APPENDIX B:

Erosion, Sediment Sources, and Channel Analysis in the Crystal River Watershed

Earth Systems Institute

Erosion, Sediment Sources, and Channel Analysis in the Crystal River Watershed, Colorado

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Introduction

The Roaring Fork Conservancy commissioned an analysis of erosion sources in the Crystal River watershed (938 km^2/ 362 $miles^2$) with a focus on sediment sources in Coal Creek Basin (69 km^2/ 26.6 $miles^2$) to support the need for focused resource evaluations as part of the Crystal River Management Plan process. Study objectives include identifying the relative contribution of sediment supply to the mainstem Crystal River from Coal Creek Basin (Figure 1) compared to the upper Crystal River basin (342 km^2/ 132 $miles^2$), and to determine what proportion of erosion sources in Coal Creek Basin are controllable. Further objectives are to determine the causes and potential mitigation of the channel sedimentation and associated flooding in the vicinity of the community of Redstone, CO, located immediately downstream of the Coal Creek confluence along the mainstem Crystal River. The community analysis system NetMap (www.terrainworks.com) comprised of digital landscapes and analysis tools was used in all components of this analysis (Benda et al. 2007, 2009).

Methods

A digital landscape of the Crystal River basin was developed using a 10 m digital elevation model (DEM, National Elevation Dataset [NED]). The digital landscape includes a synthetically derived stream layer using a set of flow routing algorithms within NetMap. Based on discussions with Brian McMullen (US Forest Service) and Sharon Clarke (Roaring Fork Conservancy) the dominant erosion sources in the Crystal River basin include: (1) gully erosion, (2) shallow landsliding, (3) hillslope surface erosion, and (4) road surface erosion (unpaved roads).

Gully erosion and shallow landsliding (Figure 2) deliver a range of boulder to silt/clay sized particles to channels. Bedload size sediment (cobble, gravel, sand) is implicated in accelerated sediment storage in channels and hence flooding in the mainstem Crystal River below the Coal Basin confluence. Hillslope surface erosion and road surface erosion contribute mostly fine sediment to streams and rivers (sand and smaller), and is considered suspended load. Although suspended load can increase turbidity and impact aquatic life, it is not a significant contributor to in-channel sediment storage and thus flooding. Each of the four sediment sources is evaluated in this study.

Gully and Shallow Landsliding

Gully erosion and shallow landsliding are considered together since the topography associated with each is similar. Both processes are driven by hillslope (or swale) gradient, degree of topographic convergence, and contributing drainage area (Montgomery and Dietrich 1994, Miller and Burnett 2007, Parker et al. 2010). To analyze these processes we use the parameter in NetMap called 'Generic Erosion Potential' (GEP). GEP provides a relative measure of potential erosion based on slope steepness and convergence, recognized topographic indicators of shallow landsliding and gully erosion. GEP is based on topographic attributes of slope gradient, local contributing area, and topographic convergence derived from the DEM:

$$GEP = S*aL/b$$

where S is slope gradient (m/m), aL is a measure of local contributing area to a DEM pixel equal to the number of adjacent pixels that drain into it (varies between 0 and 8), and b is a measure of topographic convergence equal to the projection of flow direction out of a pixel onto the pixel edges. Values of b are 1 on planar slopes, less than 1 on convergent topography, and greater than 1 on divergent topography. Higher values of GEP are calculated in areas of steeper, more convergent topography. Higher values of GEP correspond to higher landslide densities and to higher gully-initiation-point densities (Miller and Burnett 2007).

GEP can stand alone providing a relative index of erosion potential. We convert GEP indices into spatially distributed sediment supply (t/km^2/yr) using estimates of basin sediment yield. However, there are no independent estimates of sediment yield for the Crystal basin to convert GEP. As an approximation, we apply two erosion rates estimated by different methods. The first rate (35 t/km^2/yr) is based on regional denudation determined from suspended sediment records. The reference region encompasses eastern CO, including the Western Slope (Judson and Ritter 1964). The second rate is estimated using a surface erosion model (WEPP) for post fire conditions in forested areas of Colorado; rates in the general vicinity of the Crystal basin range are between 50 and 200 t/km^2/yr (Miller et al. 2011). Studies of post fire erosion have shown increases ranging from one to three orders of magnitude after wildfire (Morris and Moses 1987, DeBano 2000, Benavides-Solorio and MacDonald 2005). Considering that post fire erosion rates in semi-arid areas are likely much higher than during non-fire periods, a conservative basin average erosion rate for the Crystal River basin is 10 t/km^2/yr. Since the estimated hillslope surface erosion in the Crystal basin is approximately 1 t/km^2/yr (see below), we apply a value of 10 t/km^2/yr to illustrate the average rate of erosion associated with gullying and shallow landsliding.

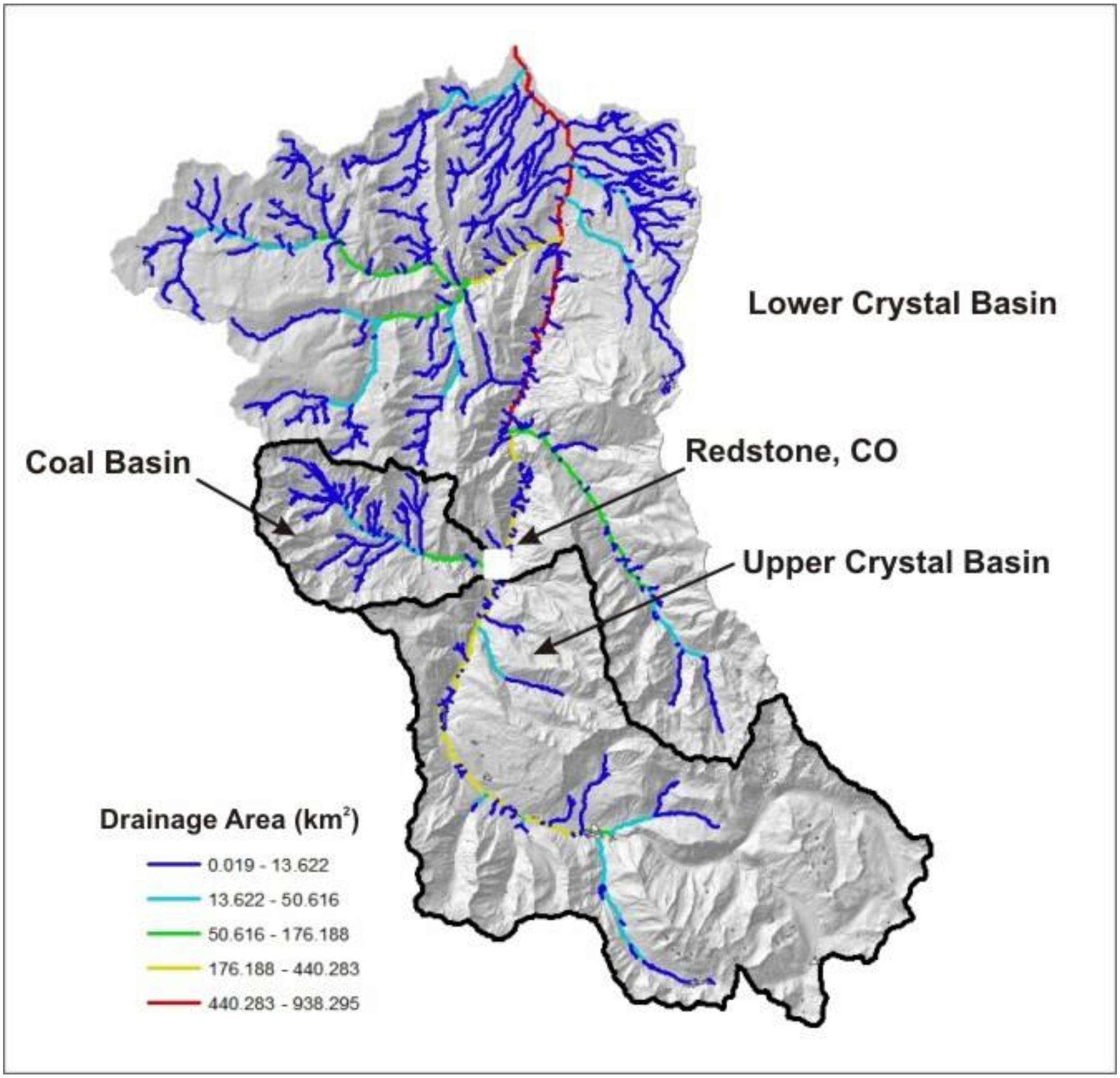

Figure 1. An erosion and sediment source analysis was conducted in the Crystal River basin (938 km^2/ 362 $miles^2$). Of particular interest is the relative importance of Coal Creek Basin (69 km^2/ 26.6 $miles^2$) compared to the upper Crystal basin (342 km^2/ 132 $miles^2$).

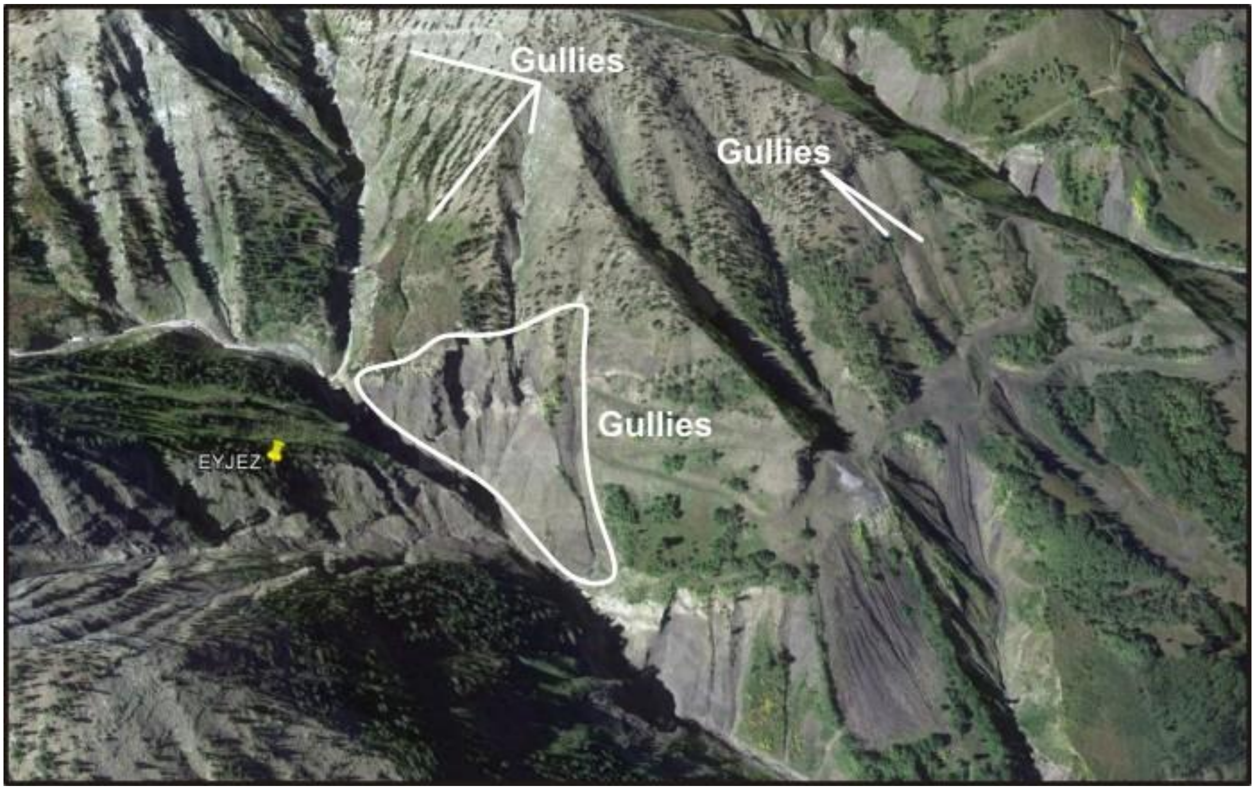

Figure 2. The dominant erosion processes in Coal Basin are gullying and shallow failures.

Hillslope Surface Erosion

A surface erosion model in NetMap, Watershed Erosion Prediction Project or WEPP (Flanagan and Livingston 1995, Elliot et al. 2001) was applied using 100 years of simulated climate. The WEPP model incorporates relationships between slope steepness and erosion, the slope profile and sediment delivery to streams, influence of soil and vegetation types, and the frequency and magnitude of rain storms, all recognized universal drivers of surface erosion. Thus, required parameters in WEPP include vegetation type (forest, grass land, etc.), soil texture (clay loam, loam, silt loam, sandy loam), slope steepness, length and profile, and distance of hillslopes to streams. NetMap's digital landscape was used to derive the necessary topographic indicators.

The four soil textures used in WEPP are those used in the Disturbed WEPP interface[1] and they reflect site specific parent rock and geomorphic features. Clay loams are soils derived from shales, limestone and similar decomposing fine-grained sedimentary rock. They also are found in lakebeds and areas of ancient lacustrian deposits. Silt loams are ash cap and loess soils, soils derived from siltstone or similar sedimentary rock, or found in highly erodible mica/schist geologies. Sandy loam is found in glacial outwash areas or areas of decomposed granites and sandstone, and sand deposits. Loams are found in areas of glacial till and alluvium. Soil data

[1] http://forest.moscowfsl.wsu.edu/fswepp/docs/distweppdoc.html

were obtained from the Natural Resources Conservation Service (NRCS)[2] and the Holy Cross Area Soil Survey[3], and converted to the four types used within WEPP (Brian McMullen, US Forest Service).

The climate simulator in WEPP (CLIGEN, Nicks et al. 1995) is based on empirically derived time series of 24-hr storm magnitudes in the US. For the WEPP analysis, CLIGEN stations included Crested Butte and Glenwood Springs (CO). Land cover data were obtained from the National Land Cover Database (NLCD) and GAP data (USGS); data were converted to the vegetation types required for WEPP (Sharon Clarke, Roaring Fork Conservancy).

Road Surface Erosion

Surface erosion on unpaved roads is governed by road gradient, length of road that is hydrologically connected (e.g., length of overland flow on a road surface), road width, road surfacing (native, gravel), traffic level (high to low), and time since grading (Luce and Black 1999, Sugden and Woods 2007). The WEPP road surface erosion model[4] in NetMap employs road width, drainage length, road gradient, surface material, soil type, and traffic level. Since WEPP predicts sediment delivery to streams (t/yr), the intervening hillslope distance and gradient between individual road segments and the nearest stream (referred to as the "buffer") influences the amount of sediment delivered to channels. If the road drains directly to a stream channel, no buffer is considered.

We obtained a shapefile of varying road widths, surface type, and traffic levels (Jane Frambach US Forest Service). NetMap divides roads into hydrologically connected segments to calculate road drainage diversion and road surface erosion potential. Road segments are broken into smaller segments that reflect road drainage into streams and drainage from roads at other locations (e.g., road drain points). The road drainage tool is used to create a segmented road layer for use in the WEPP road surface erosion model.

Roads do not effect either the predictions of GEP landslide and gullying or the WEPP surface erosion. However, the occurrence of roads could be used to modify the model predictions similarly to how lithology is used to modify the landslide and gully prediction of erosion and sediment supply.

Basin-scale and Channel Analysis

Erosion results were aggregated to basin-scale and ranked to indicate which subbasins have higher erosion rates. Profiling tools in NetMap were used to examine how longitudinal profiles, valley gradients, and valley (floodplain) widths correspond to predicted point influxes of

[2] http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm
[3] USFS, unpublished data
[4] http://forest.moscowfsl.wsu.edu/fswepp/docs/wepproaddoc.html

sediment. Cross sectional profiles were used to measure the proximity of river elevations to nearby valley floor elevations.

NetMap hillslope aggregation and channel routing tools were used to calculate cumulative or aggregated sediment yield from hillslopes and roads to channels. In this application, predicted sediment supply (flux) is summed and area weighted downstream. Sediment is not physically routed in terms of predicting bedload transport rates (based on channel gradient, stream power, grain size etc.). However, NetMap's tools and sediment supply predictions could be used to inform physically or statistically based sediment transport models in the Crystal River watershed.

Results

The analysis is divided into two parts based on sediment grain size and thus the type of impact associated with different erosion processes: (1) gullying and shallow landsliding and (2) surface erosion on hillsides and along unpaved roads. Gullying and shallow landsliding are responsible for supplying bedload size sediment to channels (i.e., 2 mm to > 250 mm; coarse sand, pebbles, gravel, cobbles and boulders). Bedload constitutes the vast majority of in-channel sediment stores in the Crystal watershed and thus is associated with channel processes including channel bed aggregation, channel changes and flooding. Sediment particles less than 2 mm (less than coarse sand and including silt and clay) are derived from surface erosion processes on hillsides and on unpaved roads. Suspended load contributes to turbidity which can threaten aquatic life, including fish, and water quality.

Coarse Sediment: Gullying and Shallow Landsliding

The generic erosion potential index (GEP) is used to estimate the location and magnitude of gullying and shallow landsliding sediment. In the Crystal River, as elsewhere, lithology (rock type) strongly influences erosion. In Coal Basin and in other areas of the watershed, the most erosion prone rock types are the Maroon siltstones and the Mancos shale (Figure 3).

To account for the role of rock type on erosion potential, GEP values were modified by an estimated factor of increase, a numerical value between 1 and 3 that was used to multiply the original GEP value (Figure 4). The highest factor of increase (3) is associated with Mancos Shale, Mesaverde Group, Wasatch Formation, and Maroon Formation; the second highest factor (2) is associated with Minturn and Belden formations. All other rock types were assigned a value of one, that is, the erosion potential was not modified.

The resulting modified GEP values mapped across the Crystal basin, and in Coal Basin specifically, are shown in Figures 5 and 6. Coal Basin has a concentration of high magnitude gully and shallow landslide potential, a pattern that occurs within the central part of the Crystal River watershed, due, in part, to steep and highly dissected topography in association with the erosion prone rock types. Figure 7 shows an example of how modified GEP represents steep, dissected areas in the Coal Basin that are being eroded by gullies and associated shallow failures.

NetMap was used to translate modified GEP values into hillslope erosion rates with units of tons per square kilometer per year. An average basin sediment yield value of 10 t/km^2/yr was used; this value is spatially distributed across the basin with values higher than average corresponding to areas of high GEP and lower values than average in areas of low GEP.

NetMap uses its flow direction grids, via drainage wings, to transfer predicted hillside erosion to individual stream segments throughout the basin (Figures 8 and 9). Predicted stream segment erosion values ranged between less than one and 33 t/km^2/yr. Converting GEP into cumulative and basin sediment yield requires that channel segment sediment yields aggregated downstream (and area normalized) be equal to the average sediment yield value in the lower most stream segment (e.g., 10 t/km^2/yr). The sediment yield values provide a numeric baseline to consider sediment yields in the Crystal River watershed. Nevertheless, accurate values of sediment yield are not required because the relative differences in predicted erosion potential and sediment yield provide sufficient information about spatial variability in erosion rates.

To examine large scale patterns in predicted sediment sources (and sediment yields) in the Crystal River basin, the predicted average annual sediment yields are summarized by 12 digit (6th field), Hydrologic Unit Code (HUC) boundaries. The classification reveals that Coal Basin and adjacent areas have the highest predicted erosion and sediment yields at 13-14 t/km^2/yr (Figure 10). Coal Basin has approximately a one third higher average erosion rate compared to the upper Crystal River watershed.

To estimate how predicted sediment yields accumulate downstream revealing tributary scale patterns of erosion potential, NetMap aggregates individual hillslope-channel segment values (Figures 8 and 9) downstream (Figure 11). High values of predicted sediment yield (13 – 42 t/km^2/yr) are concentrated in Coal Basin, as well as in nearby areas, revealing the significant erosion source areas at those locations. By removing all first, second, and third order channels (Strahler 1952), the spatial pattern of predicted erosion is evident in the largest streams in the Crystal basin (Figure 12).

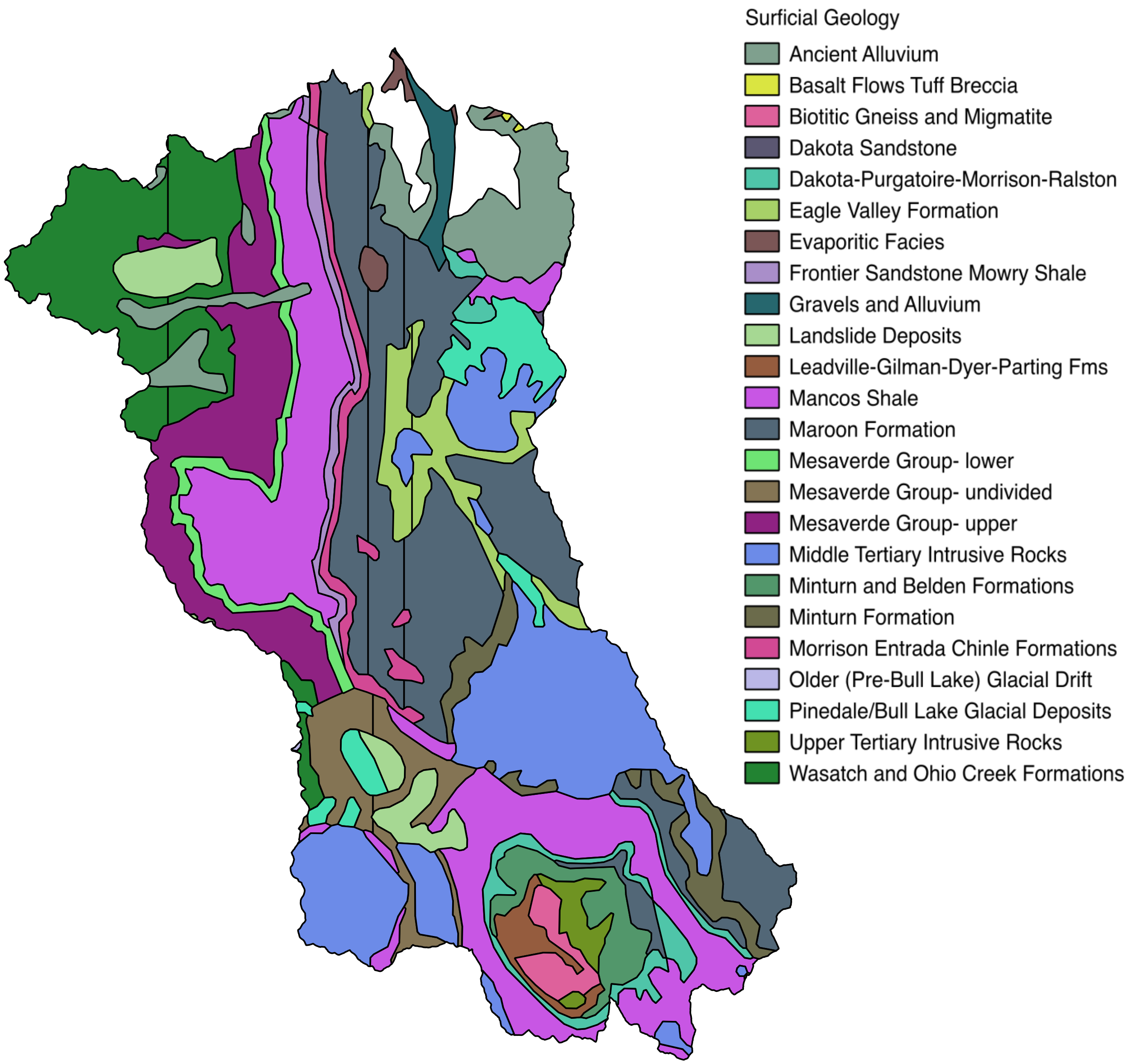

Figure 3. Lithological units in the Crystal River basin (Colorado Division of Geology) are dominated by sandstone, shale and siltstone.

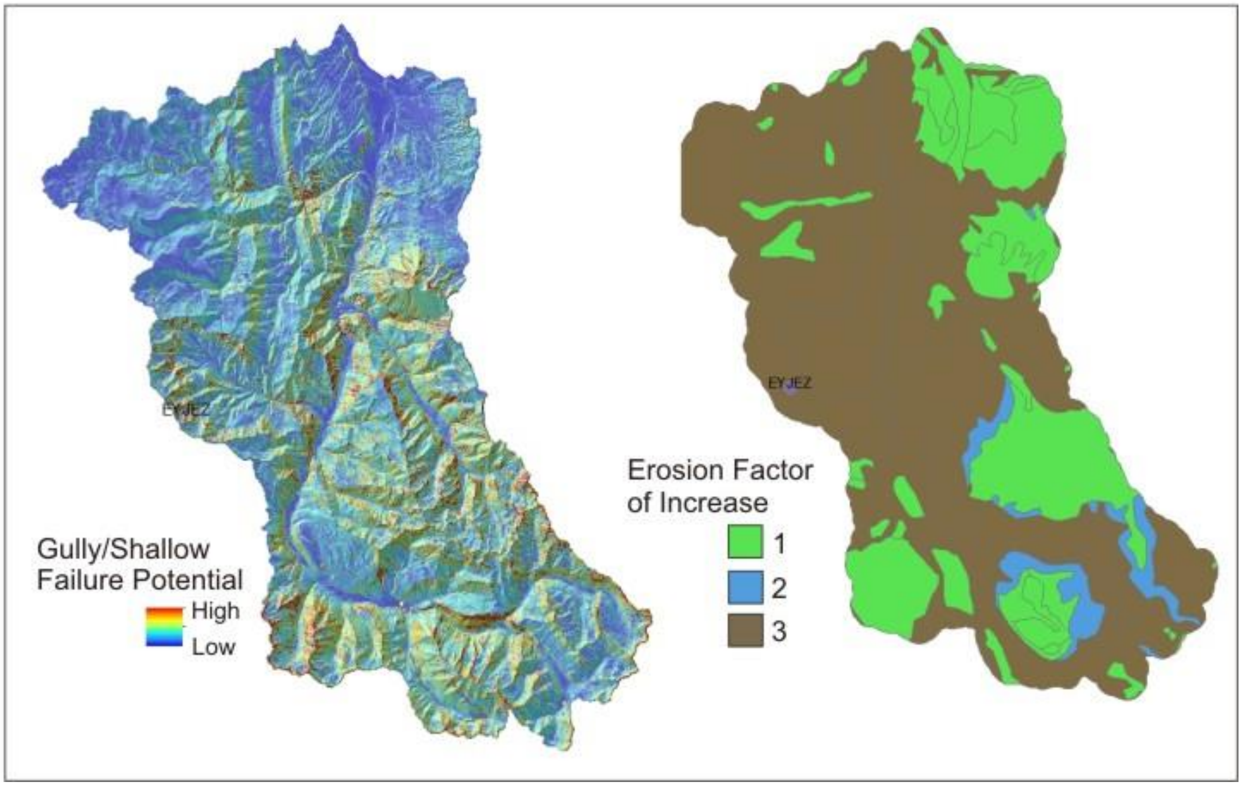

Figure 4. Original Generic Erosion Potential (GEP) values in the Crystal River basin on the left with the erosion factor of increase values on the right (linked to rock types, Figure 3). Factors of increase are used to multiply the original GEP values to account for the role of rock types on erosion potential.

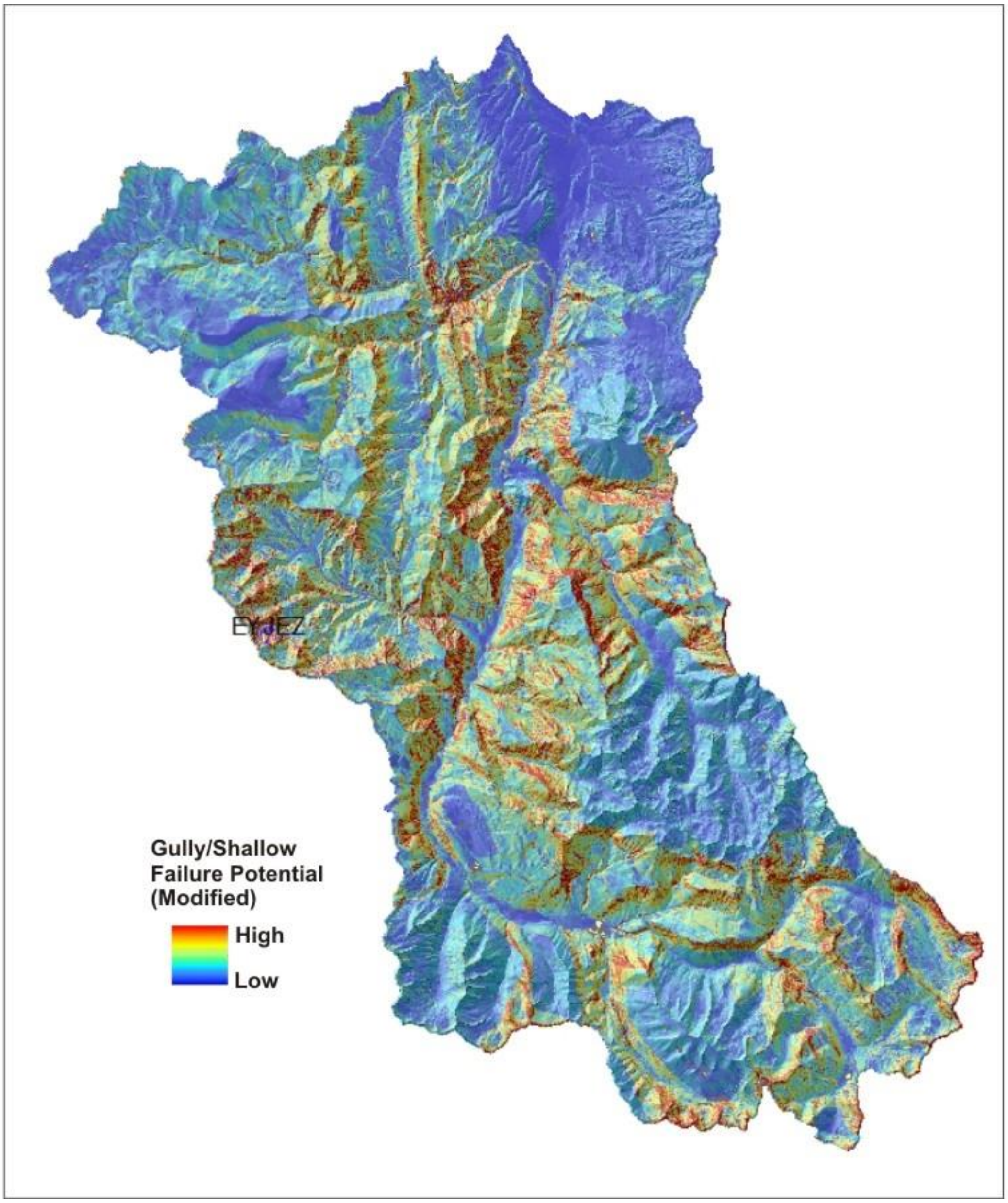

Figure 5. The final (modified) GEP values in the Crystal River watershed reveal distinct spatial patterns of erosion potential, with the highest values associated with the steep and highly dissected terrain in conjunction with erosion prone rock types.

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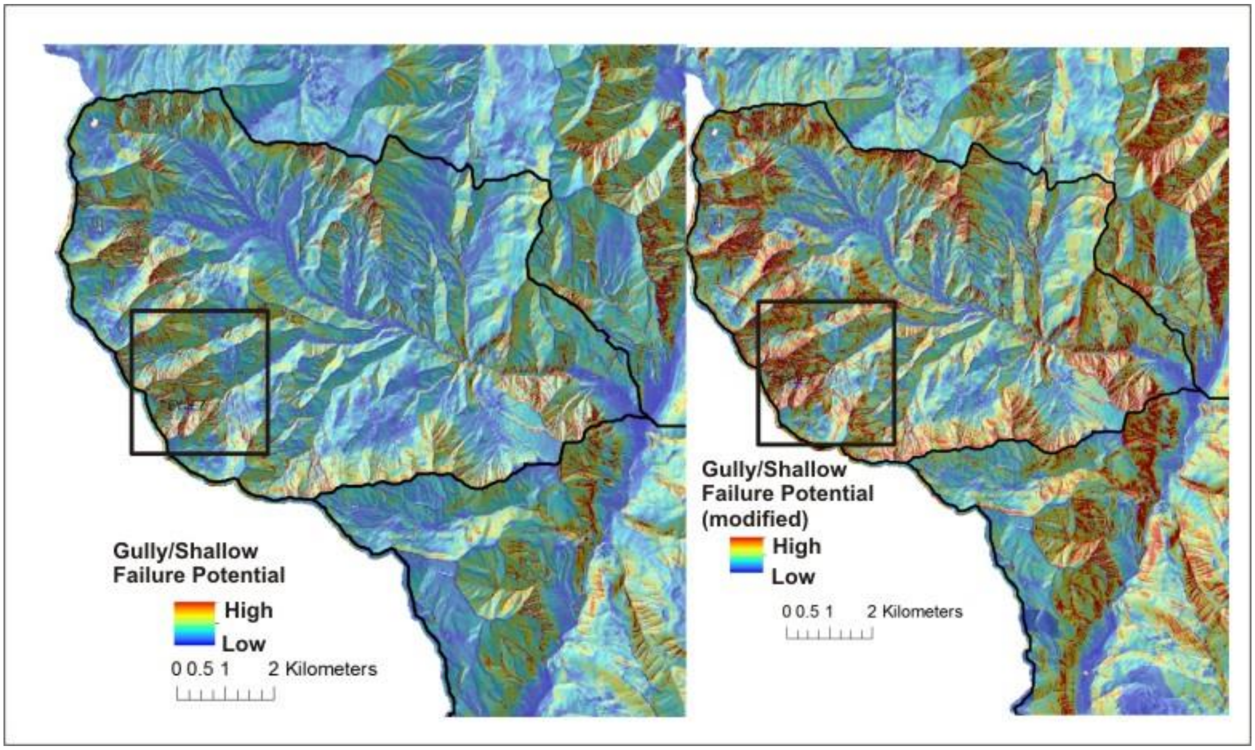

Figure 6. A comparison between the original GEP values of gully and shallow landslide potential (left panel) and the modified GEP values (right panel) in Coal Basin.

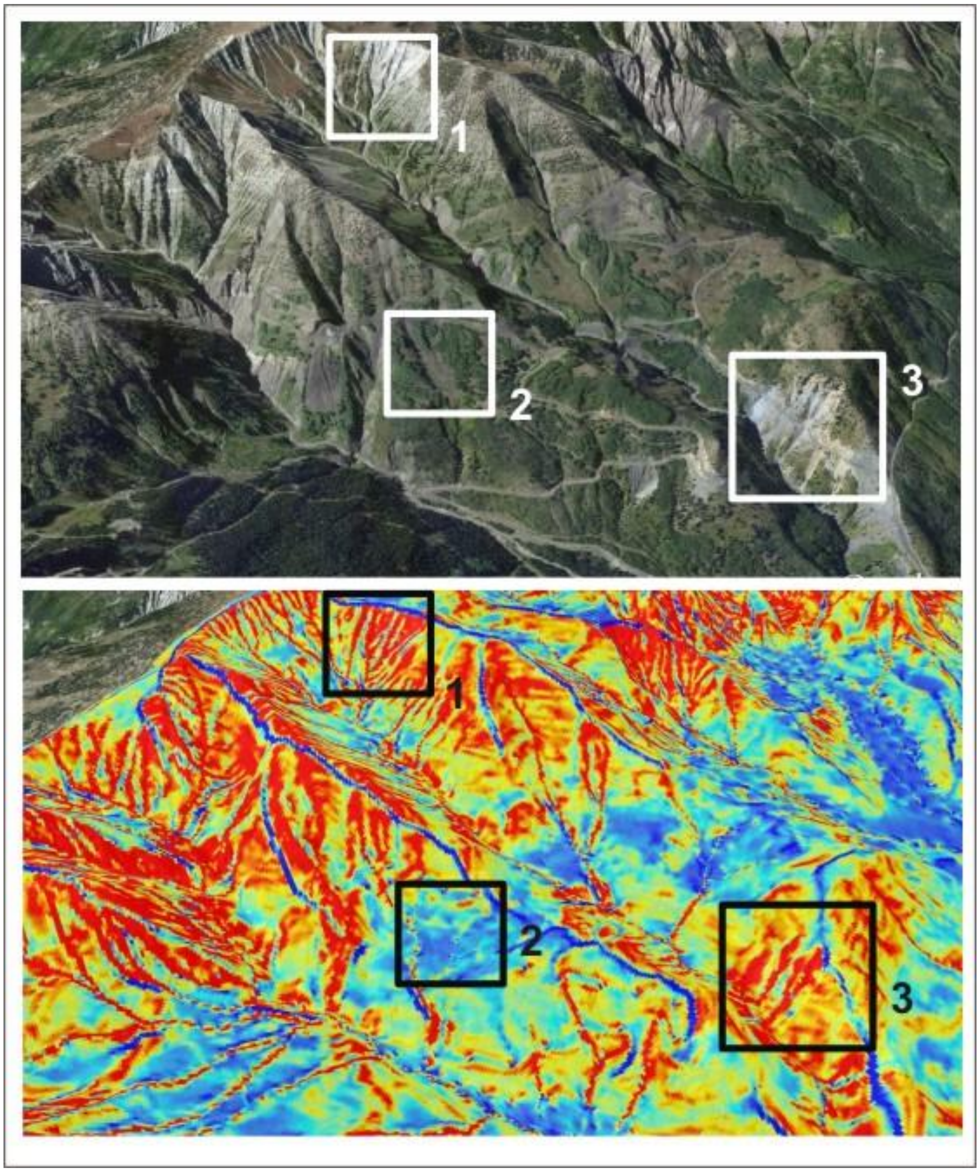

Figure 7. An example of how NetMap's GEP index corresponds to steep, highly dissected and erodible terrain in upper Coal Basin. Boxes 1 and 3 correspond to steep, dissected and erodible terrain. Box 2 highlights an area of low erosion potential (e.g., lower gradient, less dissected).

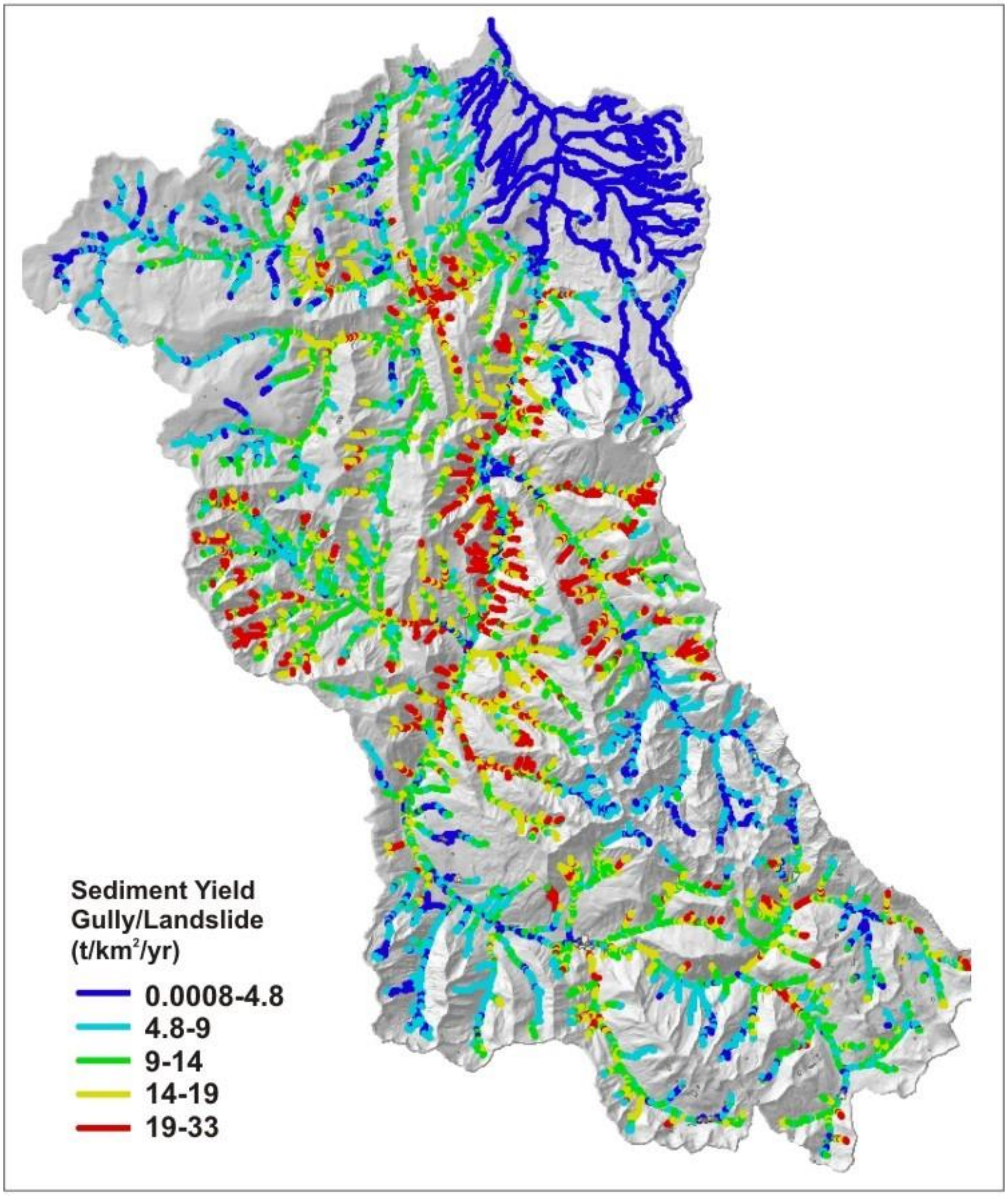

Figure 8. GEP values were converted to sediment yield units in the Crystal River basin. With a basin wide average of 10 t/km^2/yr, predicted values as reflected at the scale of individual drainage wings and 100 m stream segments ranged between less than one and 33 t/km^2/yr.

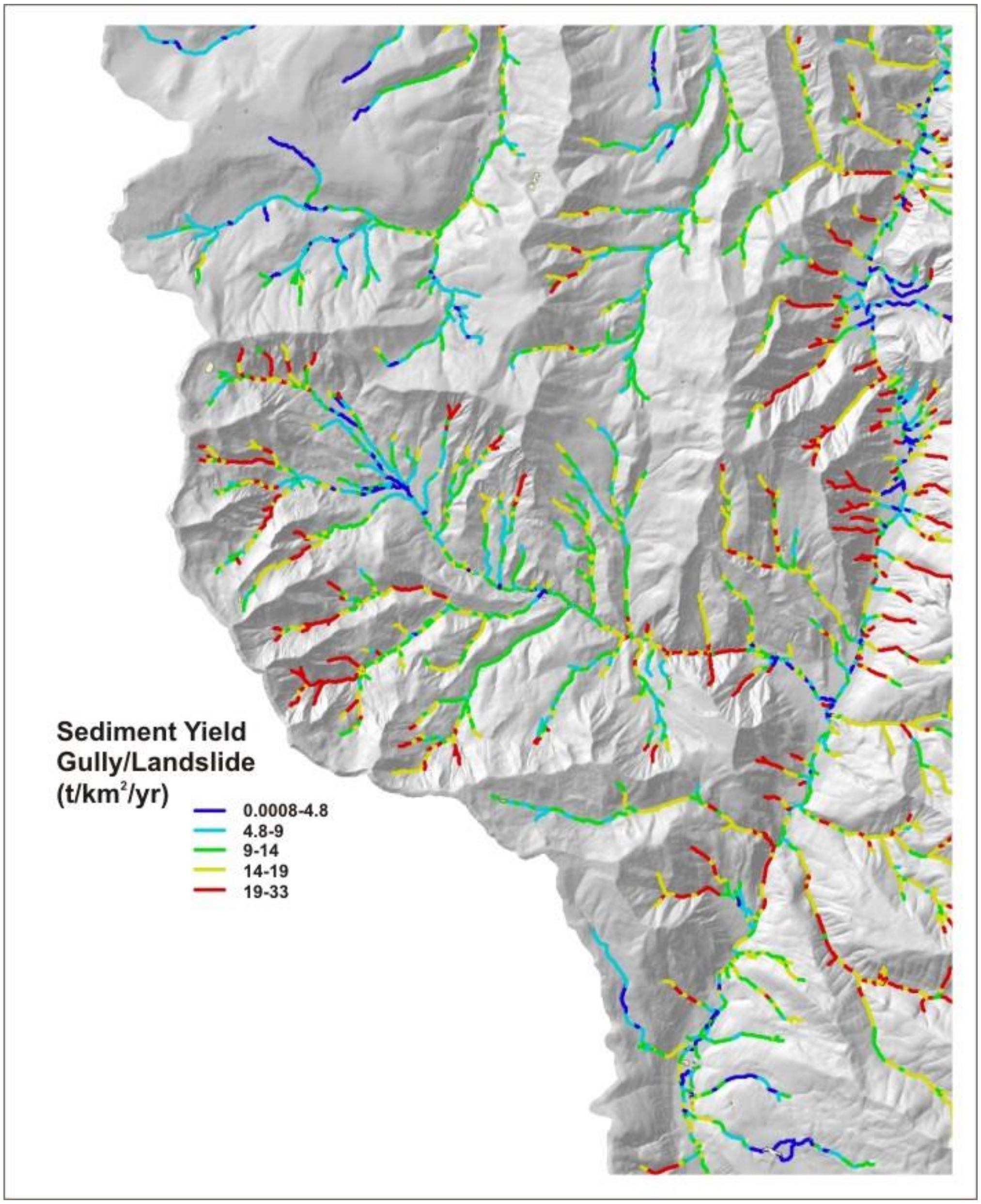

Figure 9. The predicted gully and shallow landslide sediment yield (average), highlighting Coal Basin.

Fine (Suspendable) Sediment: Hillslope and Road Surface Erosion

Hillslope surface erosion and road surface erosion from unpaved roads were predicted in the Crystal River basin. These potential erosion sources are easier to control compared to gully erosion (Figure 7) and, in particular, road surface erosion. The values displayed in the following figures refer to sediment that reaches stream channels, of a size range typical of suspended load (generally < 1-2 mm, sand size and finer).

Hillslope Surface Erosion

Predicting hillslope surface erosion using the WEPP model in NetMap revealed that the majority of the Crystal River basin has low to zero predicted sediment yield (Figure 13). Even within the Coal basin, predicted WEPP surface erosion yields are concentrated in a couple of dozen hillslopes, steep areas with some vegetation. Many of the unvegetated areas in the Crystal River watershed, including in Coal Basin (Figure 14), are predicted to have zero or close to zero erosion because they are classified as bedrock, and thus have no soil to erode.[5] Low values of surface erosion are predicted in areas of low gradient or dense vegetation, including forests, or some combination of these factors.

WEPP predicted surface erosion (annual average) mapped to channels (Figure 15) indicates that surface erosion risk is quite variable across the Crystal River watershed, with the highest surface erosion in areas of Coal Basin and in the lower portion of the Crystal River watershed (Figure 15). In contrast, gully and shallow landslide potential is concentrated in the steeper and highly dissected areas of the erosive rock types located in the central part of the Crystal River watershed, including Coal Basin (Figures 5, 8, 10 and 11).

The channel segment sediment yield values range widely from < 1.0 t/km^2/yr to 46 t/km^2/yr. High values also occur in the upper most areas of Coal Basin (Figure 16). A classification of HUC 12-digit (6th field) basins using mean surface erosion reveals that Coal Basin and the lower basin HUCs have relatively high rates of predicted hillslope surface erosion (Figure 17). Surface erosion summed across the entire Crystal River watershed is approximately 150 t/yr, equivalent to approximately 1 t/km^2/yr (Figure 18).

[5] Both Coal Basin and the Crystal River are highly turbid during rainfall events, indicating that the predicted sediment yield from hillslopes derived from WEPP is likely too low. Though there is no soil to erode, the bedrock shale is easily eroded, contributing high amounts of fine sediment to the channel (Sandra Ryan Burkett—USFS).

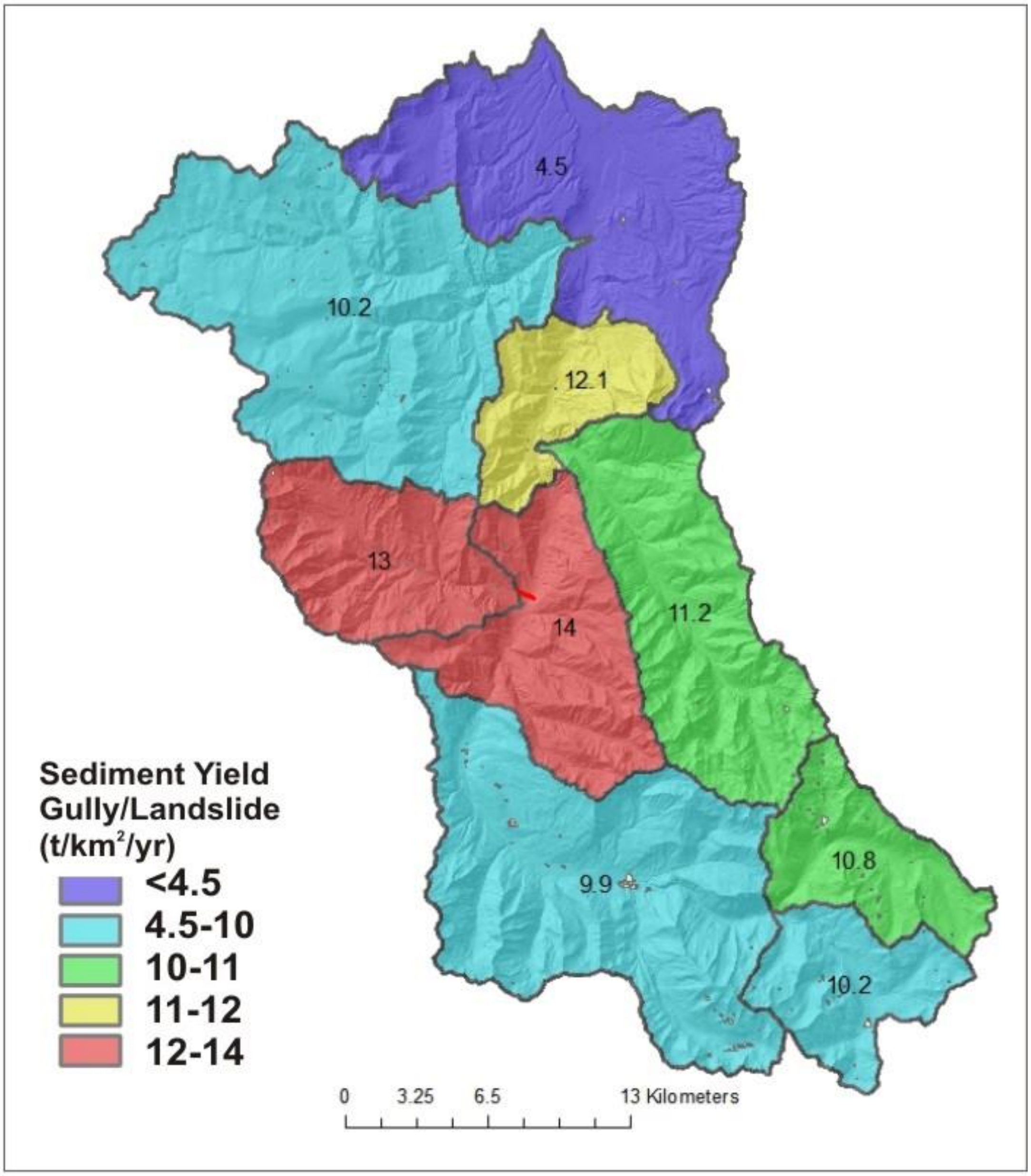

Figure 10. A HUC 12 subbasin classification of average predicted sediment yields reveals that Coal Basin and adjacent areas have the highest values across the Crystal River watershed.

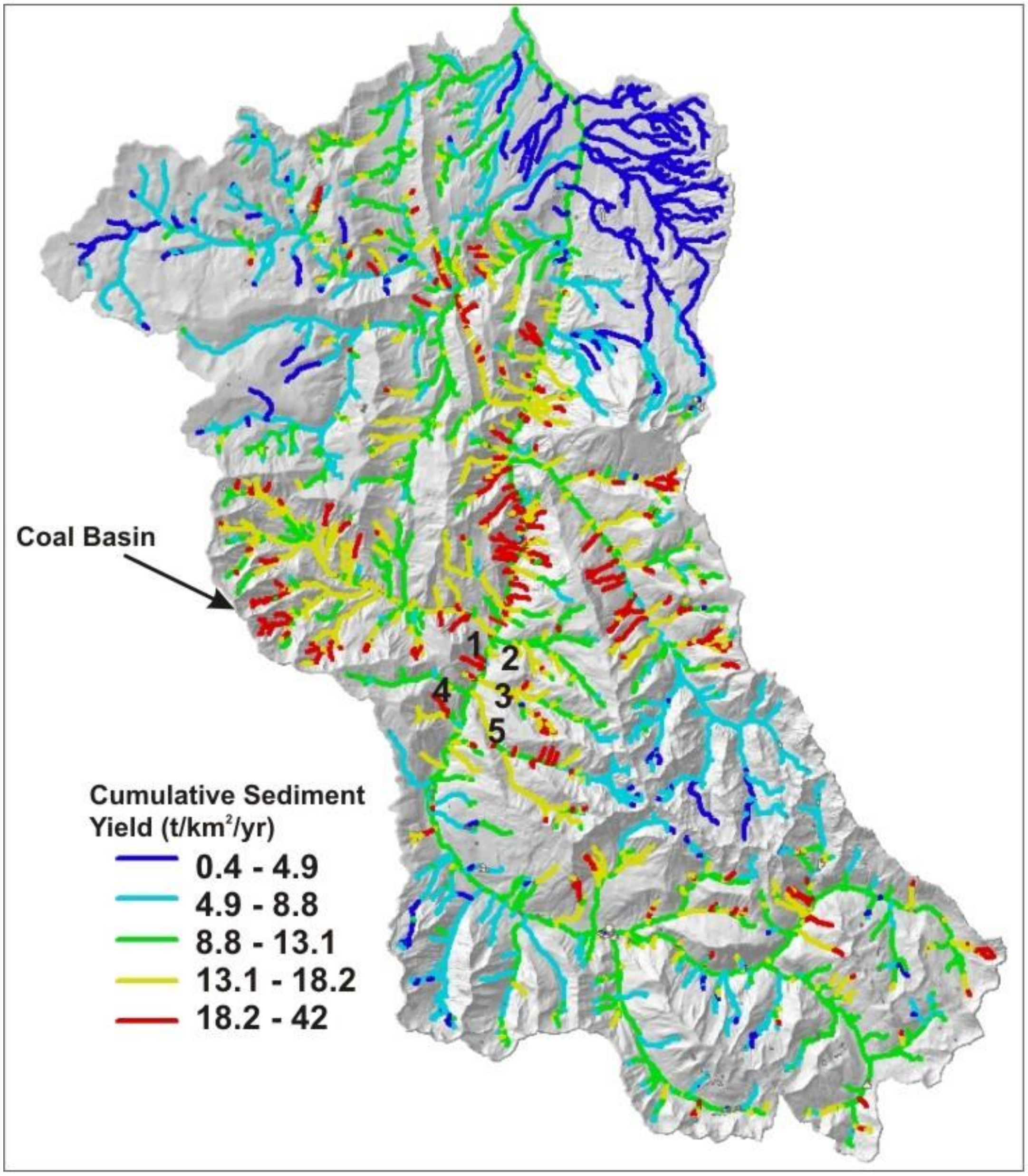

Figure 11. NetMap is used to aggregate the predicted individual hillslope-channel sediment yield values (Figures 8 and 9) downstream, revealing tributary scale patterns. Coal Basin and surrounding areas are predicted to have the highest concentrated erosion potential. Numbers 1-5 correspond to unamed tributary point sources of sediment in Figure 14 (lower panel).

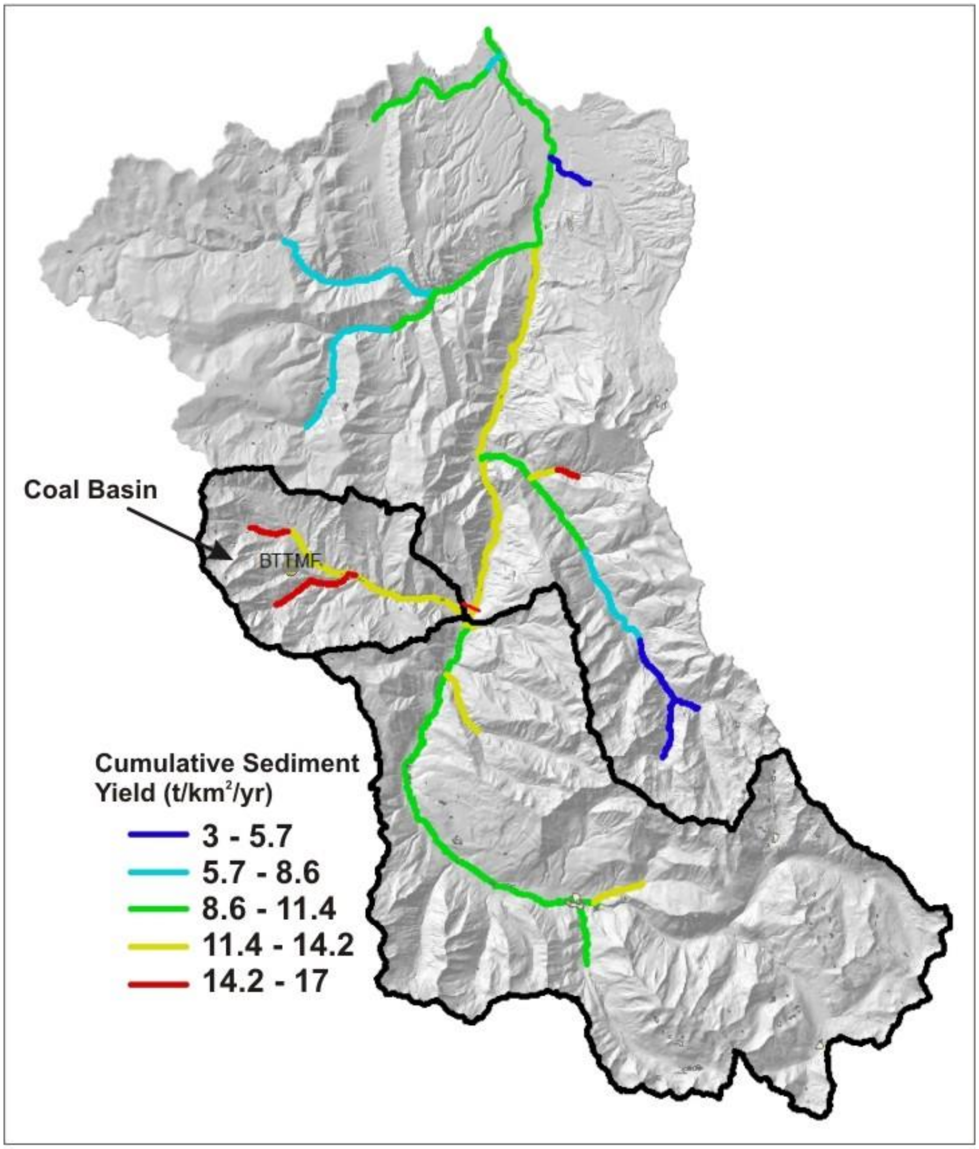

Figure 12. With Strahler (1952) order streams three and lower removed, the pattern of cumulative sediment yields are shown for the larger channels. Coal Basin stands out as a high sediment producer.

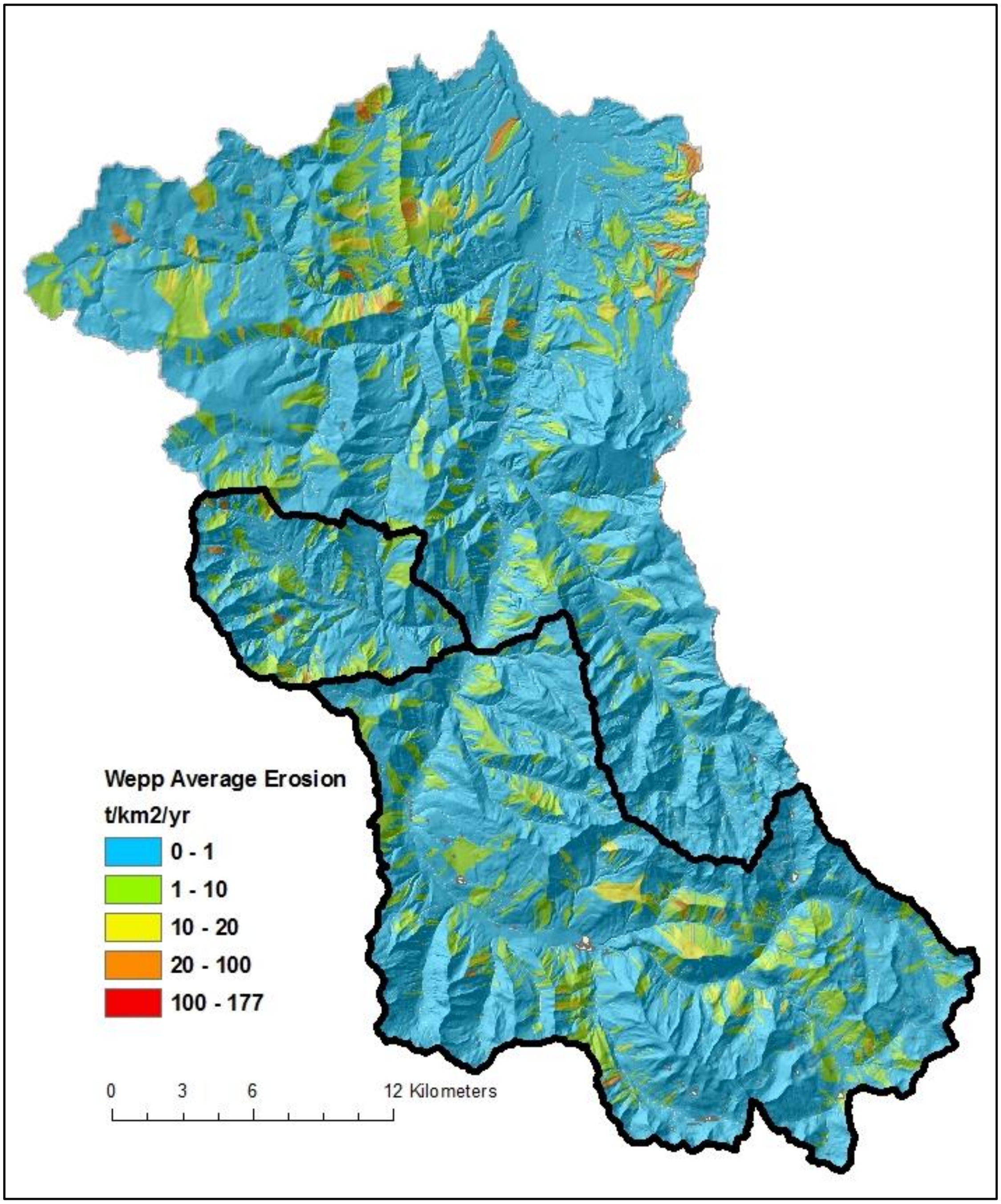

Figure 13. The WEPP model in NetMap is used to calculate the average hillslope erosion rate in t/km^2/yr. Areas of low erosion are typically bare rock, forested or low gradient.

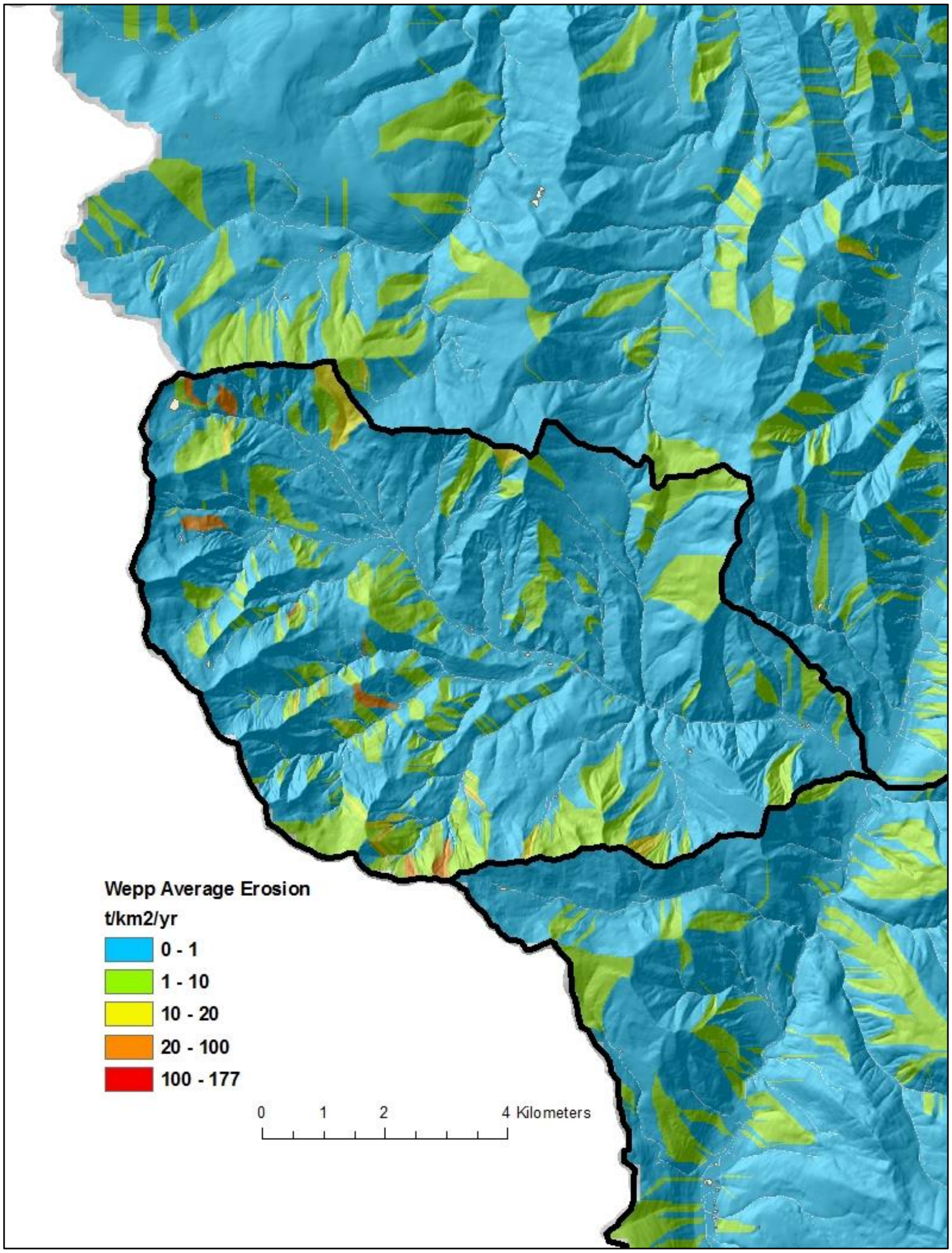

Figure 14. NetMap: WEPP is used to calculate the average hillslope erosion rate in t/km^2/yr. Coal basin is highlighted and it contains several hillslopes with rates above 20 t/km^2/yr.

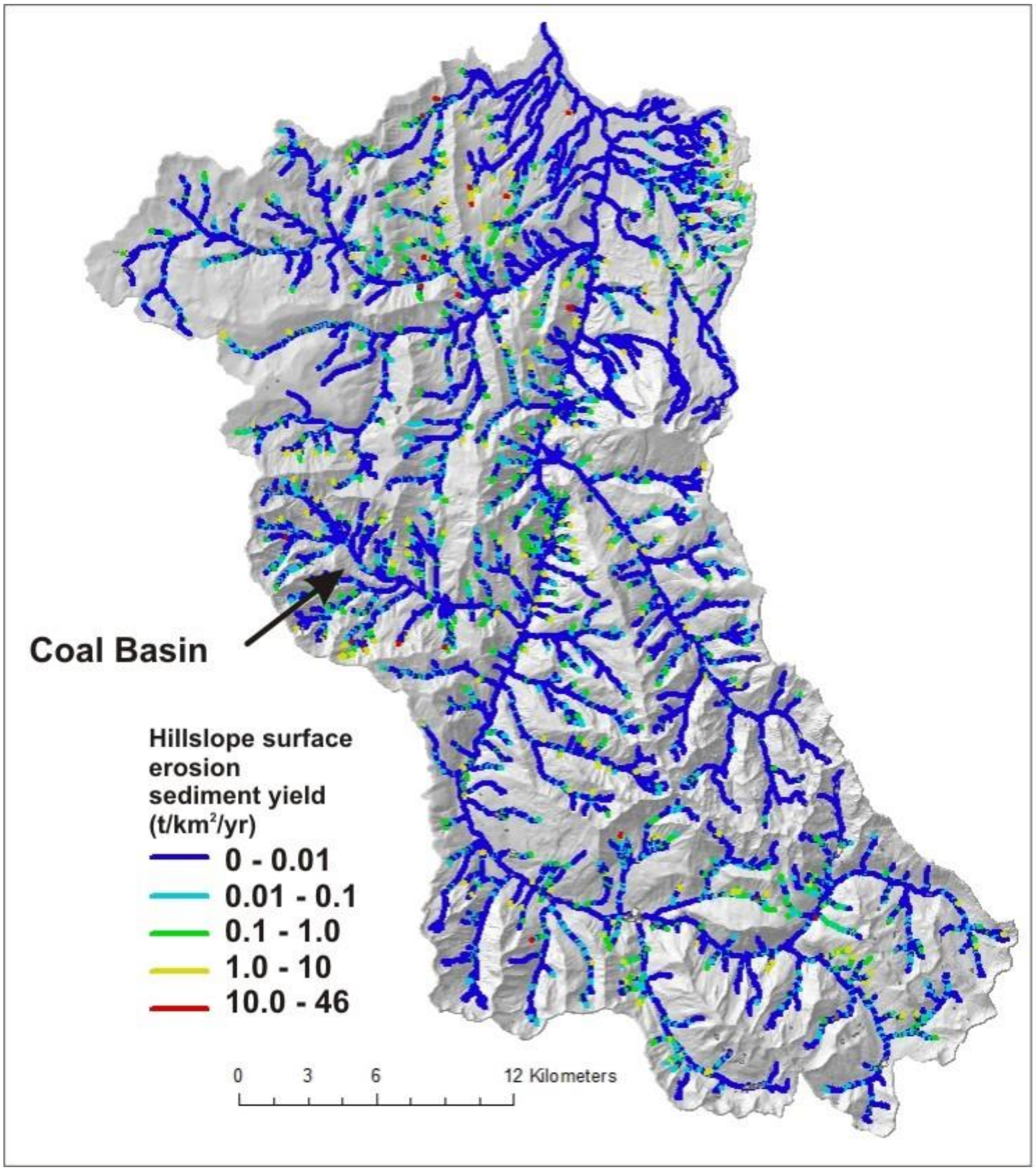

Figure 15. WEPP hillslope erosion is aggregated to channel segments and indicates a wide range of values across the Crystal Basin up to 46 t/km^2/yr.

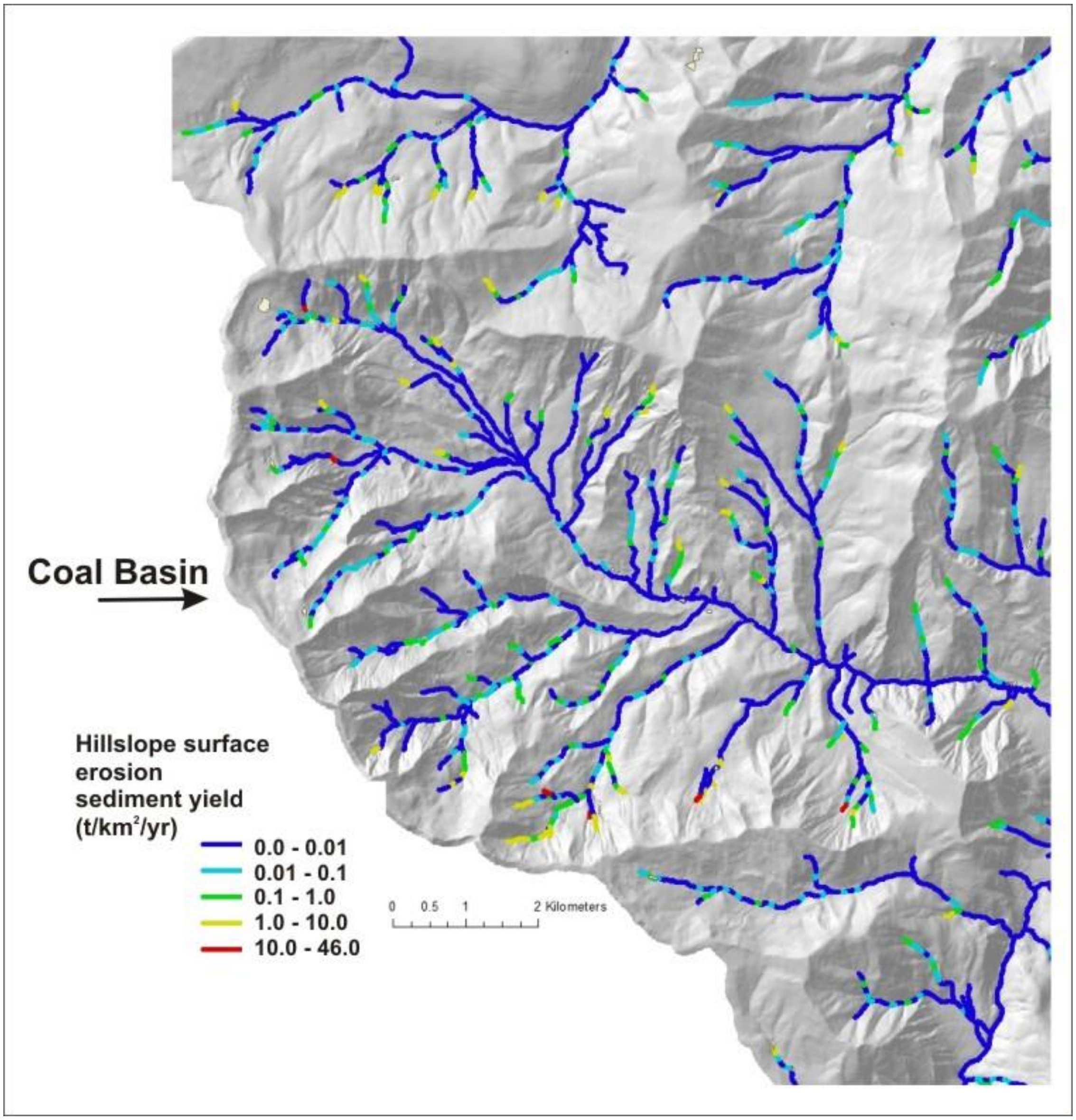

Figure 16. WEPP hillslope erosion is aggregated to channel segments. Coal basin contains several stream segments where aggregated sediment rates are above 10 $t/km^2/yr$.

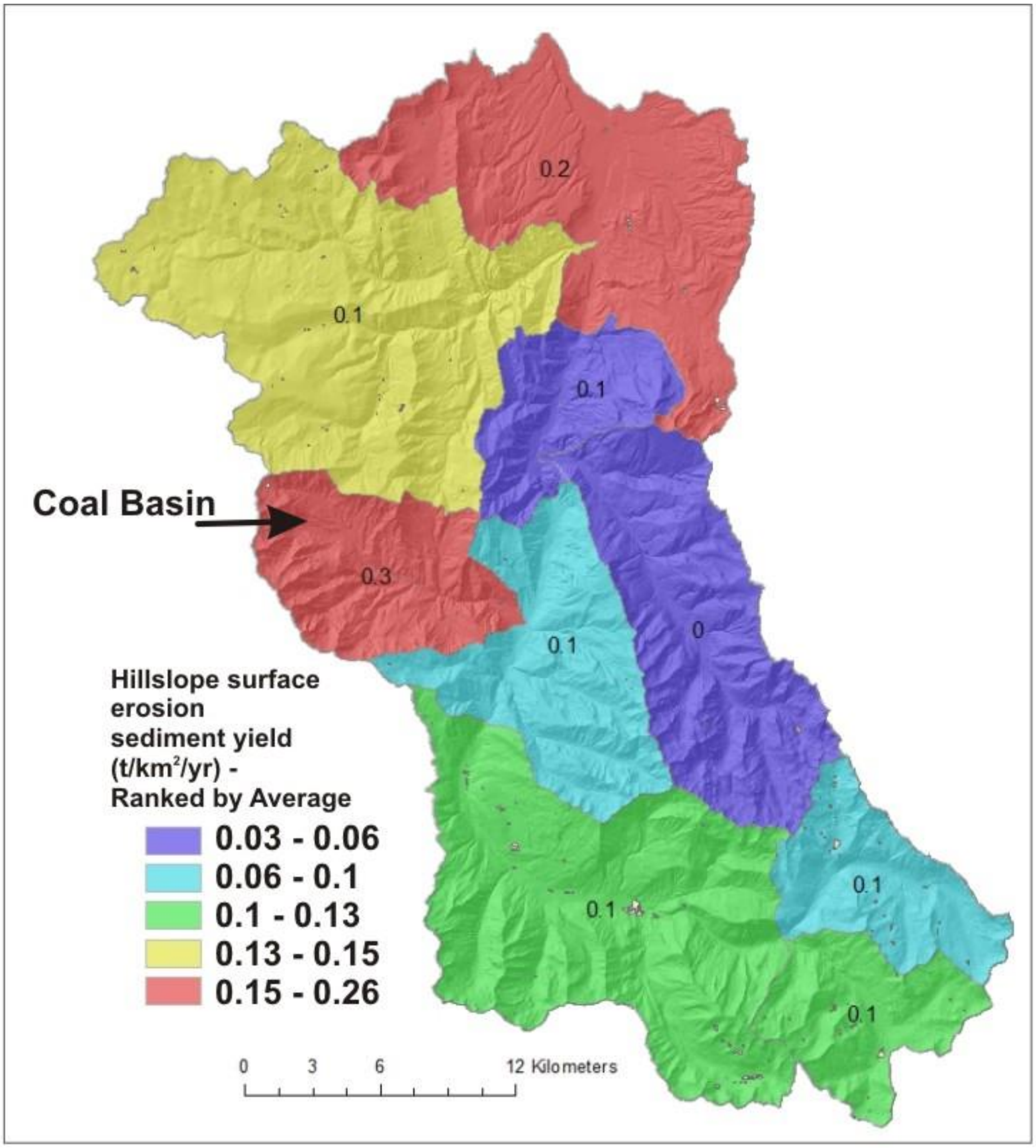

Figure 17. Average subbasin hillslope sediment yield (t/km^2/yr) of the Crystal Basin by HUC 12s. Predictions show that Coal basin produces the highest sediment yield at 0.3 t/km^2/yr.

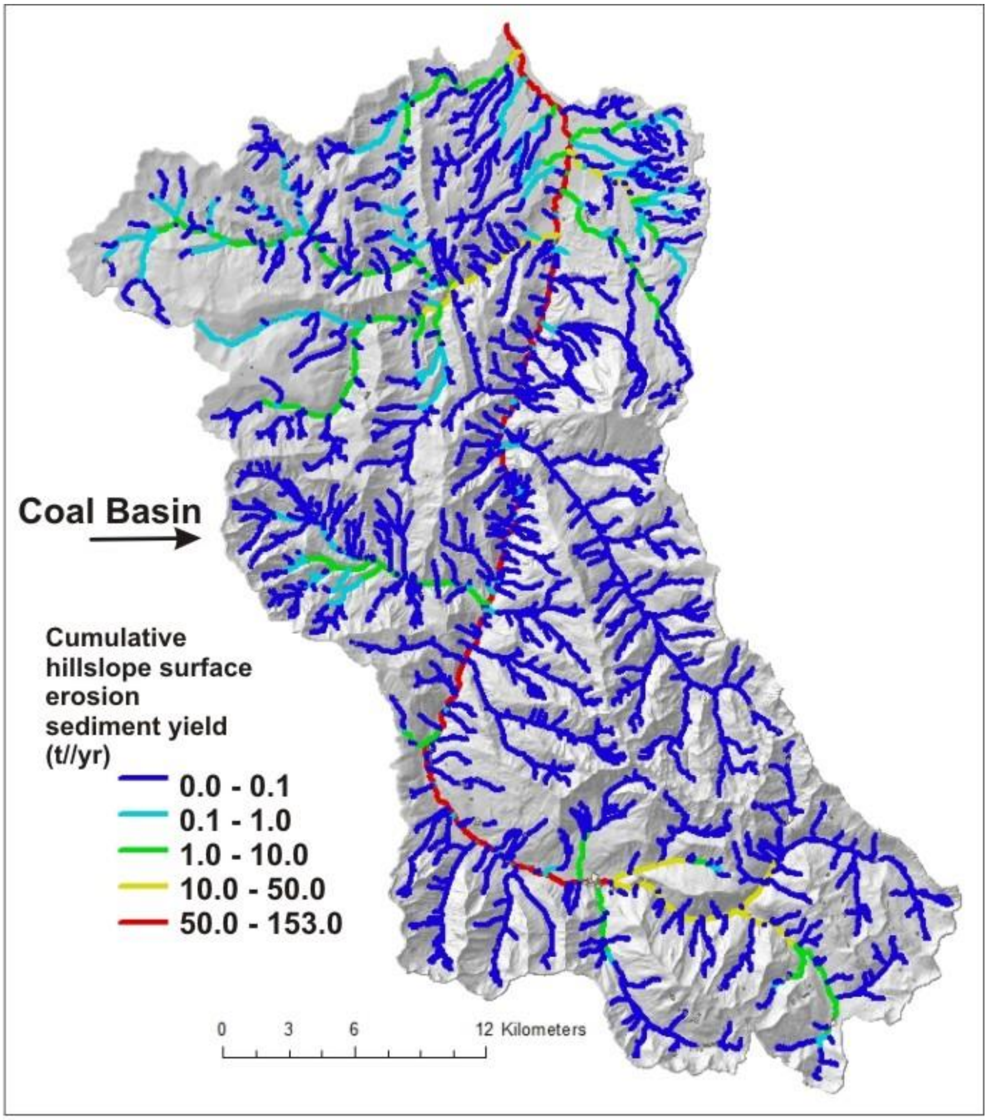

Figure 18. WEPP hillslope erosion aggregated to channels and accumulated downstream indicating that the entire Crystal basin produces about 153 t/yr or about 1 t/km^2/yr and sediment accumulation is high all along the mainstem Crystal River.

Road Surface Erosion

Road surface erosion is generally considered a controllable source of fine sediment to streams and rivers. Important factors in the WEPP model are road segment length (hydrologically connected), road gradient, climate, road surface type, road width, road traffic level, soils, and distance of the road segment to the stream. Road input parameters (including the US Forest Service road layer) were provided by Jane Frambach (US Forest Service) including data on extra wide road widths in Coal Basin. WEPP: Road used the same CLIGEN climate stations that were used for hillslope erosion (Crested Butte, Glenwood Springs, CO). NetMap predicts road segment length and slope based on the alignment of the road layer on the DEM and determines road high and low points (e.g., drain points), as well as all road-stream crossings. In NetMap's digital landscape, the distance between all road segments and the stream segments they drain into are used in the WEPP calculation of surface erosion.

The WEPP road surface erosion model used in NetMap predicted a wide range of road surface erosion rates for each road segment (t/yr) (Figure 19). The highest values > 0.1 t/yr occur in the steepest parts of the Crystal River watershed, including in Coal Basin (Figure 20). The lowest predicted road erosion rates occur along valley bottoms. Paved roads will have zero surface erosion (not including ditches alongside).

A basin classification of average road erosion rates (Figure 21) reveals the highest average rates occur in the southeastern most set of HUC 6 basins due to the highest erosion values in the few road segments located there. Predicted road surface erosion was also mapped to streams in NetMap (Figure 22) revealing spatial patterns in the channel network.

Channel Sedimentation in the Redstone, Colorado Area

Another study objective is to determine the relationship between spatial patterns of erosion potential in the Crystal River, and in Coal Basin in particular, and the channel sedimentation in the vicinity of the community of Redstone, Colorado. Redstone (population 130) is located immediately downstream of the Coal Basin confluence (Figure 1).

A longitudinal profile along the Crystal River mainstem reveals a relatively linear elevation gradient between River Kilometer (RK) 1 and 50 with an abrupt steepening in the river's headwaters (RK 50 to 70). There are several elevation perturbations in the lower section with one of them located just downstream of the Coal Basin confluence at about RK30 (Figure 23).

The elevation perturbation near the Coal Basin confluence reveals a distinct bulge in the longitudinal profile approximately 5 km long and about 60 m thick at its deepest (Figure 24, top panel). Bulges in channel longitudinal profiles are often caused by sediment wedges, or standing waves of sediment, linked to tributaries with high sediment loads (Benda and Dunne 1997, Benda 2008). The standing wave of sediment located below Coal Creek is also located immediately downstream of four other major sediment producing tributaries, all within four river kilometers of Redstone (Figure 24, bottom panel). Locations of all five unnamed tributaries are also shown in Figure 11.

An approximate 2-km long canyon located between RK 23 and 25 may be altering the river longitudinal profile, creating a steeper elevation gradient (Figure 25). Using the alternate profile, the sediment wedge or standing wave of sediment just downstream of Coal Basin remains evident. With the alternate profile, the sediment wedge is approximately 4 km long and 30 m deep. The slope gradient on the sediment wedge is considerably less than either long profile (approximately 0.1 to 1.5% on the wedge compared to twice that steep upstream and downstream of it). The lower gradient of the sediment wedge is likely enhancing sediment storage in that area.

The Crystal River located on the 4 to 5 km sediment wedge located immediately downstream of Coal Basin is characterized by braiding and large gravel bars (Figure 26). This is characteristic of fluvial river forms in areas of low gradient and high sediment supply, as evidenced by plots of river elevation and cumulative sediment supply (Figures 24 and 25). The sediment wedge effectively fills the valley floor with sediment, creating a low relief environment between the channel and the adjacent valley floor. This is apparent in a comparison of valley floor cross sections on the wedge (in Redstone) and upstream and downstream of it (Figure 27). The cross sections reveal that in the vicinity of the sediment wedge the change in elevation between the relatively flat valley floor and the Crystal River is relatively small (< 4 m) and thus these areas are prone to flooding. Upstream and downstream, the elevation difference between the channel and valley floor is considerably greater. The pattern of local valley widening is also evident using NetMap's floodplain mapping tool (Figure 28).

In addition to the zone of high sediment supply and the sediment bulge between RK 31 and 25, there is an overall higher predicted sediment supply that extends downstream from that area to RK 10. Hence, the zone of higher sediment supply, and potentially greater sediment storage along the mainstem Crystal River, may extend over this longer length of channel. This may have consequences for flooding potential and also for water extraction since larger sediment stores would create larger opportunities for inter-gravel flow (hyporheic flow) and thus less available surface flow.

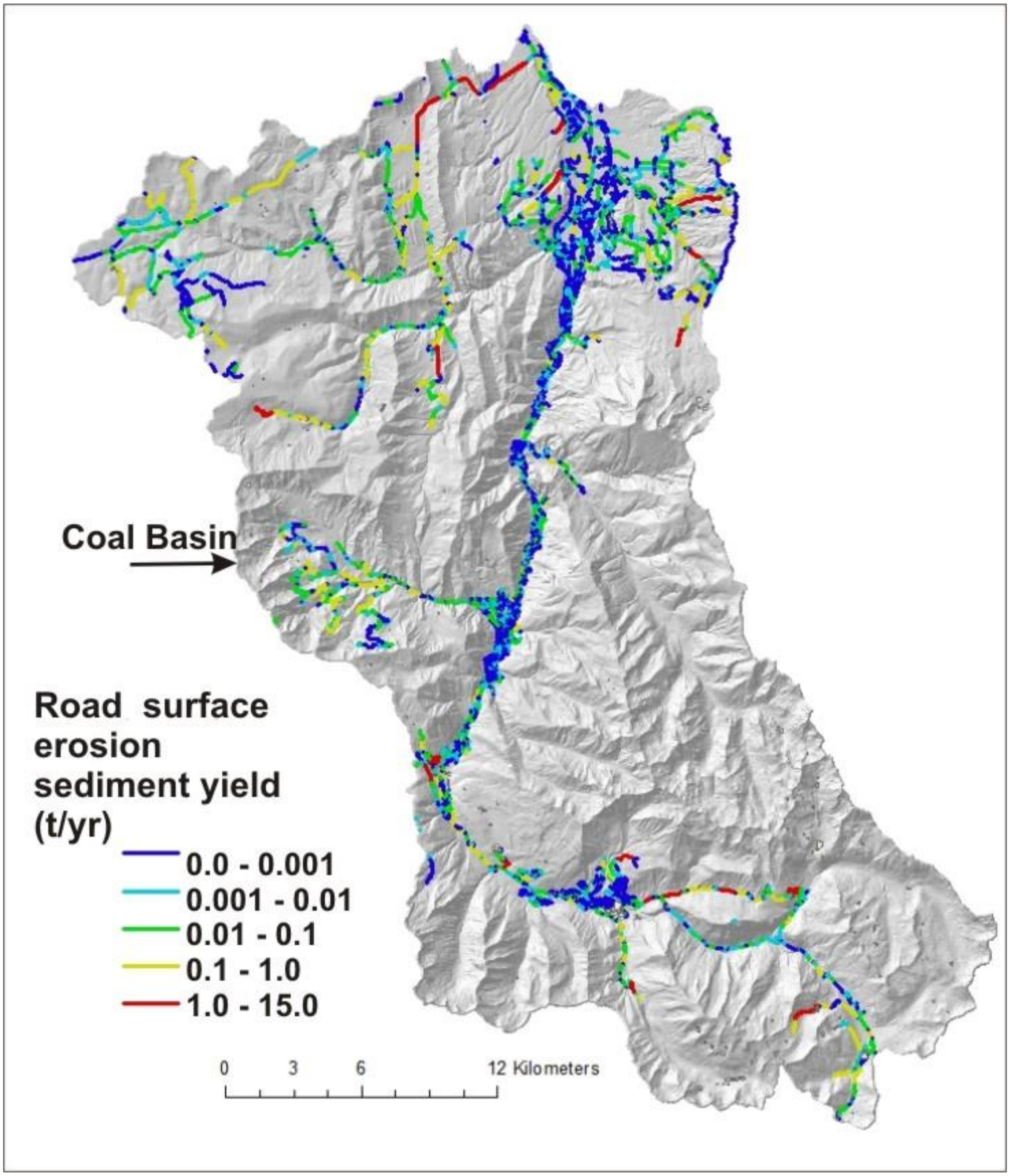

Figure 19. NetMap WEPP: Road was used to calculate road surface erosion per road segment. Higher erosion rates correspond to steeper terrain in the Crystal River basin.

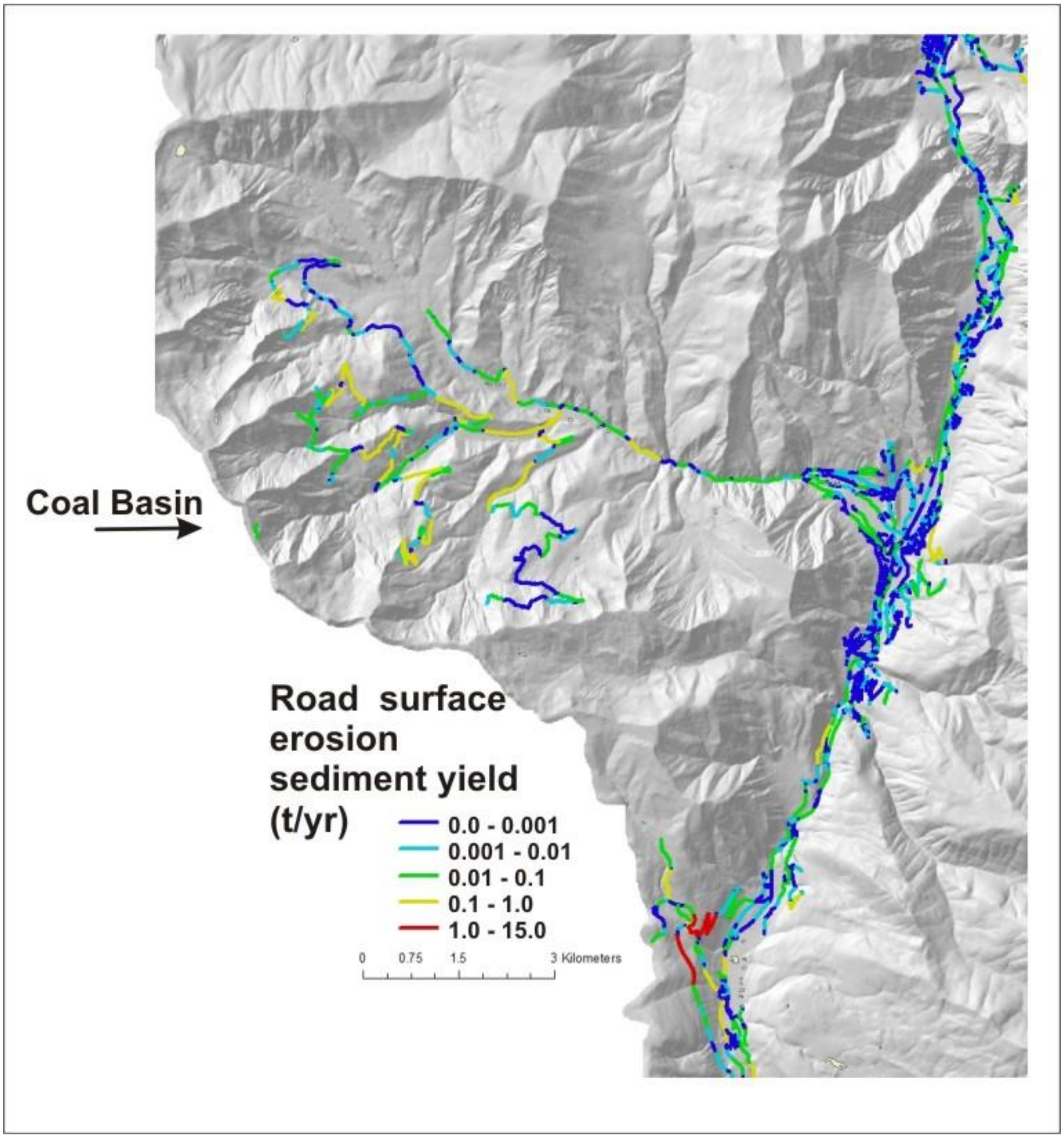

Figure 20. NetMap WEPP: Road was used to calculate road surface erosion per road segment. The focus is on Coal basin within the Crystal River basin where several road segments yield above 0.1 t/yr.

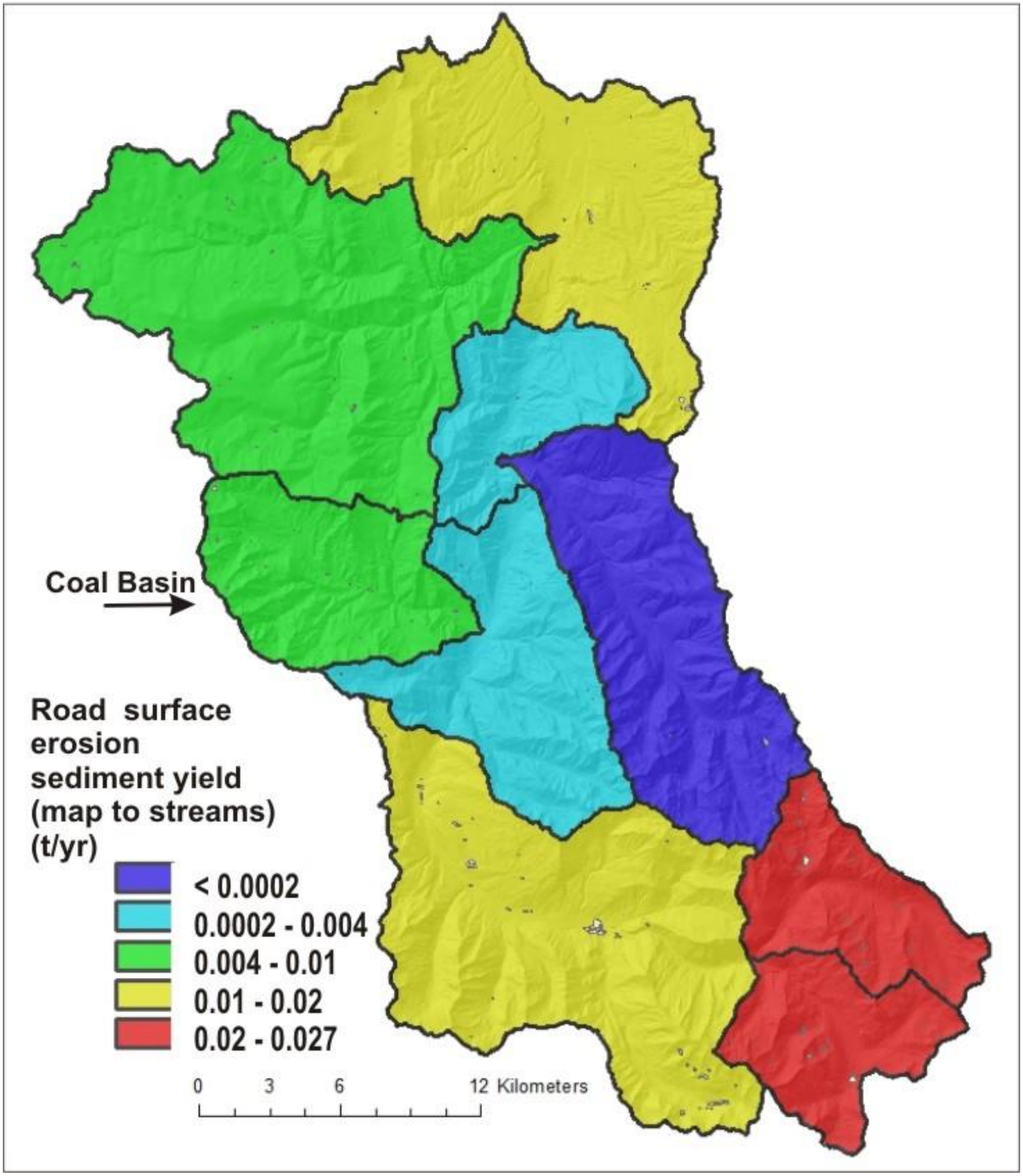

Figure 21. A HUC 12 basin classification of predicted and basin-averaged road surface erosion rates reveal that the southeast subbasins – the North Fork and South Fork Crystal River subbasins - have the highest average road erosion values across the Crystal River watershed.

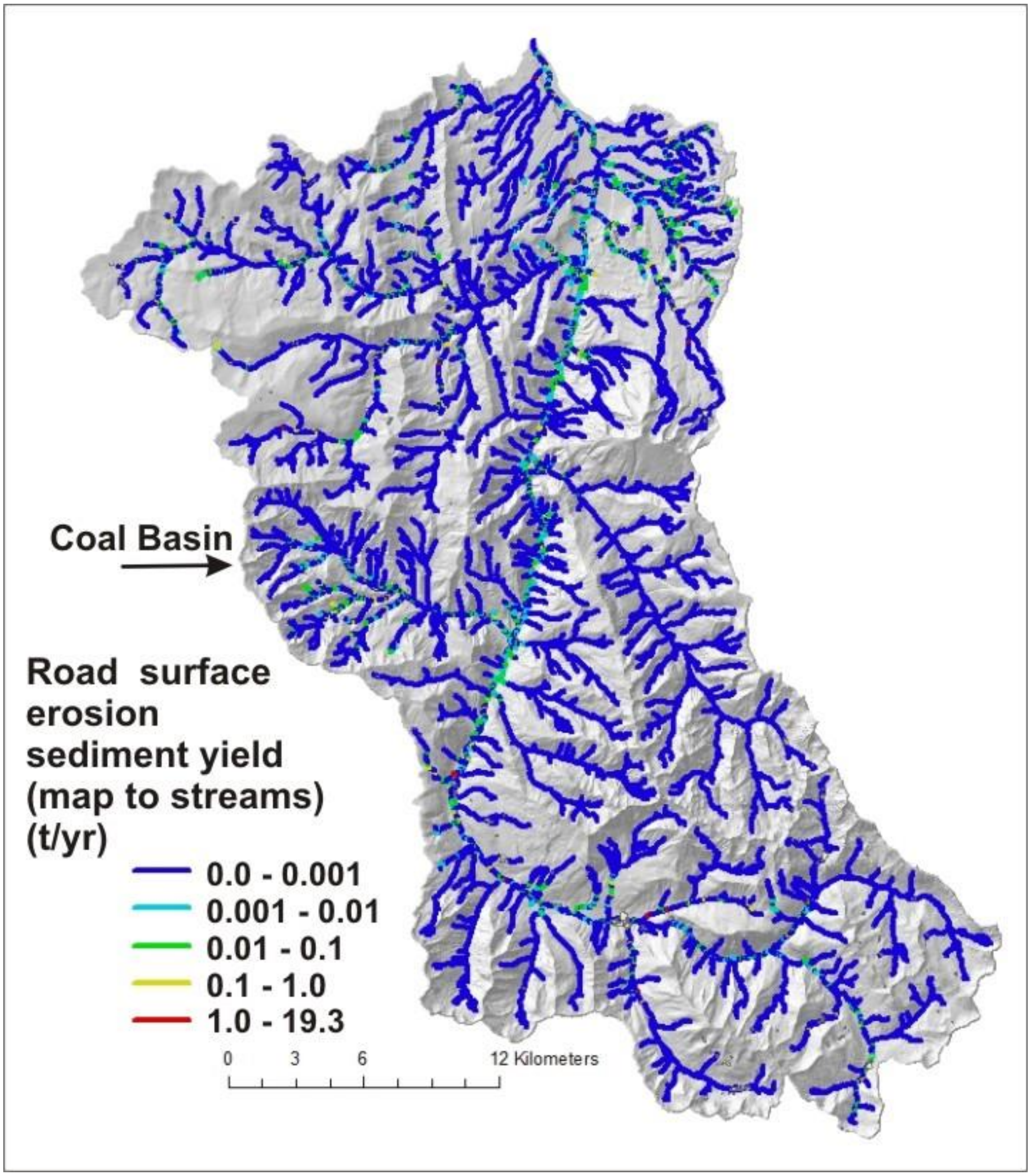

Figure 22. NetMap WEPP: Road predicted road surface erosion mapped to channel segments. The sediment yields range broadly from less than 0.001 t/yr with a few hotspots of up to 19 t/yr.

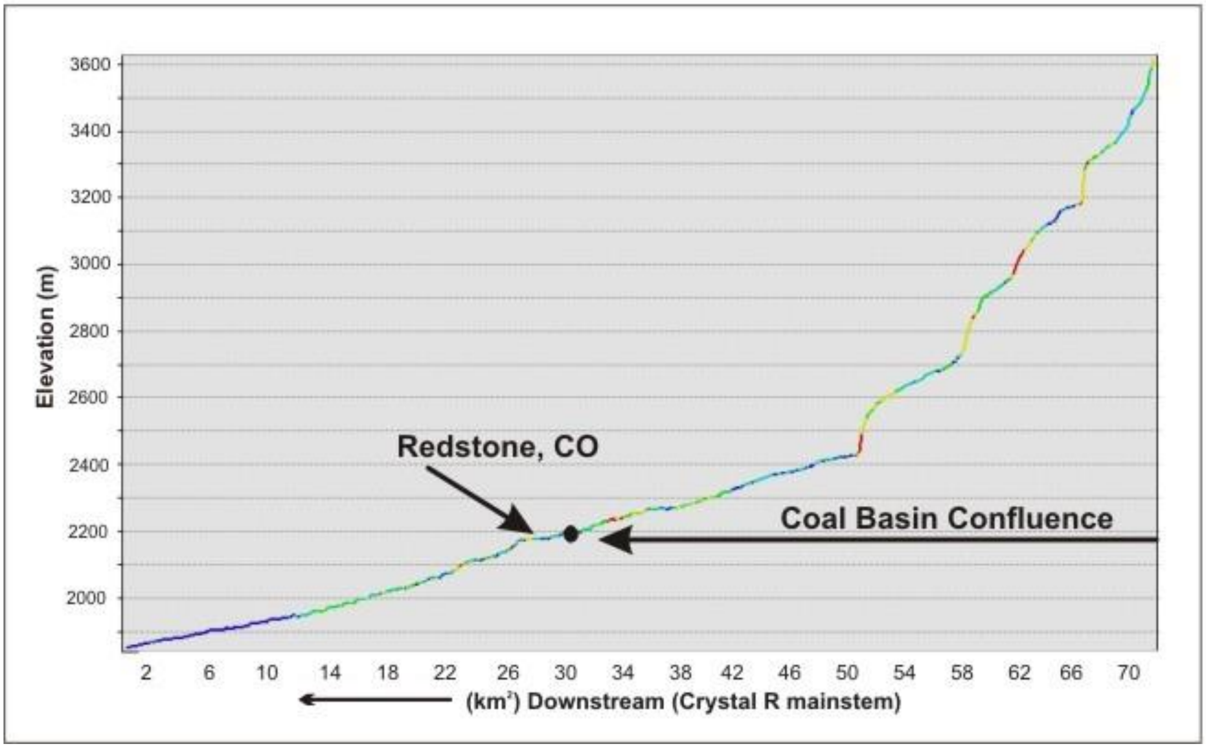

Figure 23. A longitudinal profile along the Crystal River mainstem reveals a relatively linear elevation gradient to River Kilometer (RK) 50 with profile steepening occurring upstream. There are several elevation perturbations in the lower section with one of them located just downstream of the Coal Basin confluence.

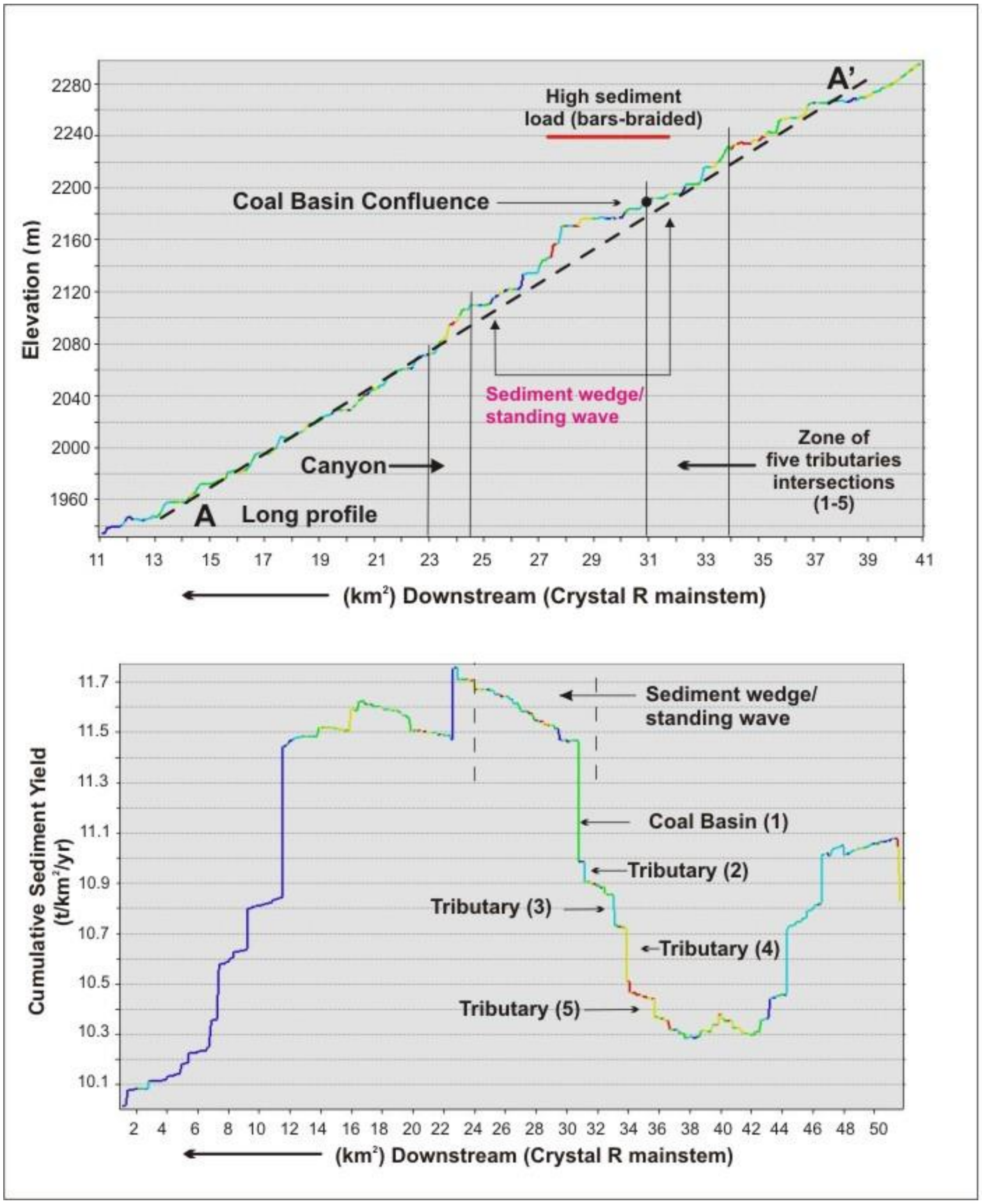

Figure 24. Upper panel-River elevations A-A' reveals a large bulge in the profile between River Kilometer 25 and 31. The bulge is approximately 5 km long and 60 m thick at its deepest point. The budge or hypothesized standing wave of sediment occurs immediately downstream of Coal Basin and also within 4 river kilometers of four other high sediment producing tributaries (unnamed tributaries numbered in Figure 11). Lower panel-A longitudinal plot of cumulative sediment yield (Figures 11 and 12) reveal how the predicted sediment yield abruptly increases from RK34 through RK 31 (Coal Basin) associated with five intersecting tributaries. The length of the horizontal step in the plot scales with the magnitude of the tributary's input of sediment (in terms of annual sediment yield, t/km^2/yr).

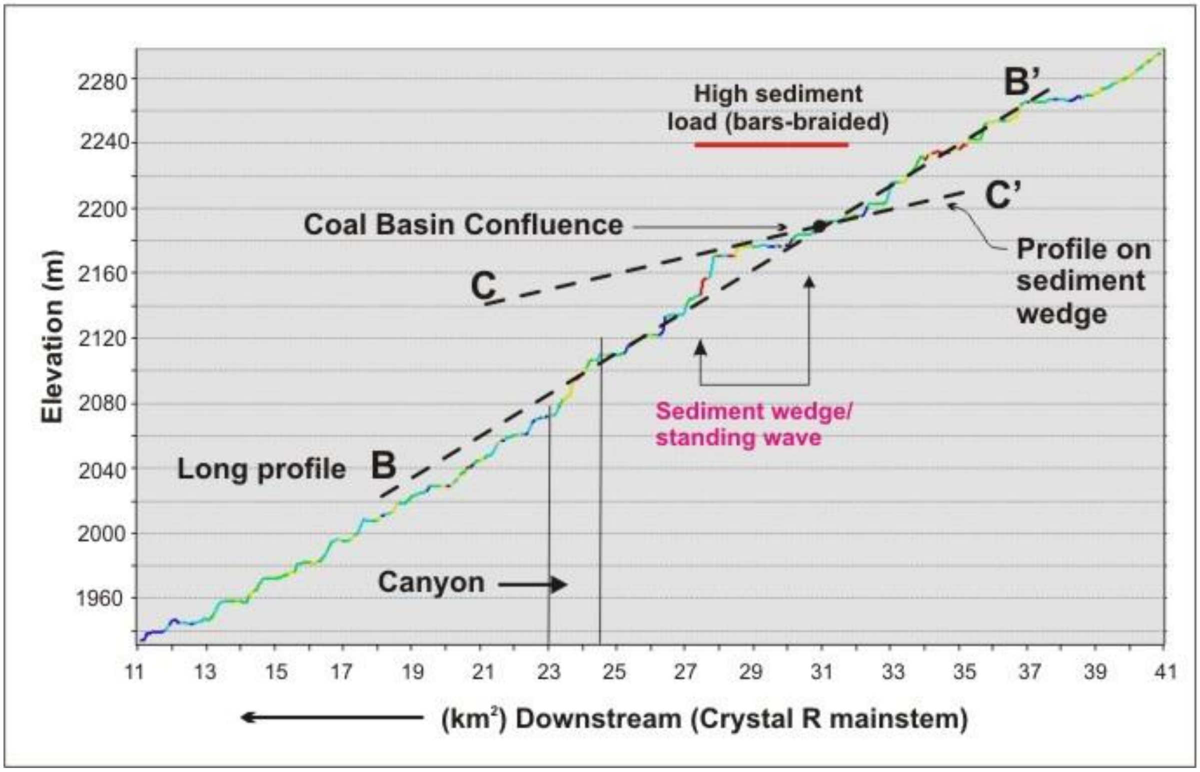

Figure 25. A canyon located between approximately RK 23 and 25 may be influencing the river long profile upstream of it. An alternate profile (B-B') still reveals a sediment wedge between approximately RK 28 and 31; the sediment wedge is approximately 4 km long and 30 deep. The lower gradient on the sediment wedge (C-C'), compared to river reaches upstream and downstream, would enhance sediment deposition in the standing wave of sediment.

Figure 26. The approximate area of the sediment wedge that corresponds to Figure 24 is illustrated. The low gradient channel is characterized by large gravel bars and braiding, fluvial forms indicative of high sediment supply and sediment storage.

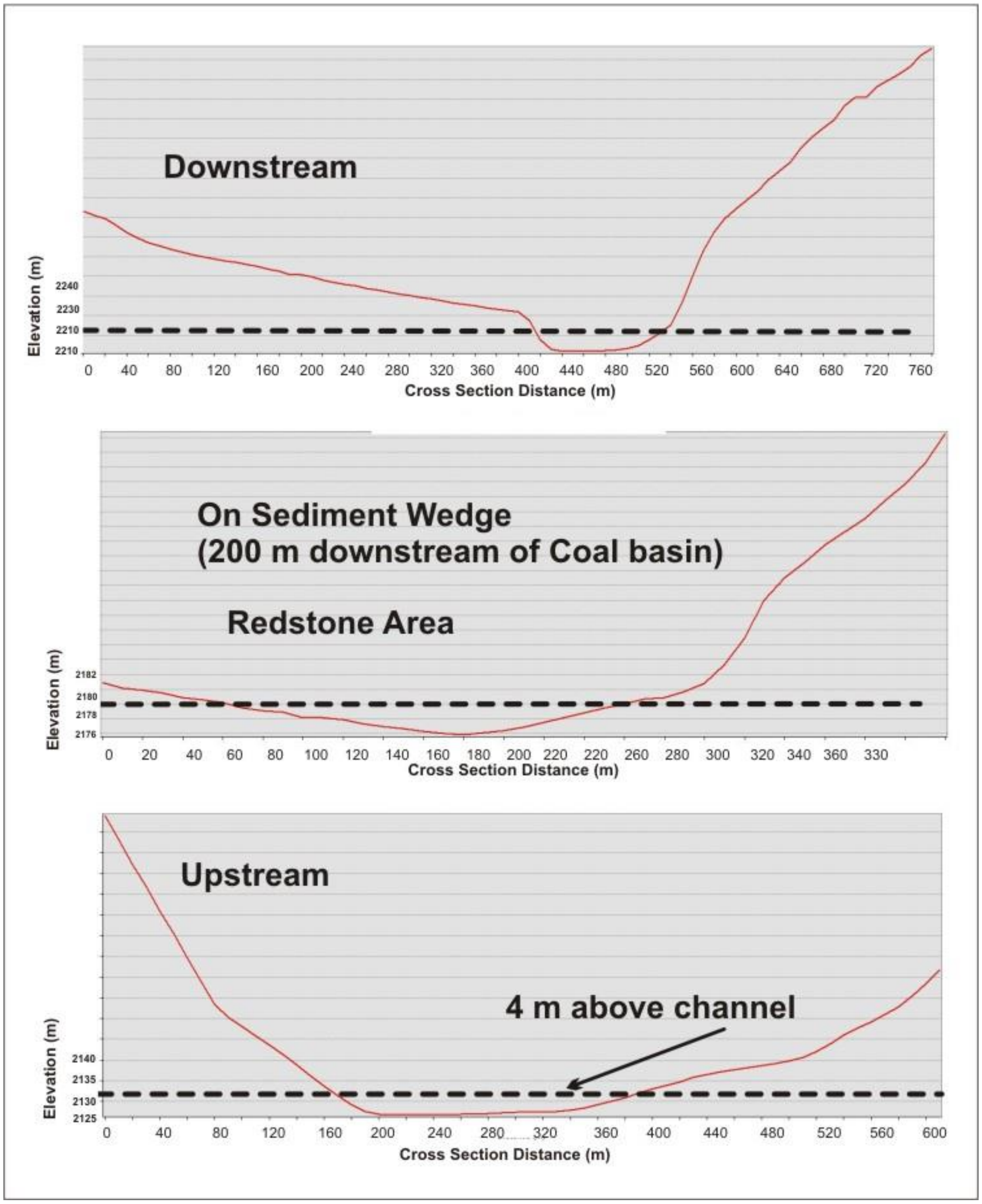

Figure 27. Valley floor cross sections on the sediment wedge downstream of Coal Basin (in the vicinity of Redstone) and upstream and downstream of the wedge reveal very different patterns of relief. On the sediment wedge (middle), the change in elevation between the channel and adjacent valley floors is minimal (< 2 to 5 m). In comparison, the change in elevation between channels and valley floors both upstream and downstream (lower and upper panels) is considerably greater. The low relief on the wedge would promote over bank flooding in the area of Redstone.

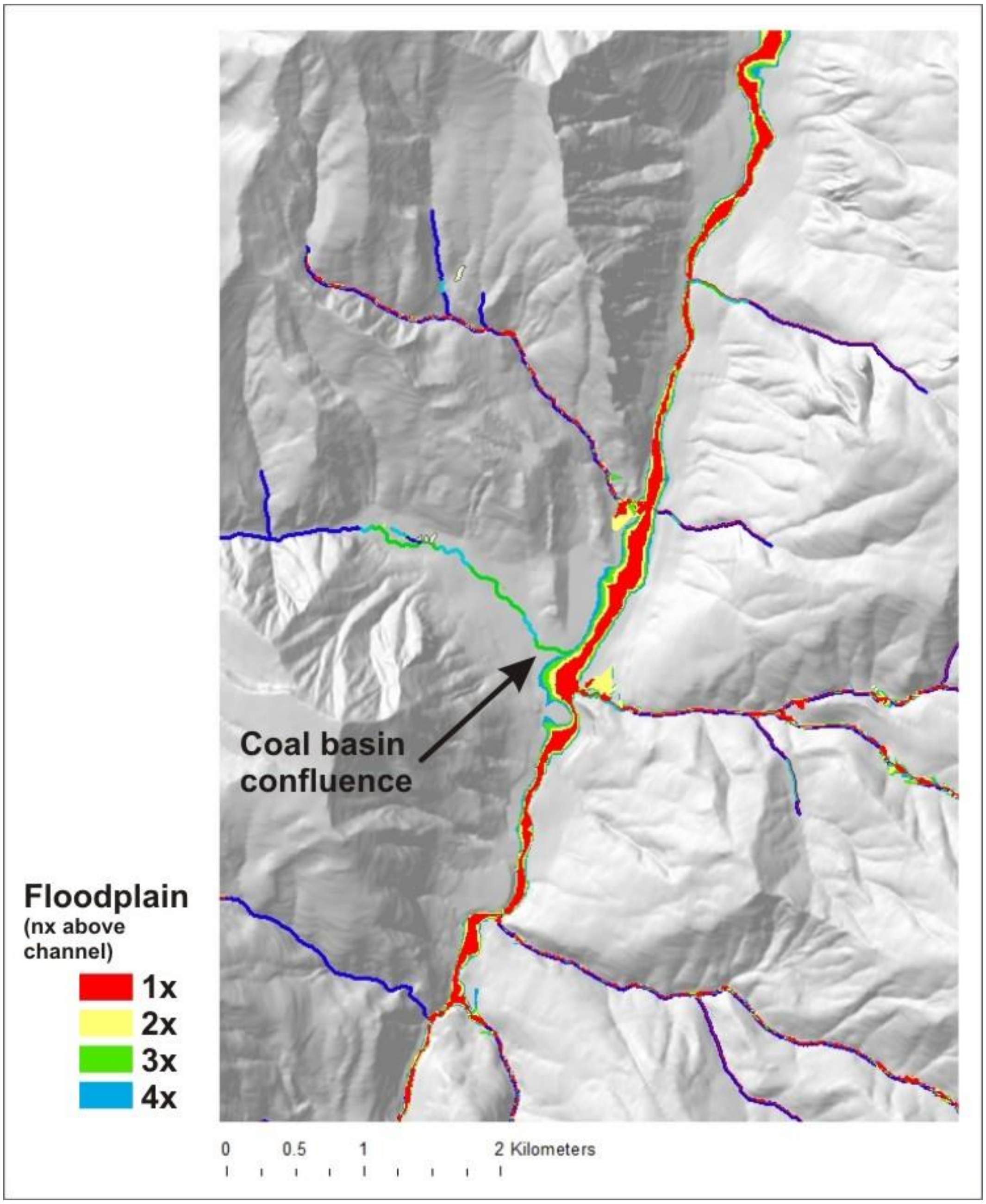

Figure 28. NetMap's floodplain tool was used to map floodplains and terraces at varying elevations above the channel. 1X through 4X corresponds to one multiple through 4 multiples of bank full depth above the channel. Hence, 1X and 2X likely represents the zone of floodplains that are frequently inundated during floods (e.g., once every one or two years). 3X and 4X likely represent terraces that are infrequently inundated by flood waters.

Controllable Sources of Sediment in Coal Basin

An additional study objective is to determine what proportion of sediment supply to the Crystal River, specifically from Coal Basin, is controllable by reclamation or restoration techniques. Using Google Earth, areas of obvious land use disturbance (mining and roads related) were mapped (Figure 29) and polygons created (Figure 30). [Road related surface erosion is calculated using another method, see below.] For this analysis, we assume that erosion on disturbed areas (bare ground) in mining areas and on slopes below and above roads are controllable to some extent.

The sum of the GEP index (Figure 6, right panel) encompassed by both the mining and road disturbed areas (polygons, Figure 30) were tallied and compared to the total summed GEP over the entire Coal Basin. The mining areas encompassed 1.7% of the Coal Basin GEP index and the road related areas encompassed 0.3%. In other words, approximately 98% of the coarse sediment supply to channels originating from gully and shallow landslide landforms in Coal Basin are not associated with human activities (past or present) and cannot be practicably controlled. Note that most of the mining areas have already received some type of erosion control (e.g., Figure 29, lower panel).

The 2% estimate of controllable erosion sources of coarse sediment supply contains errors of approximation. First, the GEP analysis omits the role of vegetation in controlling erosion because only the effects of variations of lithology on erosion was considered (e.g., GEP values on hillslopes with the same gradient and curvature are the same whether a slope is vegetated or not). Hillslopes not vegetated should have a higher erosion rate. The majority of controllable sources of erosion, particularly those associated with roads, are unvegetated. Second, most of the mining areas have received some type of erosion control, and many of these areas are revegetated to some extent, or some areas are contoured to reduce erosion. Third, there are other, smaller disturbed areas that were not mapped. Fourth, erosion control will not be 100% effective, particularly on steep, dissected and unvegetated portions of hillslopes associated with roads (e.g., Figure 29, upper panel). All of these approximations will lead to errors in estimating the proportion of sediment that is controllable. But given all the available information, the controllable sources of sediment probably do not exceed 10% of the total sediment sources in Coal Basin.

In addition, the sediment wedge downstream of Coal Basin in the vicinity of Redstone (RK 31-26) is likely being supplied from areas of upstream of the Coal Basin confluences from the closely spaced set of 4 tributaries (Figures 24-25). Thus, consideration of controllable sources of sediment, if the target was reducing sediment supply to the mainstem Crystal River in the vicinity of Redstone, would need to consider these other sources. In that case, controllable sources of sediment may diminish to 1% or less.

If an objective was protecting Redstone from flooding because of the enhanced sedimentation on the standing wave just downstream of Coal Basin, controlling sediment sources in Coal Basin or in the nearby upstream tributaries (e.g., Figure 24) does not appear to be a viable option. Rather, mitigation might take the form of gravel mining (in the lower reaches of Coal Basin or more likely on the Crystal sediment wedge itself).

Figure 29. Controllable sources of sediment in the Coal Basin include eroding hillslopes below and above roads (upper panel) and mine related ground disturbance (lower panel). Controllable sources of sediment in Coal Basin make up approximately 2% of all potential sediment sources.

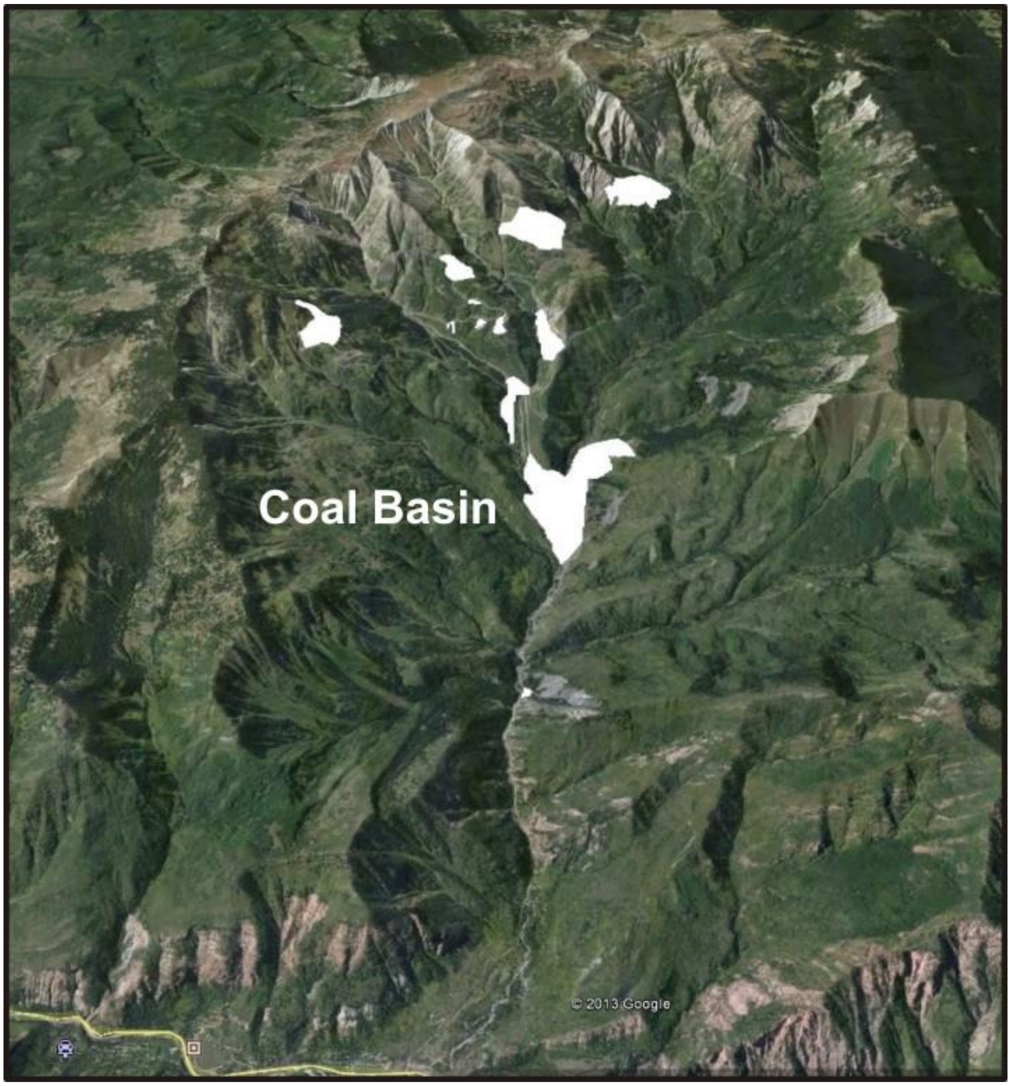

Figure 30. Areas (white polygons) mapped using Google Earth of mining and road related land disturbance areas (Figure 20) that were used to estimate the proportion of predicted erosion that is controllable.

Summary

Our analysis indicates the importance of gully and shallow failure erosion in supplying channels in the Crystal River with coarse sediment and how its distribution varies across the watershed. In particular, the supply of coarse sediment from a closely spaced set of five tributaries, including Coal Basin, in the center of the Crystal River watershed appears to be a major contributor to a standing wave of sediment, or sediment wedge, located in the vicinity of the Coal Basin confluence near the community of Redstone, CO. The sediment wedge is likely causing increased potential for overbank flooding in the vicinity of the Coal Basin confluence and Redstone.

Fine sediment sources in the Crystal River watershed are predicted using WEPP technology. The relative magnitude of fine sediment supply appears to be considerably smaller compared to coarse sediment supply from gullying and shallow landsliding. However, an absolute comparison between the relative magnitudes of sediment supply is not feasible given the two different methods used to estimate them and because of the differences in grain sizes of the sediment involved. Nevertheless, the maps of surface erosion potential from hillsides and from roads could be used to help prioritize erosion control aimed at reducing fine sediment delivery to streams.

The type of analysis conducted here on the Crystal River basin, using fluvial and aquatic tools in NetMap, can be used for restoration projects or management planning (Benda et al. 2009). NetMap tools combined with readily available data were used to create a multi-scale analysis that conveys relative insights into road, channel, and basin scale potential erosion or sediment yields. The data and maps can be used to identify candidate sites for restoration by examining highly productive sites at the different scales. We recommend that field visits are used in conjunction with the NetMap analysis for a final restoration site determinations. Earth Systems Institute is providing the data and NetMap tools used in this analysis to the Roaring Fork Conservancy in case further analyses are needed or data are updated.

No field work was conducted during this study, although consultations occurred with individuals who have extensive on the ground experience within the Crystal River basin (Brian McMullen, White River NF, US Forest Service; Sharon Clarke, Roaring Fork Conservancy; Sandra Ryan-Burkett, RMRS, US Forest Service, and Seth Mason, S.K. Mason Environmental, LLC).

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