found in alluvial fans) can be sourced/targeted.

Terraces and alluvial fans were mapped by hand from lidar and aerial imagery and subsequently ground-truthed (E. Portugal, Personal Communication, March 2012). Manual mapping of terraces exclusively from lidar and aerial imagery was tedious and imprecise because of the subtle topographic transitions from alluvial fan to terrace. It was our goal to determine if the TerEx could differentiate between these landforms simply based on the change in local relief.

Differentiate between alluvial fans and terraces

The Bridge Creek study reach is comprised of a series of inset active floodplains and older terraces intermingled with low-gradient alluvial fans issuing from tributary drainages. Results from the validation study demonstrate high precision and versatility of TerEx. Specifically, using a relief threshold of 0.5 m and an area threshold of 200 m^2, TerEx did not select alluvial fans, but instead correctly mapped the river terrace formed at the toe of the fan despite the fact that the transition between the two was often too subtle to identify visually from lidar. Figure 7(a) shows manually digitized (from field work and remote sensing) alluvial fans depicted by white polygons and TerEx-selected fill terraces mapped as the hatch-mark polygons.

During summer 2011 field work, the TerEx-delineated surfaces were checked for accuracy. Areas that were manually mapped as alluvial fans had angular clasts at the surface indicating that these areas were not fluvial terraces, whereas areas which had been mapped as a terrace by the TerEx tool contained rounded gravels and sands indicating that these surfaces were indeed fluvial terraces. From this validation reach, it is evident that the TerEx tool can differentiate between alluvial fans and fluvial terraces. This further emphasizes the need for field validation of the surface mapped by the tool, and that the tool should be used as a rapid assessment of potential terrace and floodplain features.

A second validation reach (Figure 7(b)) was located further upstream in a constricted and relatively steeper gradient

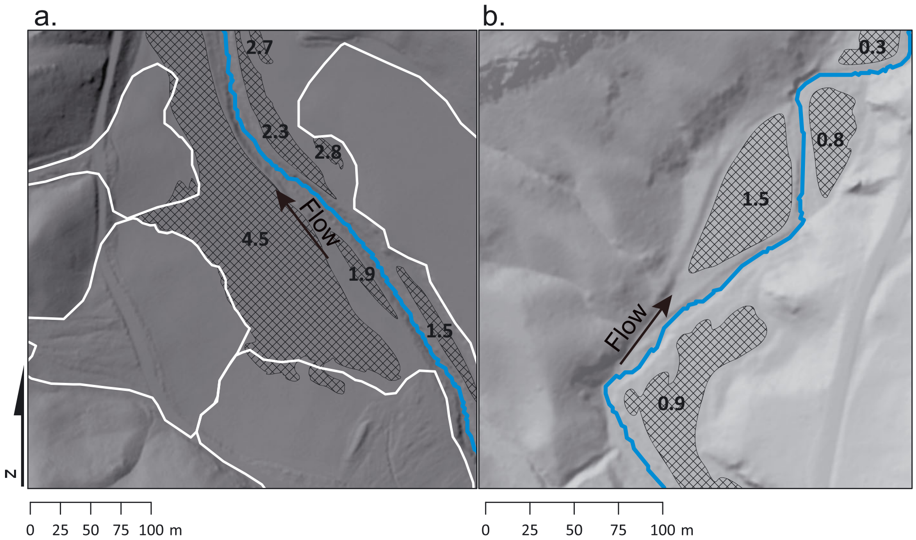

Figure 7. Results from validation along Bridge Creek, OR: (a) terraces mapped on Bridge Creek did not select the alluvial fans; (b) the other terraces selected along Bridge Creek. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

section of Bridge Creek. The tool was run on this reach to determine its effectiveness in a confined valley setting. The concern was that in a confined and relatively steep stream, the steep valley slope would result in unrealistic terrace elevation estimates. In an effort to minimize this error, we discretized the channel into relatively short reach lengths (20 m) as described above (i.e. Step 2). The optimal reach length was determined systematically, noting that as reach length decreased from 100 to 50 to 20 m, the estimated terrace elevation transitioned from a negative value to a positive value, and when checked against field-measured elevations, a 20 m length was most accurate. On this validation reach, using reach lengths less than 20 m did not improve accuracy of terrace elevation estimates.

TerEx performance across different landscapes

After validation of the selection process on the Le Sueur River and Bridge Creek we tested the tool on four additional rivers with substantially different geomorphic characteristics to determine the effectiveness of the tool in relation to river and terrace scale, vegetation effects and DEM resolution. These sites were selected to indicate how the tool would perform across different landscapes, and because the authors had some previous knowledge regarding the geomorphic history of each river.

A simple rubric was developed to aid in assessing the performance of the TerEx toolbox on each of these different sites (Table I). The performance score (from zero to ten, with ten being perfect) is based on three areas; initial surface delineation, amount of manual editing needed, and accuracy of calculated heights above the channel when compared to cross sections extracted from the DEM. Table II provides relevant information for each watershed, the optimal parameters used to develop the final terrace map, and the performance score. Optimal parameters were generally obtained by trial and error, however, the change in elevation and focal window were most sensitive in the initial delineation of surfaces. Automatically measured heights were manually checked by extracting cross-sections along selected terraces and floodplains and comparing the calculated height above the channel with the cross-section, but results were not field verified. The sites were selected simply to test the tool on a variety of landscapes and scales. No further analyses were preformed regarding the mapped surfaces as these are meant to provide help to future users to identify appropriate starting parameters.

Minnesota River, MN, USA

TerEx was applied to a 370 km long reach of the Minnesota River from roughly the City of New Ulm downstream to the confluence with the Mississippi River. The Minnesota River has been rapidly aggrading in this reach over the Holocene (Wilcock, 2009). The Minnesota River Valley incised nearly 70 m 13 400 years ago when glacial Lake Agassiz catastrophically drained through the valley (Clayton and Moran, 1982). Upon initial assessment of the valley, floodplains are comprised of cut-off meanders and large (approximately 1.0 to 1.5 m of local relief) scroll bars. The tool was not able to accurately delineate both the floodplain and terraces together in the same run due to the presence of scroll bars. However, the tool could select either the terraces, which are likely remnants of the late Pleistocene flood, or the floodplains without scrollbars, but not both surfaces in a single iteration because the two surfaces required different relief thresholds. The final map was produced by analyzing the river with two separate runs of the tool, the first was used to select near channel surfaces (floodplains with variable topography) and a second run to select terraces, which had a lower local relief relative to the floodplains. Even though multiple runs resulted in a finalized map, the amount of time spent was considerable and as a result lowered the overall performance score to five.

Gordon Gulch, CO, USA

Gordon Gulch is a small sub-alpine catchment in Colorado's Front Range. This small (4 km^2) catchment has a series of complex fill terraces which were initially mapped by hand and later digitized by Warrel (2011). The small catchment is dominated by a mix of vegetation types, including Aspen (*Populus tremuloides*) and Lodgepole pine (*Pinus contorta*). Due to the density of vegetation in the catchment, the 1 m lidar DEM exhibits a considerable amount of noise (i.e. vertical error), especially on steep vegetated slopes.

The TerEx tool did not perform well in this catchment, with an overall performance score of one. We attribute the delineation errors to the fact that the terraces are exceptionally small (on the order of 10 m^2). Further, errors were encountered in measurement of terrace height. We attribute measurement errors to the high steepness of the channel (average slope 0.09), which resulted in negative terrace elevation estimates for terraces on the valley margin. This is due to meanders in the stream planform, and the terrace being spatially linked to that

Table I. Performance rubric. Final scores are the sum of scores from the three performance areas

	Performance scoring			
Initial delineation	**1** More than 5 iterations needed to delineate surfaces visible on the hillshade, DEM and aerial imagers	**3** 3 to 5 iterations needed to delineate surfaces	**5** Less than 3 iterations needed	
Manual editing	**-1** Nearly every feature must be edited to produce a map that the user feels accurately represents features on the landscape that are visible on the hillshade, DEM, and aerial imagery	**0** Many features need to be generalized due to floodplain topography and/or man made features	**1** Multiple features need to simply split or generalized to split surfaces into discrete surfaces	**3** Minimal editing needed, simply remove man made features or upland surfaces that were selected
Accurate surface heights	**0** Need to either readjust reach lengths or perform more manual editing to provide a better height calculation when compared to cross sections extracted from the DEM	**2** Initial reach lengths and editing result in an accurate height calculation when compared to cross sections extracted from the DEM		
Final score	**Poor** (0–4)	**Good** (5–7)	**Excellent** (7–10)	

meander, meaning that the elevation above the channel for these particular terraces was calculated from a reach upstream of the terrace. Although the tool did produce a reasonable finalized map of terraces, the amount of time spent on iterations and on editing was probably larger than simply mapping the terraces by hand. Using the local relief method to identify flat areas on the landscape and subsequently digitizing the polygons would have resulted in the selection of many near channel surfaces that were removed by the TerEx tool as part of the automated process. As a result, TerEx should be used with caution for delineation of very small terraces ($<10\,m^2$) from DEMs with dense vegetation and steep channel gradients.

King River, VIC, AU

The King River is located in Northeast Victoria, Australia. The King River is characterized by two separate reaches. The first reach has many high terraces and alluvial fans along the valley walls with a flat floodplain near the channel, and a distinct second reach as the river flows onto a low-gradient floodplain where it becomes an anastomosing system with active anabranches. Although the tool was designed to operate on single threaded rivers it can still be applied to rivers with multiple channels. Anabranches were treated as part of the floodplain by removing the polylines representing the anabranches from the shapefile, which forces the tool to calculate elevations of mapped surfaces in relation to the main channel.

The TerEx tool was applied to both reaches in a single analysis. We found manual editing to be essential in the anabranching section and in areas with many paleo channels. Due to the low gradient of the river and valley, the optimal configuration of user-defined selection parameters resulted in large polygons contiguous to the channel for distances greater than 1 km. This long distance parallel to the channel resulted in more variability in the calculated surface height when compared with cross-sections extracted from the DEM. This was remedied by simply splitting the polygon into separate features, which had no bearing on the final spatial map of surfaces, but did result in a more accurate calculation of local bank height above the channel.

The reaches have slopes ranging from 0.008 to 0.0008. The tool performed well in selecting terraces and floodplains from the 1 m lidar receiving an overall performance score of 6. The lidar in this area has large vegetation errors, although these are usually concentrated around the channel, as most vegetation in the valley is a very thin yet dense riparian strip. At many points on the King River, vegetation-induced errors produced dams across the channel, which influenced the calculation of the selected surface's height above the channel and erroneously mapped several floodplain surfaces that crossed the streamline. To circumvent the effect of the vegetation in the channel and assure a reasonable height estimate, the stream line was first burned into the stream channel by 2 m, as this was the typical height of the dams across the channel. Although this does not remedy the elevation errors induced by the dam, it did result in two separate surfaces mapped on either side of the channel. As a result, estimates of elevation above the channel were more accurate for those surfaces.

Nariel Creek, VIC, AU

Nariel Creek is a 120 km long tributary to the Upper Murray River, a single-threaded meandering gravel bed river with sand and silt sized overbank sediment. The catchment area is $980\,km^2$. Fill terraces, which are assumed to be early Holocene in age, flank portions of the river in the upper reaches.

In order to use TerEx on Nariel Creek the river was split into three separate reaches, specifically, a confined reach, semi-confined reach and an unconfined reach. Channel gradient varied systematically for each reach type (see Table I). In setting the user defined parameters we found that in the steeper (0.01 slope) confined section, a shorter reach length (20 m) was necessary to accurately calculate the terrace and floodplain heights above the channel. Measured heights were manually checked by extracting cross-sections along select terraces and

Table II. Provides information regarding area and slope of river where TerEx was run, as well as the time spent, whether it functioned or not and the final parameters that resulted in the best map of terrace and floodplain features. Performance scores were given as follows. The first number represents ease of the initial delineation, the second the amount of manual editing needed, and third the accuracy of calculated terrace heights

River	Watershed area (km^2)	River length tested (km)	Slope	River type	Vegetation type, height, errors in DEM	DEM (cell size, vert.error)
Minnesota River, MN, USA	44000	350	0.0015	Aggrading, single thread semi-confined	Agriculture fields, Maple/oak forest (10-15 m), no	3 m, ±0.18
Bridge Creek, OR, USA	700	10	0.008	Incising, single thread, semi-confined	Agriculture fields, sagebrush, willow riparian, no	1 m, ±0.20
Gordon Gulch, CO, USA	5	8	0.09	Single thread, confined	Pine, Aspen (30-40 m),yes	1 m, ±0.30
Le Sueur River, MN, USA	2300	32	0.0009	Incising, single thread, semi-confined	Agriculture fields, Maple/oak forest (10-15 m), no	3 m, ±0.18
Root River, MN, USA	4300	630	0.0009	Aggrading, single thread, unconfined	Agriculture fields, Maple/oak forest (10-15 m), no	3 m, ±0.18
King River, VIC, AU	3050	69	0.0009	Aggrading, anabranching, unconfined	Agricultural fields, Eucalyptus forest (20-30 m), yes	1 m, ±0.10
Nariel Creek (A.), VIC, AU	2175	21	0.002	Aggrading, unconfined	Agricultural fields, Eucalyptus forest (20-30 m), yes	1 m, ±0.15
Nariel Creek (B), VIC, AU	320	12	0.005	Aggrading, single thread, semi-confined	Agricultural fields, Eucalyptus forest (20-30 m), yes	1 m, ±0.15
Nariel Creek, (C), VIC, AU	115	43	0.01	Single thread, confined	Agricultural fields, Eucalyptus forest (20-30 m), yes	1 m, ±0.15
User-defined parameters						
River	**Change in elevation (m)**	**Minimum terrace area (m^2)**	**Focal window (cells)**	**Smoothing parameter**	**Time spent (min)**	**Performance**
Minnesota River, MN, USA	0.5	5000	5	100	350	(3,0,2) = 5
Bridge Creek, OR, USA	0.75	200	3	20	60	(5,1,0) = 6
Gordon Gulch, CO, USA	1.0	10	3	20	200	(1,0,0) = 1
Le Sueur River, MN, USA	0.5	8000	5	70	120	(5,1,2) = 8
Root River, MN, USA	0.75	5000	5	65	70	(5,1,2) = 8
King River, VIC, AU	0.3	5000	5	80	75	(3,1,2) = 6
Nariel Creek(unconfined), VIC, AU	0.2	8000	5	60	50	(5,-1,2) = 6
Nariel Creek(semi-confined), VIC, AU	0.5	5000	3	50	40	(3,0,2) = 5
Nariel Creek, (confined), VIC, AU	0.5	1000	3	40	50	(5,3,2) = 10

floodplains and comparing the calculated height above the channel with the cross- section. In the semi-confined reach (0.005 slope), reach lengths were increased to 100 m, but due to the longitudinally continuous nature of the floodplain, manual editing was needed to split the floodplain into discrete polygons, so that the calculated elevation above the channel was accurate when compared with measurements taken from extracted cross-sections. Lastly, in the unconfined area (0.002 slope) vegetation-related errors in the DEM caused errors in automated measurement of bank height. This problem was again remedied by burning the stream into the DEM by 2 m, and then adding the 2 m back to the final height above the channel. Overall, the tool extracted terraces and floodplains from the DEM with very little need for manual editing, with a total of 140 min run time for all three river reaches.

Generally, the TerEx tool facilitated efficient and effective mapping of terraces and floodplains, requiring relatively little effort to produce high quality draft maps. The tool functions best in catchments where terraces are large and there is a distinct elevation difference between terrace treads and the active floodplain. Steep catchments with dense vegetation and very small (<10 m^2) terraces were challenging for the semi-automated techniques. A useful map was still generated even in our worst case scenario (Gordon Gulch, Colorado), but only with a significant amount of manual editing. As with any DEM analysis, vertical elevation errors can result in a misclassification of landforms. The user defined 'elevation change' parameter must not be less than the overall vertical error of the DEM, otherwise, the user cannot be confident of a true elevation difference between selected surfaces. The presence of dense riparian vegetation produces errors in the DEM which can act to dam the channel thereby forming a single surface which crosses the channel.

Application of TerEx on the Root River, MN, USA

We applied the TerEx tool to the Root River, a tributary to the Mississippi River in southeastern Minnesota, to demonstrate how it can be used to identify potential near-channel sediment sources and inform field sampling campaigns. Mapped floodplains and terraces throughout the watershed can provide critical information regarding areas of potential storage and (where tall fill terraces are found to be degrading) potential hotspots of sediment inputs.

Root River background

The Root River watershed (4300 km^2) in southeastern Minnesota is an important multiple-use resource, lying partially within an area that has not been glaciated in at least the past 500 kyr, known as the Driftless Area. After European settlement (*c.* 1800) erosion rates increased significantly (Knox, 1977; Trimble and Crosson, 2000). Estimated erosion for the region, from the onset of European settlement to the 1930s, indicates that nearly 4 cm, on average, of soil was eroded from hillslopes in the Driftless Area and deposited in the floodplain (Knox, 1977, 2001, 2006; Trimble, 1999). Soil conservation practices, first implemented in the Root River watershed in the late 1930s (Dogwiler, 2010), have improved the water quality and stream habitat throughout the Driftless Area (Trimble and Crosson, 2000).

Even now, after implementing conservative farming practices within the watershed, the Root River has 43 reaches that are considered impaired by the Minnesota Pollution Control Agency (MPCA). Of the impaired reaches, 73% are listed as impaired due to Mercury (Hg) and turbidity (MPCA, 2010).

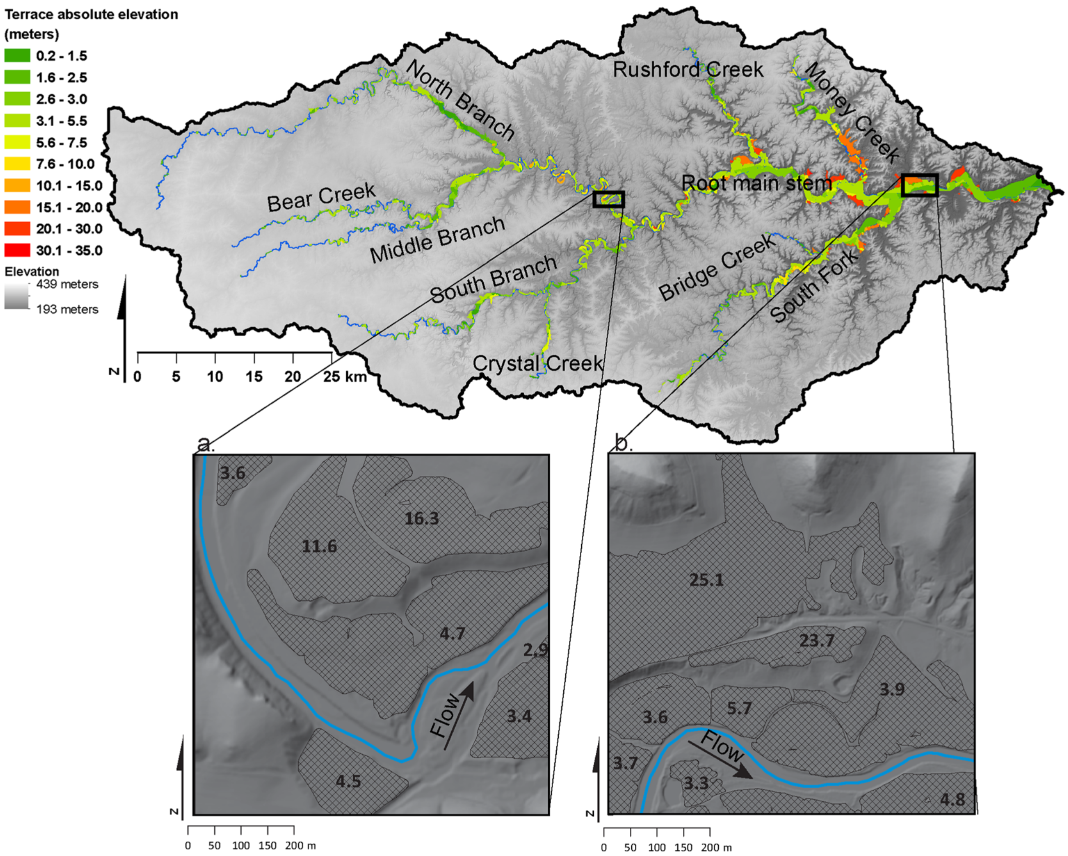

Figure 8. Results from TerEx application to Root River watershed. Insets A and B show a set of unpaired and paired terraces that were selected along two reaches in the watershed.

When in excess, fine sediment can degrade aquatic habitat. In addition, pollutants such as heavy metals, nutrients and toxins from pesticides and herbicides are typically transported via fine sediment.

Terrace and floodplain maps provide relevant information for identifying reaches where taller-than-average terraces may be significant net sediment sources via channel migration and/or channel widening. The final output from TerEx was used in conjunction with sediment fingerprinting results and hydrologic analysis to address the sediment dynamics of the Root River. The results from the sediment fingerprinting and hydrologic analysis are not reported in this paper, but rather are reported in Stout *et al*. (in press). TerEx-derived maps were used to identify potential near-channel sediment sources, inform field sampling campaigns, and provide critical information regarding areas of potential storage.

Terrace selection in Root River

The TerEx tool was applied to the entire Root River channel network (total stream length 630 km). Focal window size and elevation change threshold values used for TerEx were initially estimated based on field observations and iteratively improved via trial and error. Prior to TerEx analysis, we noted in the field that terraces had very little local relief and were relatively large, on the order of 1000 m^2. The tool was run on a subset of the DEM, with different combinations of focal window size, elevation threshold and smoothing window size. Each run resulted in a slightly different outcome, but the resulting maps were broadly consistent for a wide range of combinations. A point that must be stressed is that there is no single definitive combination of inputs for any landscape. Mapping terraces is a qualitative exercise; only through field observations and redundant trial and error will a satisfying terrace map be produced. However, even for a watershed the size of the Root River (4300 km^2) the automated processing steps illustrated in Figure 1 required only 70 min of run time, making iterative parameter optimization attempts feasible.

The final combination that visually produced the best results for the Root River watershed was a focal window of 5x5 cells (3 m grid resolution), elevation change threshold of 0.75 m, and a smoothing window of 65 m. Resulting shapefiles for a section of the river are shown in Figure 8(a) and 8(b). Select terraces were field-checked in June 2011 and October 2011.

Analysis of terrace map results

Mapping the spatial distribution of terraces can be useful in pinpointing areas that have unpaired terraces, or finding locations of paired terraces. Unpaired terraces are surfaces that occur at unequal elevations on opposite sides of the valley. These are in contrast to paired terraces which have a terrace at a similar elevation cross stream (Ritter, 1974). Figure 8(a) illustrates both of these points, as several unpaired terraces ranging from 5 to 12 to 16 m above the channel are visible at this section of the river. In this same section of the river, a paired terrace with a height of 5 m is also mapped.

The map of terrace heights throughout the watershed provides useful information for development of a field-based sampling strategy. For example, the map shown in Figure 8 was used by Stout (2012) to (1) identify areas with anomalously high channel banks (likely hotspots for sediment inputs to the channel), (2) target locations for extracting floodplain/terrace sediment cores for measurement of geochemical tracers for sediment fingerprinting as well as grain size distributions, and

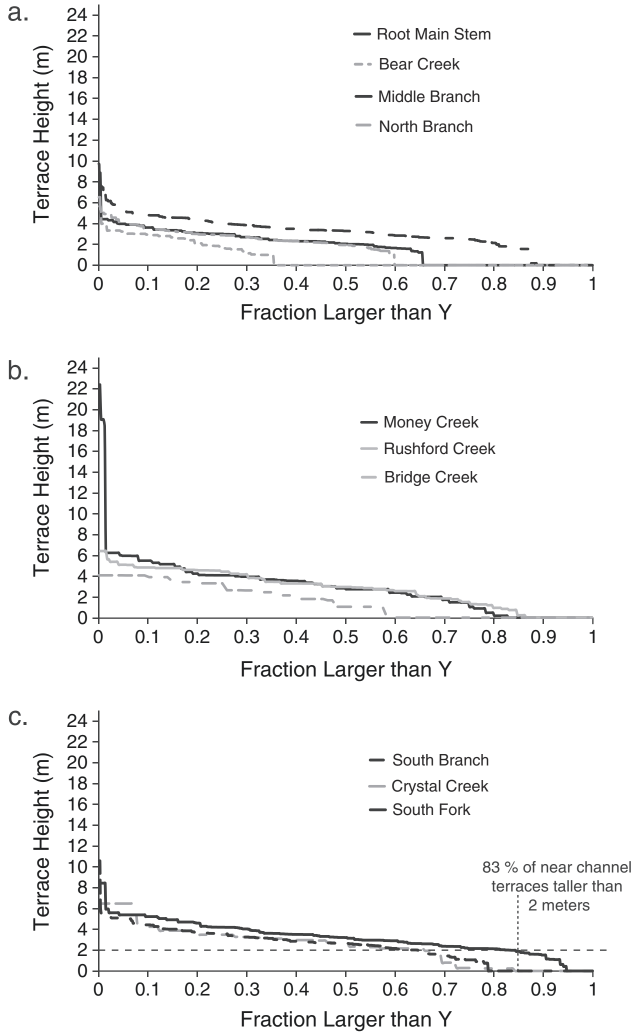

Figure 9. Distribution of terraces along each major tributary of the Root River. Each curve represents the height of banks that one might expect to find along each of these tributaries. Note the probable bank heights along the South Fork of the Root River. Approximately 80% of all near channel terraces are taller than 2 m. As the river cuts into these terraces, the river banks become a major source of fine sediment.

(3) identify a flight of terraces for Optically Stimulated Luminescence dating to understand the geomorphic evolution of the river basin. This map also provides information for watershed management groups, indicating areas where tall banks might be likely sources of sediment. If managers determine that bank stabilization might be the best method for sediment reduction practices in a watershed, a map which exhaustively indicates the height of near-channel terraces and floodplains provides a method to locate and prioritize potential stabilization points.

Figure 9 shows the cumulative distribution of bank heights along the Root River and major tributaries. The curves represent the fraction of banks above a certain height along the length of the river. To develop this plot, terrace elevation above the river (from the stream polyline with terrace heights in the attribute table) was used to calculate the fraction of terraces immediately adjacent to the river that exceeded any given height. Composite analysis of the entire watershed is useful, but does not indicate along which of the tributaries these areas of tall terraces might be located. When comparing each of the individual tributaries of the Root River (Figure 9), it is evident that particular tributaries exhibit a relatively high proportion of tall terraces near the channel. For example, Figure 9(c) highlights the fact that 83% of the South Fork of the Root River is lined by banks that are taller than 2 m with several of the actively undercut (observed in aerial photos and in the field) terraces reaching heights greater than 10 m. The information in Figure 9 acts as a supporting line of evidence for sediment fingerprinting results and to reinforce the conclusion that near-channel sources of sediment are the dominate source of sediment to the Root River (Stout, 2012; Stout *et al.*, in press).

As the Root River continues to migrate across its floodplain and cut into the tall near-channel terrace, the net source of sediment from these terraces may dominate sources of sediment to the South Fork of the Root River. Such information can be used by managers and consulting agencies to determine which of the tributaries are most likely receiving significant amounts of sediment from degrading near-channel sources. In watersheds with a history of anthropogenic disturbances, the a priori assumption that modern sediment sources are dominated by terrestrial erosion should be applied with caution. Only through multiple lines of evidence such as sediment fingerprinting, watershed hydrologic analysis, and source mapping can managers gain an understanding of sediment dynamics and develop robust management strategies (Smith *et al.*, 2011).

Conclusion

The TerEx tool is a simple PYTHON script that can be run from either a PYTHON interface or via ArcDesktop Toolbox. The required input data sets and parameters are simple to acquire from a DEM, streamline, and field and aerial imagery observations and are easily adjustable to optimize automated feature delineation. The resulting output shapefiles and local relief grid are a robust first pass of terrace and floodplain mapping that can be useful for a wide range of applications and can ultimately save a project both time and effort.

The tool was validated on two river systems and tested on four additional rivers covering a wide range of geomorphic environments. We were able to successfully delineate terraces in five of the six study landscapes and only failed in the most extreme example, a steep river channel with very small terrace surfaces and significant vegetation-induced error in the DEM in the riparian zone. The scale of the river analyzed, related landform sizes and the resolution of the DEM will directly influence the effectiveness of the approach described above. Based on tests performed using the tool over a wide range of geomorphic settings we conclude that the tool functions best when applied in rivers that have medium to large terraces ($>100\,m^2$) and with high resolution DEMs (< 3 m grid spacing) that have moderate to low amounts of vegetation-induced error in elevation values. In very low gradient rivers, the amount of necessary manual editing will increase, and is of particular importance when paleochannels or large scroll bars are common features of the floodplain.

In a more detailed case study, the tool was applied to the Root River, where the resulting terrace map and stream polylines were useful for planning field sampling campaigns and identifying locations where near-channel terraces potentially serve as significant sediment sources. The rapid processing time (70 min for a watershed of $4300\,km^2$) combined with the ability to easily manipulate input parameters, should greatly facilitate semi-automated mapping as well as basic measurement of terraces and floodplains for most riverine landscapes.

Supplemental material

- Link to Terrace and Floodplain Extraction Tool python script and Arc Toolboxes: <https://www.cnr.usu.edu/htm/facstaff/belmont-hydrology-and-fine-sediment-lab/belmont-research>.
- Tutorial and example data can be found in TerEx_example zip on same website
- Full Python script available from online supplemental material

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