It is generally accepted in stream ecology that habitat heterogeneity and patchiness at multiple scales increases ecosystem resilience through niche diversification. Heterogeneous stream habitats include a complex mosaic of hydraulic features, large woody debris, anabranches, substrata and channel forms — this complexity tends to increase as streams progress towards later stages based on the Stream Evolution Model. Recent restoration work on Whychus Creek in Central Oregon has sought to create complex, late-stage systems in order to improve the ecological function of artificially simplified reaches. One way to measure and track lotic system habitat complexity is through substrate analyses because a heterogeneous patchwork of substrata can act as a proxy for diversity of aquatic habitat types. The goal of this pilot project was to develop a replicable and robust monitoring protocol that quantifies substrate heterogeneity conditions among four priority reaches in Whychus Creek. To do this, I developed a monitoring protocol that utilizes three methods to capture substrate heterogeneity on four, 500-m reaches of the creek. Each sample reach included a nested sampling design of 12 floodplain-wide transects that allowed me to quantify micro, meso or macro-level substrate heterogeneity. I collected data using standard pebble counts, two-dimensional areal plot estimates and one-dimensional patch width measurements. I used the data from each of these three methods to calculate habitat heterogeneity using four metrics — Simpson’s Diversity Index, Shannon’s Evenness Index, Lloyd’s Index of Patchiness and Fortin’s Spatial Diversity Index. The results indicated that the two recently restored reaches were on average, 38% more heterogeneous than the untreated reach while the older, more established project reach was on average, only 15% more heterogeneous. The chi-square test for independence for the pebble count indicated significant differences between all the reaches and substrate classes ($X^2$ (18, $N = 1865$) = 210.23, $p < .001$) except one — which signaled that the untreated reach requires a slightly larger sample size in future years. For the plot method, the differences among the reaches were more significant with $X^2$ (18, $N = 2306$) = 836.57, $p < .001$. The plot method resulted in the highest Cramer’s V value of 0.35 ($p < 0.001$) — indicating a strong relationship between substrate composition and individual reach. These results illustrate that the three methods were robust enough represent stream substrate conditions. Recommendations include, foregoing the pebble count in order to prioritize larger sample sizes of the plot method and the transect patch method.
Quantifying the Geomorphic Response of Stream Habitat Restoration
A Pilot Project on Whychus Creek

By
Alex Scagliotti

A CAPSTONE PROJECT

Submitted to Oregon State University in partial fulfillment of the requirements for the degree of Master of Natural Resources

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

_________________________________________
Alex Scagliotti, Author
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I am forever grateful to my patient wife, Sarah Scagliotti, who has supported me every step of the way – I could not have gone through graduate school or completed this project without her constant positivity and encouragement. Finally, I would like to extend my deepest appreciation to my parents for instilling in me the passion for nature and environmental stewardship that has been the driving force behind my work.
List of acronyms

CFS – Cubic feet per second  
CP-R2 – Camp Polk Reach 2  
DLT – Deschutes Land Trust  
DRC – Deschutes River Conservancy  
ESA – Endangered Species Act  
LIP – Lloyd’s Index of Patchiness  
LWD – Large woody debris  
NMFS – National Marine Fisheries Service  
ODEQ – Oregon Department of Environmental Quality  
ODFW – Oregon Department of Fish and Wildlife  
OWEB – Oregon Watershed Enhancement Board  
OWRD – Oregon Water Resources Department  
PGE – Portland General Electric  
SDI – Simpson’s Diversity Index  
SEI – Shannon’s Evenness Index  
Spl.DI – Spatial Diversity Index  
TSID – Three Sisters Irrigation District  
UDWC – Upper Deschutes Watershed Council  
USDA – United States Department of Agriculture  
USFS – United States Forest Service  
USFWS – United States Fish and Wildlife Service  
WC-R3 – Whychus Canyon Reach 3  
WC-R4 – Whychus Canyon Reach 4
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1. **Introduction**

1.1 **Issue Statement**

For over a century, Whychus Creek in Central Oregon has undergone largescale alterations to its pre-settlement ecological function. These changes stem from anthropogenic pressures of local land management, urbanization, agriculture and infrastructure that have created degraded reaches and simplified stream habitats (Mork and Houston 2015). Straightened and embanked channels, local extirpation of ecosystem engineers, water diversions, on-channel infrastructure, widespread grazing and other influences have contributed to this degradation (Mork and Houston 2016). Recent work by the Upper Deschutes Watershed Council (UDWC) and restoration partners have contributed to a concerted effort to improve the ecological function of Whychus Creek.

A useful approach to measure ecosystem response to restoration efforts as well as to track large changes within the basin is through substrate analyses. Substrate heterogeneity and patchiness can be important determinants of lotic system health because they reflect key components of stage-zero restoration [appendix A (Cluer and Thorne 2014)] and are some of the earliest indicators of change within the watershed (Dietrich et al. 1989). A complex mosaic of substrate classes reflects hydraulic and topographic heterogeneity (e.g. riffles, pools, backwaters etc.) which can ameliorate the effects of environmental stochasticity on the ecosystem as a whole (Schindler, Armstrong and Reed 2015). Additionally, substrate patch heterogeneity allows for ontogenetic migration of aquatic species, increases diversity in the invertebrate community through niche diversification (Milesi, Doledec and Melo 2016) and improves the resiliency of the ecosystem to disturbance (Pederson and Friberg 2007). Since one of the primary goals of the UDWC restoration projects is to restore simplified reaches into complex, late-evolutionary stage systems (Stage 8 or 0 per Cluer and Thorne’s Stream Evolution Model [2014]), this pilot project aimed to develop a substrate analysis protocol as a tool that can provide useful information about a key indicator of stream evolution stage.

1.2 **Goals and Objectives**

Specifically, the main goal of this project was to develop a monitoring protocol that quantifies aquatic habitat complexity so that the UDWC can analyze and compare key reaches as well as track habitat changes over time.

The objectives to accomplish this goal were:

1. Develop and test monitoring methods for long-term, replicable analysis of substrate patch heterogeneity of current and future restoration sites along Whychus Creek.

2. Research and test a variety of metrics that can compare substrate conditions among the four sites.

3. Characterize the substrate patch diversity and spatial distribution in four reaches of Whychus Creek that are in various stages of stream evolution.
The ability to quantify and compare the geomorphic response of fluvial processes among sites that represent various stages of stream evolution will allow the UDWC and its restoration partners to measure and track habitat heterogeneity in four priority reaches. These project sites presented a unique opportunity because three of the reaches have received restoration work at various times from 2008 to 2016 and one reach has yet to be treated – thus representing a comparable control reach. The results of this pilot project indeed indicated that there were higher rates of patch heterogeneity in the restoration project reaches than in the untreated reach. Furthermore, each of the three methods of data collection used for this study showed significant differences among reaches and consistent relative values of heterogeneity which indicates that they were responsive to the geomorphic conditions of the creek. Continued annual monitoring using these methods will be able to expand upon the conclusions found here and allow for more in-depth analyses that can signal changes within the basin.

1.3 Geophysical, Biological and Hydrological Context

1.3.1 Geophysical Landscape

Whychus Creek is a spring-fed tributary to the Upper Deschutes River [Hydrological Unit Code 17070301 (U.S. Geological Survey 2018)] that originates on the eastern slopes of the Oregon Cascades and drains approximately 65,560 hectares (UDWC 2009). The headwaters of this 40-mile stream begin in an alpine environment above 3,000 meters and rapidly descend into the subalpine environment of the Three Sisters Wilderness. The steam continues into the ponderosa pine (*Pinus ponderosa*) forests that surround Sisters, Oregon and slowly transitions into a xeric, sagebrush steppe landscape where it enters the Middle Deschutes River at 640 meters of elevation [figure 1(UDWC 2009)]. The confluence is approximately 5 km above Round Butte Reservoir - created by the Pelton Round Butte Dams. Of the 64 kilometer creek, 24.8 kilometers are designated as either *wild* or *scenic* under the Wild and Scenic Rivers Act (U.S. Fish and Wildlife Service n.d.).

1.3.2 Water Quantity and Quality

The majority of the volume in the creek comes from snow/glacial melt and springs because much of the precipitation permeates the highly porous layers of basalt common in Central Oregon – very little flow comes from direct runoff (UDWC 2009). The mean daily flow from 1906 to 2018 was 85.3 cubic feet per second (cfs) above all irrigation canals, though flows can exceed 2,000 cfs during spring floods (figure 2). By contrast, the mean daily flow several kilometers away and below most of the irrigation withdrawals has historically been much lower at 23.7 cfs [figure 3 (Oregon Water Resources Department 2018)]. Due to the diversions that pull 90% of the stream flow out during the irrigation season, elevated stream temperatures and the resultant lowered dissolved oxygen levels have led to the creek being listed as *water quality limited* by the Oregon Department of Environmental Quality (ODEQ) under Clean Water Act section 303(d) (UDWC 2009).
1.3.3 Climate

Whychus Creek passes through three eco-regions: Cascade Crest Montane Forest at the headwaters, Ponderosa Pine/Bitterbrush Woodland above the town of Sisters and Deschutes River Valley from Sisters to the mouth [figure 4 (Environmental Protection Agency 2017)]. Since Whychus Creek runs off the east side of the Cascade Range, there is a distinct rain shadow effect in the region so it receives little rainfall. The nearby town of Sisters, Oregon receives an average of 34.5 cm of rain and 76.5 cm of snow annually (Weather Atlas 2018). These amounts are likely higher near the headwaters and lower near the mouth.

1.3.4 Soils

Due to local volcanic activity, the soil profile in this sub basin is predominantly composed of volcanic ash, pumice and cinder (U.S. Forest Service 2014). The fine grain volcanic ash erodes easily – especially without bank stabilizing vegetation. This material is present in the upper 0.5 - 1 meter of soil (Yake 2003) which compos the majority of the rhizosphere and constitutes low fertility levels. Soil productivity and nutrients are predominantly derived from plant duff or detritus which forms the upper most layer of soil (Yake 2003). Riparian soils along the creek are more productive than the sub basin as a whole due to a higher water table and nutrient availability.

1.3.5 Endangered or Threatened Species

The only known species currently listed under the Endangered Species Act (ESA) is the Middle Columbia evolutionarily significant unit of steelhead (O. mykiss) – listed as threatened (U.S. Fish and Wildlife Service n.d.).

1.3.6 Invasive/non-native species

Several invasive or alien species exist within the Upper Deschutes basin. One concern is reed canary grass (Phalaris arundinacea) which has developed in the floodplain wetland areas of the creek. The four reaches in question have known populations of mullein (Verbascum thapsis), spotted knapweed (Centaurea maculosa), bull thistle (Cirsium vulgare) and cheatgrass (Bromus tectorum). In addition, there are nearby populations of, Dalmatian toadflax (Linaria dalmatica), dandelion (Taraxacum officinale), Kentucky bluegrass (Poa pratensis), western dwarf mistletoe (arceuthobium campylopodum) and Eurasian watermilfoil (Myriophyllum spicatum) (U.S. Forest Service 2014). There are also several non-native mollusks known to be within the basin – though not necessarily in Whychus Creek specifically. Asian clam (Corbicula fluminea), European ear snail (Radix auricularia) and Chinese mysterysnail (Cipangopaludina chinensis) are exotic species found within the basin – albeit sparsely (U.S. Geological Survey 2018). There are also efforts to control brown trout (Salmo trutta) which were intentionally introduced as sport fish but have since outcompeted and depredated on native redband trout in Whychus Creek.
Figure 1: Whychus Creek basin map of land ownership and restoration project reaches (UDWC n.d.).
Figure 2: Three-year mean daily flows on Whychus Creek at OWRD gage 14075000 above Sisters (Oregon Water Resources Department 2018).

Figure 3: Three-year mean daily flows on Whychus Creek at OWRD gage 14076050 at Sisters (Oregon Water Resources Department 2018).
1.4 Regional Context

1.4.1 Water development

Beginning in the late 19th century and early 20th century, water right claims on Whychus Creek aided in the development and expansion of farming and ranching. By 1895, the creek was fully allocated and it regularly went dry during the summer months - from 1960 to 1999, this occurred two out of every three years (UDWC 2009). In 1998, the Deschutes River Conservancy (DRC), UDWC, the Three Sisters Irrigation District (TSID), the city of Sisters and multiple government agencies such as the Oregon Water Resources Department (OWRD) and the U.S. Bureau of Reclamation have worked together to increase instream flows through ecologically critical areas below the diversions (Tillman et al. 2010).
1.4.2 Habitat degradation and restoration

Since the 1960’s, over 50% of the creek was straightened and embanked in order to quickly move water through the system and reduce chances of flooding (Mork 2018). This significantly degraded aquatic and riparian habitat by concentrating high hydraulic energy that entrained macroinvertebrates, young fish and gravels required for fish spawning. It also reduced and simplified aquatic habitats, limited pools and instream structure, reduced hyporheic exchange and increased the flashiness of flood pulses (UDWC 2009). Livestock grazing, urban expansion and channel structure have also contributed to general habitat degradation.

In recent years, efforts by numerous government agencies and NGOs have been made to restore ecological functions to some of these degraded reaches. These efforts were largely aided by land acquisition from the Deschutes Land Trust (DLT). They currently own 6.4 km of creek in Whychus Canyon Preserve, 2.25 km in Camp Polk Preserve, 1.6 km of Willow Springs Preserve, 0.8 km of Aspen Hollow Preserve and multiple conservation easement rights on private lands along the creek [appendix B (DLT n.d.)]. This has created numerous opportunities for the DLT and UDWC (who manage the aquatic and riparian restoration projects for DLT) to explore various restoration strategies throughout the lower reaches of Whychus Creek. In addition, the UDWC and the Deschutes River Conservancy (DRC) have worked with local land owners to remove several diversion dams that impede fish migration and to install fish screens on the diversion canals to improve fish survivorship.

1.4.3 Flow regulation

To augment the effectiveness of the habitat restoration projects, DRC has worked to buy, lease and conserve Whychus Creek water for instream purposes. In the years since 1999, flows have been continuously restored to the creek through these efforts and this has resulted in improved water quality in some of the most critical low-flow reaches (UDWC 2009). For example, the TSID, in partnership with the DRC have piped 80 out of 96 km of the district’s irrigation canals which eliminates seepage that has historically been as high as 50% of the volume from the old open canals (Thalacker 2012). This conserved water increases flows for both junior rights holders and instream purposes. In addition, the pipes create a pressurized delivery system which saves pumping costs for irrigators and allows for the use of more efficient water delivery mechanisms such as center pivots – thereby saving even more water. While efforts to lower water temperature by increasing shade, creating pools and raising the water table can help, increasing flows more directly and ubiquitously lowers the water temperature for the entire creek (Mork 2018). Late summer flows below the diversions continue to be lower than what is required to meet ODFW water quality standards for salmonid species (figures 5 and 6), (UDWC 2009).

As of 2018, the DRC has secured 38 cfs of mixed junior and senior water rights (DRC 2018).

---

1 18 degrees Celsius is the threshold at which native fish species begin to be affected by low dissolved oxygen levels and 24 degrees Celsius is the threshold that begins to be fatal for salmonid species (UDWC 2009).

2 These rights are often ‘straddled rights’ that are junior to the pre-1895 rights and as a result, may only be partially filled (Tillman et al. 2010). Therefore, the ‘paper right’ of 33 cfs of instream rights does not mean that a minimum of 33 cfs will flow through the creek all year long.
Figure 5: Whychus Creek water budget as of 2005 (Tillman et al. 2010). Flows in recent years are generally higher than the 8.8 cfs shown here (OWRD 2018).

Figure 6: May – September average temperatures that meet or fail to meet temperature standards (Mork 2018). Note that these temperatures are recorded at river mile 6, above significant inputs from Alder Springs.
1.4.4 Species reintroduction

In the 1950's construction of the Pelton Round Butte dams on the Deschutes River prevented runs of Chinook salmon and steelhead from returning to Upper Deschutes River basin. In the last recorded run of these anadromous species in 1953, an estimated 1,000 anadromous species returned to spawn in Whychus Creek alone (UDWC 2009). During the relicensing process in 1995, Portland General Electric (PGE), the Confederated Tribes of the Warm Springs Reservation (Tribes), ODFW, the Oregon Watershed Enhancement Board (OWEB) and other partners worked to create integrated plans for installing fish passage on the dams and implementing habitat restoration strategies throughout the Upper Deschutes basin. UDWC has been partnering with these other stakeholders to improve habitat for these culturally, ecologically and economically significant species. In 2007, the first cohort of steelhead fry were released into Whychus Creek and two years later in 2009, the first cohort of Chinook fry and smolts were also released into the creek (UDWC 2009). New cohorts of hatchery fish have been released each year since then. These large scale reintroduction efforts have predominantly been the main catalyst for developing continual and robust monitoring on Whychus Creek. This pilot project is one small piece of a larger effort to measure and track habitat viability for steelhead and Chinook salmon reintroduction.

1.4.5 Basin Stakeholders

Below is a list of major stakeholders that directly manage, benefit from or fund projects on Whychus Creek (table 1). A list of secondary stakeholders such as the USDA or Deschutes River fishing outfitters would be extensive and beyond the scope of this project.

Table 1: Primary Whychus Creek stakeholders and their interest in the creek.

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>UDWC</td>
<td>Oversees and manages restoration of DLT stream restoration projects</td>
</tr>
<tr>
<td>DRC</td>
<td>Works to restore instream flows</td>
</tr>
<tr>
<td>DLT</td>
<td>Owns and manages land on the lower reaches</td>
</tr>
<tr>
<td>TSID patrons</td>
<td>Represents the majority of the irrigators the draw on the creek’s water</td>
</tr>
<tr>
<td>Non-TSID irrigators</td>
<td>Water-right holders in the basin that divert water on private ditches</td>
</tr>
<tr>
<td>Tribes</td>
<td>Have invested enormous time and money into fish reintroduction efforts</td>
</tr>
<tr>
<td>PGE</td>
<td>Provides restoration funding and manages the Pelton Round Butte dams</td>
</tr>
<tr>
<td>USFS</td>
<td>Owns most of the land from the headwaters to the City of Sisters</td>
</tr>
<tr>
<td>NMFS</td>
<td>Manages marine fisheries including anadromous species being reintroduced</td>
</tr>
<tr>
<td>USFWS / ODFW</td>
<td>Partners in managing ESA listed species</td>
</tr>
<tr>
<td>OWRD</td>
<td>Manages and oversees water rights enforcement and water transfers</td>
</tr>
<tr>
<td>Major funders</td>
<td>Include OWEB, Bonneville Environmental Foundation, Pelton Round Butte Fund and others that fund UDWC restoration efforts</td>
</tr>
<tr>
<td>ODEQ</td>
<td>Tracks water quality standards required under the Clean Water Act</td>
</tr>
<tr>
<td>City of Sisters</td>
<td>Municipal water use – recently switching to groundwater withdrawals</td>
</tr>
<tr>
<td>General public</td>
<td>Locals and visitors that live and recreate along the creek</td>
</tr>
</tbody>
</table>
2. Literature Review

2.1 Background and significance

A substrate monitoring protocol will be a useful addition to the monitoring schemes already being implemented on Whychus Creek (water quality, macroinvertebrate sampling, fish population estimates, and riparian vegetation sampling). A key component of stage 0 restoration is that the geomorphic form of the river incorporates complex systems of anastomosing branches, a wide variety of substrate sizes and distributions, large woody debris (LWD), hydrologically connected floodplains, and multiple habitat types such as riffles, pools, sloughs and ephemeral side channels [appendix A (Cluer and Thorne 2013)]. Numerous studies have shown that interactions between these complex abiotic systems increases biodiversity on multiple scales (Boyero 2003: Polvi, Nilsson and Hasselquist 2014), adds complexity to trophic interactions (Winemiller, Flecker and Hoeinghaus 2010) and increases detrital decomposition and nutrient cycling (Frainer et al. 2018). These and other influences of habitat heterogeneity on local biota represent key parameters of restored ecosystems.

2.1.1 Definitions

The terms habitat heterogeneity, patchiness and complexity are widely used in ecological literature and they are often used interchangeably as catch-all terms. Various definitions include spatial distribution of patches, the number of habitats in an area, variability within habitats (Palmer, Menninger and Bernhardt 2010), patch shape, size and interconnectedness (Cooper et al. 1997) and others. Without a clear definition to provide structure, the results of this monitoring program will be muddled. The definitions used here will be based on Li and Reynolds’ (1995) definitions of heterogeneity which involves two components – the system property and its complexity or variability. In this case, the property being measured is substrate patch diversity. The second component is complexity (categorical descriptors) or variability (numerical descriptors) (Li and Reynolds 1995). The categorical descriptors in this case are substrate type such as fine sediment, gravels, boulders etc., while the numerical descriptors are the range of substrate size classes and the abundance of each. Therefore, substrate patch heterogeneity will be determined by assessing both complexity and variability across space and time. The terms patch and patch boundary are also important to define. In the context of this project, a patch is an area where the dominant substrate size class is relatively homogenous and differs from the larger matrix of its surroundings (Winemiller, Flecker and Hoeinghaus 2010). Patches can range in scale from being measured in millimeters to kilometers within a watershed. Patch boundaries can change along a gradient or can be abrupt discontinuities between size classes (appendix C).

2.1.2 Effects of substrate/patch heterogeneity on aquatic biota

Most studies that aim to determine biotic responses to habitat heterogeneity compare substrate diversity to macroinvertebrate assemblages. In these cases, substrate heterogeneity has not only been shown to increase macroinvertebrate species richness through niche diversification and habitat availability for ontogenetic migration, but it increases resistance to disturbance and exacerbates post-disturbance recolonization such as after a flood or drought(Milesi, Doledec and
Melo 2016). These disturbance-mediating properties are due to the fact that complex systems provide more refugia from disturbance, allow for a variety of life history traits for numerous species and increase the chance that entrainment from high flows will place macroinvertebrates near suitable habitats (Silver, Wooster and Palmer 2004). Since different species respond to disturbances (e.g. floods, droughts, high temperatures, changes in sediment load etc.) differently, it can also be assumed that higher species diversity will result in improved ecosystem resilience overall.

Other studies specifically incorporate patch shape, size, number and distribution into their substrate analyses. For example, macroinvertebrate richness has been found to be higher in streams with more substrate types, high patch perimeter to area ratios, and reduced distance between patches (Beis, Usseglio-Polatera and Moreteau 2000). While patchiness is associated with higher biodiversity, areas with high frequencies of small patches can be detrimental to the stream ecosystem and there must be a balance between high patch diversity and patch area (Winemiller, Flecker and Hoeinghaus 2010).

Fewer studies link substrate heterogeneity to responses by higher trophic levels such as fish or avifauna, though there is a good deal of literature that links substrate size to fish spawning and juvenile success rates (Shellberg, Bolton and Montgomery 2010). Fish diversity relies on the variety of habitat types since they require different habitat characteristics during various phases of their life cycles (Polvi, Nilsson and Hasselquist 2014). Such habitat requirements include deep pools that act as thermal refugia during the late summer flows, large gravel beds to build redds, backwaters that act as prey hotspots and refugia from floods (Junk, Bayley and Sparks 1989), and LWD that increases shade and protection from depredation.

Fine sediment release events have been shown to significantly reduce salmon embryo survival (Levasseur et al. 2006) but a stream with a wide range of habitat types, in-channel structure and geomorphic features can attenuate the fine sediment loads of these release events (Cluer and Thorne 2013). There have also been studies done that aim to determine how substrate and patch heterogeneity can influence vegetation. Several authors have shown that substrate patchiness in slow moving sections of stream channels can benefit the hydrophytic plant community (Winemiller, Flecker and Hoeinghaus 2010) and can increase niches for algae and vascular plants (Cluer and Thorne 2013).

### 2.1.3 Effects of substrate patchiness on nutrient cycling

Hydraulic heterogeneity and the resultant substrate patchiness have been shown to slow down detrital entrainment which attenuates debris pulses and increases the rate at which organic material is decomposed (Muotka and Syrjanen 2007). This in turn will influence the macroinvertebrate community which can then affect higher trophic levels. Substrate patchiness also creates conditions where the detrital decomposition rates will vary from patch to patch and macronutrients will become bioavailable at different times which further underscores species diversity (Winemiller, Flecker and Hoeinghaus 2010).
2.1.4 Substrate as a proxy for habitat complexity

Substrate and patch heterogeneity can be used as a proxy for other habitat features. Sediment sorting and heterogeneity is in part, a response to a diversity of hydraulic form, which is in turn a response to channel form, in-stream structures, longitudinal profile and hydrologic regime (Cluer and Thorne 2013; Polvi, Nilsson and Hasselquist 2014). Stream substrata also influence hyporheic flow which affects water storage, temperature and late summer flow release - important factors affecting the stream hydrograph. Habitat heterogeneity and patchiness in an ecosystem can improve its resiliency to disturbances (e.g. floods, droughts and invasive species) because the impacts to the aggregate of habitat types is typically less variable than impacts to any one habitat type (Schindler, Armstrong and Reed 2015). Therefore, aquatic habitat heterogeneity – as reflected by substrate patch heterogeneity – will tend to ameliorate environmental stochasticity in a stream system.

2.1.5 Substrate as an indicator of ecosystem change

Stream substrata can be one of the first variables to respond to largescale change within a basin (Dietrich et al. 1989) and thus, can act as a metric of degradation, restoration or general land use change. Alterations in patch and substrate heterogeneity, sediment sorting, sediment degradation/aggradation or bed armoring carry specific implications for the basin. These changes can signal changes in sediment supply verse transport capacity, land use, water management, climate variation or a host of other influences. A stream’s distinct substrate signature can also affect its largescale morphological evolution by influencing hydraulic friction and sediment mobility (Cluer and Thorne 2013). These responses to small and large-scale changes within the basin underscores the importance of long term monitoring.
2.2 Sampling methods

2.2.1 Pebble counts

The most widely used method of substrate sampling is the pebble count established by Markley Wolman. The basic form of this well-established criteria involves randomly selecting 100 or more particles from a reach of interest, measuring the width of a sample’s intermediate axis, recording the results and analyzing the substrate composition and frequency distribution for that particular reach (Wolman 1954). Adaptations of this basic procedure alter the number of particles per reach, the randomization strategy of particle selection, the pattern of the grid used (transects, quadrants, continuous zig-zag, or linear progression along the thalweg), the method of measuring each sample, and the lateral extent at which samples are collected (wetted width, bankfull width or floodplain). Table 2 illustrates a variety of protocols based on the basic Wolman form.

Table 2: Methods of pebble counts

<table>
<thead>
<tr>
<th>Source</th>
<th>Grid pattern &amp; width</th>
<th>Particle # &amp; scale</th>
<th>Particle selection</th>
<th>Sample measurement and size class bins</th>
</tr>
</thead>
<tbody>
<tr>
<td>(USFS 2017)</td>
<td>Transects across bankfull width</td>
<td>3 samples/section &gt; 5 sections/ transect &gt; 20 transects/reach = 300 samples/ unspecified reach length</td>
<td>Meter stick randomly placed on stream bed and first particle touched</td>
<td>Ruler measures intermediate axis. Measurements are recorded as is - not binned</td>
</tr>
<tr>
<td>(Rentmeester 2014)</td>
<td>Transects across bankfull width</td>
<td>11 samples/transect &gt; 11 samples/transect =110 samples/ unspecified reach. Riffles only</td>
<td>Toe of boot is used to pick the first particle touched with tip of finger</td>
<td>Gravel card is used to group size classes into 11 bins: silt&gt;sand&gt;very fine gravel….&gt;large boulder</td>
</tr>
<tr>
<td>(USFS 2012)</td>
<td>Zig-zag pattern across bankfull width</td>
<td>1 particle/2 meters of zigzag until at least 100 particles are selected. Riffles only</td>
<td>Toe of boot is used to pick the first particle touched with tip of finger</td>
<td>Ruler measures intermediate axis and groups size classes in to 12 bins from fine sediment&gt;very fine gravels&gt;fine gravels...very large boulder</td>
</tr>
<tr>
<td>(West Virginia Dep. Environmental Protection n.d.)</td>
<td>Zig zag or transect pattern across bankfull width</td>
<td>At least 100 particles measured in unspecified segments. Transects can be random, equidistant or proportional to stream habitat</td>
<td>Toe of boot is used to pick the first particle touched with tip of finger</td>
<td>Ruler measures intermediate axis and groups size classes in to 10 bins from sand &gt; fine gravels &gt; medium gravels…&gt; large boulder</td>
</tr>
<tr>
<td>Bunte and Abt 2001</td>
<td>Transects across bankfull width</td>
<td>4 samples/grid &gt; 14-15 grids/transect &gt; 4 transects per reach = mean of 465 samples in 15 meters.</td>
<td>Point intersect of crosshairs on sampling frame</td>
<td>Gravel card is used to group size classes into Wentworth size classes – &lt; 2mm, 2-4mm, 4-8mm, 8-16…&gt;512 mm.</td>
</tr>
</tbody>
</table>
There are numerous other examples of this type of procedure with various adaptations. One drawback of this method is that there can be high margins of both sample and operator error. Homogeneous substrata in a particular reach can reduce the sample size needed while a heterogeneous reach with high variability in diameter sizes can require an impractically large number of samples for the intended parameter (median size, percent distribution, standard deviation etc.) to fall within a 95% confidence interval (Bunte and Abt 2001). For example, one study estimated that just one, 300 meter reach would require 4,593 samples to fall within 5% accuracy range (Rogers 2008). Interestingly, none of the protocols encountered sampled beyond bankfull widths. This may be because the streams in question were single stem systems but in the case of Whychus Creek, the restoration sites include multiple anabranches and active floodplains. Since floodplains play a key role in stream ecosystems by absorbing, retaining and releasing floodwater, attenuating flood peaks and providing highly productive biological hotspots (Junk, Bayley and Sparks 1989), it is surprising that sampling the entire floodplain is not common.

Operator error comes in the form of a surveyor’s bias when choosing particles for the pebble count. Numerous authors have shown that there tends to be a bias towards large and medium sized particles with a built-in bias against fine sediment during the selection process (Hey and Thorne 1983: Bunte and Abt 2001: Daniels and McCusker 2010). Operator bias may also come from a tendency to avoid stepping on large boulders, reaching under thick foliage, sampling deep pools or selecting hard-to-see particles. While sampling error decreases with increased sample size, operator error increases with sample size and with the number of operators (Hey and Thorne 1983: Daniels and McCusker 2010).

Knowing these potential sources of error, one can carefully plan for and mitigate these data skewing factors. For example, Bunte and Abt found that using a point intersect particle selection method with a sampling frame reduces bias towards larger particles. They also found that gravel cards or “gravelometers” can also reduce measurement errors (2001). Other pragmatic steps such as not looking at the stream bed when selecting particles, using only one surveyor for the entire reach and sampling at pre-determined lengths along a transect can alleviate some of this bias. While observer bias should be minimized, environmental variability far outweighs the surveyor variability (Rogers 2008). For example, the differences in findings between two transects being sampled by one surveyor would be greater than the differences in findings of two surveyors assessing a single transect. This suggests that it is prudent to establish permanent transects to be sampled and resampled year after year.

2.2.2 Video analysis compared to pebble counts

One study sought to compare the accuracy of completing a standard pebble count with a sampling frame compared to videoing the streambed and estimating substrate size distributions using computer software. The author found that while videoing the streambed greatly reduces field time and increases the range that one can cover, estimating particle size from post-processing digital data reduces the accuracy compared to a pebble count (Rogers 2008). Contrary to these findings, another study found that video analysis of substrate size and composition showed comparable results to a pebble count (Frezza, Carl and Reid 2003). While this method
may have some benefits for analyzing stream substrate over a larger range, the potential for reduced accuracy and the high variation among users made the video analysis method unacceptable in the context of this study.

2.2.3 Photographic quantification of heterogeneity

A unique method meant to determine substrate heterogeneity by Luz Boyero (2003) used photographs of 225 cm$^2$ frames laid on the bottom of the stream and imaging software to calculate substrate patch type, perimeter and area of each sample. The author used a hierarchal sampling method by nesting three samples within three sections within three riffles in three segments per basin (3$^4$) in two different basins for a total of 81 samples per basin. Figure 7 illustrates the five nested scales. Substrates were characterized in broad categories (boulder, cobble, gravel, sand, macrophyte, moss and wood) and the indices of heterogeneity were calculated from those results (Boyero 2003). A benefit of this method is that heterogeneity can be calculated at multiple spatial scales which vary in importance depending on the biological parameter being analyzed. One can also determine at which scale heterogeneity is greatest.

One downside to this method is that there is a level of subjectivity involved since estimating patch area and perimeter per sample involves tracing the borders of perceived patches in software program. At times, patches can be well defined but often, they occur on gradients that make determining the perimeter an inexact science. Furthermore, categorizing the substrate patches is estimated visually rather than by physically measuring their size and this also allows
for surveyor bias. However, the use of a hierarchal sampling method can be useful because heterogeneity is scale dependent and therefore, as Cooper et al. aptly describes “a useful approach for describing spatial heterogeneity is to decompose heterogeneity into a hierarchy of components of spatial structure, including descriptions of overall variability (the dispersion of data around measures of central tendency at different scales), trends (gradients, periodicities), and residual spatial dependence (spatial autocorrelation)” (1997, 175).

2.2.4 Mapping substrate patches to quantify heterogeneity

Beisel, Usseglio-Polatera and Moreteau (2000) quantified substrate patch heterogeneity using a similar method as Boyero (2003) but rather than photographing the patches in a plot square, these authors created maps in the field based off of the major patches encountered around a sampling point. They mapped patchiness at eight different radiuses around a single sampling point that increased by 0.5 meters in diameter from 0.5 to 4 meters as shown in figure 8. Beisel, Usseglio-Polatera and Moreteau then repeated this method at multiple random locations spread throughout a given reach. Diversity and heterogeneity were then quantified using 14 different metrics (2000). The downsides to this method are similar to the Boyero (2003) method – high levels of subjectivity involved in mapping and quantifying patchiness. Both of these studies can serve as effective one-off studies (both tested substrate heterogeneity to macroinvertebrate richness and abundance) but may be too variable as a monitoring protocol that is robust enough to compare inter-annual changes.

Figure 8: Sample of plot scales used to map substrate patches and the reach level map of plot sites (Beisel, Usseglio-Polatera and Moreteau 2000)
2.2.5 Quantifying patch heterogeneity through quadrants and plots

A study by Bryan Brown (2003) quantified patch heterogeneity using similar methods as those used in vegetation surveys and landscape ecology where a 1m X 2m plot was divided into 15 quadrants and placed at ten random areas of a 150 meter reach. The author then mapped substrate patches within each quadrant that represented at least 10% of the quadrant area. Then, plot-level heterogeneities were calculated from the 15 quadrants and calculated again by scaling up and averaging the values of each diversity index used. Particle sizes were estimated based on median particle sizes that categorize each class (sand, gravel, cobble etc.) (Brown 2003). Similar protocols have been used by Pederson and Friberg (2007), and Morley et al. (2008). Once again, estimating percent cover within a small area allows for a level of surveyor bias when quantifying heterogeneity and it carries concerns about how well repeated samples through time would be able to be compared. It nevertheless provides a useful perspective into substrate dynamics that pebble counts cannot achieve and it is relatively simple implement. This means that the short time commitment may allow for large sample sizes in a single reach or more resampling in a given year.

2.2.6 Quadrat sampling methods in landscape ecology

Collins and Smith (2006) aimed to test the effects of fire and grazing on plant community heterogeneity by establishing five quadrats placed along each of four transects in two different sites. The percent cover of each quadrat was visually estimated by using a modified Daubenmire scale which gives range bins of percentages (e.g. 0-5%, 5-25%, 25-50% etc.) and the midpoint of those ranges was used to qualify broad ranges of possible species coverage. The heterogeneity was calculated at differing scales from sample level to transect level to site level, which can signal different ecological processes at each scale (Collins and Smith 2006). Using the midpoint of a Daubenmire scale can be useful because it ameliorates the range of error that comes from visual estimations and it can standardize percent cover values among surveyors. This study can easily be converted to substrate by classifying the plant species as sediment size classes and reducing the scale to fit within stream channels.
2.3 Statistical and analytical methods

There are a multitude of applicable heterogeneity indices available that depend on goals of the project and the sampling design. The term ‘heterogeneity’ can mean that patches vary in shape, size, frequency, interconnectedness, category and pattern. Therefore, no single indicator of heterogeneity is sufficient to illustrate the whole picture (Cooper et al. 1997). Single indicators can be more or less responsive to changes in input data (Brown 2003) which is a reason why a strategic ‘tool kit’ of different indices taken in conjunction can be an appropriate strategy. Here, I present some of the ways that substrate heterogeneity is quantified but this is not an exhaustive list.

One basic method that is widely used to quantify substrate heterogeneity is by using the standard deviation of median substrate size from a pebble count data set – assuming that higher standard deviation values results in more diverse substrata (Cooper et al. 1997; Cardinale et al. 2002; Polvi, Nilsson and Hasselquist 2014; Frainer et al. 2018). Another similar metric often used is a size ratio of $D_{84}/D_{50}$ where $D_i$ is the size of the particle larger than the $i$th percentage of other particles in the data set (Cardinale et al. 2002). Standard deviation of the median ($D_{50}$) and the $D_{84}/D_{50}$ ratio can be used together as complements and they are simple to use.

A number of studies have used either the Shannon-Weiner or the Simpson’s diversity index as a way to quantify substrate or patch heterogeneity (Beisel, Usseglio-Polatera and Moreteau 2000; Cardinale 2002; Boyero 2003; Brown 2003). They are commonly used in detecting species diversity but are also useful in determining the heterogeneity of substrata or substrate patches because they are responsive to the number of ‘species’ and their relative abundance within the sample (Brown 2003). Similar to these diversity indices, some studies have used an evenness index which responds most strongly to relative proportion between substrate samples or patches (Beisel, Usseglio-Polatera and Moreteau 2000; Boyero 2003; Brown 2003). In other words, it measures the proportion of each type of substrate compared to the other types within the data. Brown (2003) used the combination of Romme’s evenness index, Simpson’s diversity index and contagion to quantify substrate and patch heterogeneity. Contagion is the probability that two particles or patches selected at random will be the same size class. Cooper et al. (1997) also explained that Lloyd’s index of patchiness or Moran’s $I$, measure the level of aggregation of substrate types - which can be extremely useful in streambed analyses. By estimating the perimeter and area of each sample patch, Boyero was also able to calculate the compactness which is the ratio of the patch perimeter length and the fractal dimension (2003). This indicates how regular or irregular the patch shapes are – which holds biological implications for aquatic species.

A number of authors have also used spatial autocorrelation and semivariogram techniques to provide another layer of depth when describing habitat heterogeneity because they specifically include spatial scale (Li and Reynolds 1995: Cooper et al. 1997). A semivariogram is a graphical representation that illustrates spatial autocorrelation – or the spatial dependency between two data points – so that high semivariance indicates increased streambed heterogeneity and low values indicate a more homogenous stream bottom (Cooper et al. 1997). As space between two points (patches or reaches) increases, correlations between those two points decrease and vice
versa. This can be useful in comparing the patch matrix within a reach or it can also be useful to compare two adjacent reaches. Once a semivariogram is constructed, other indices of heterogeneity can be calculated such as fractal dimension and relative heterogeneity (Li and Reynolds 1995: Boyero 2003). These indices are commonly used in landscape ecology but are applicable to stream substrate as well. Another possible analytical method taken from landscape ecology is Fortin, Payette and Marineau’s Spatial Diversity Index (1999). This index accounts for “species” richness, abundance and spatial occupancy and it has been used effectively for characterizing spatial heterogeneity of substrate patches by Jahnig, Lorenz and Herring (2008).
2.4 Implications and potential data gaps

While substrate and patch heterogeneity have been linked to species biodiversity (Boyero 2003: Polvi, Nilsson and Hasselquist 2014), restoration projects that increase habitat complexity by adding LWD, boulders, sloughs and multiple channels have mixed results on whether the project shows significant responses from the biotic community. Restoration projects can implement a wide variety of strategies and measurement standards, and most are able to significantly increase habitat heterogeneity. However, few have resulted a significant biological response (Palmer et al. 2010). The common theme between projects that have not produced significant biological responses was the level of overall ecosystem health within the basin. The projects that were most successful were completed in basins that had desirable water quality, functional basin-wide ecosystems and unimpeded hydrologic regimes (Palmer et al. 2010). This means that restoration activities that only address instream habitat complexity while doing little do address larger, basin-wide stressors such as local land or water use, will likely have low rates of success. However, it is also possible that measuring a single ecosystem health parameter (usually macroinvertebrate response) and measuring a single indicator of substrate heterogeneity is insufficient to make strong conclusions about the effect of increasing habitat complexity (Polvi, Nilsson and Hasselquist 2014). By using multiple indices of habitat heterogeneity that quantify substrate complexity at multiple scales, and by comparing the results of this monitoring program to the results of other UDWC monitoring projects, we can gain insight into how the ecosystems have responded to the restoration work. These analyses can in turn help the UDWC adaptively manage these stream ecosystems by determining what strategies can create the most significant biological response.
3. **Methods and Materials**

Substrate monitoring on Whychus Creek was conducted between August 13 and August 26, 2018. Pebble count and plot methods were conducted August 13-15; transect patch surveys were conducted on August 26. This timeline represents base-flow conditions which improved the ease of measurement and reduced the chance that conditions would change between sampling days.

3.1 **Site layout**

3.1.1 **Sampling reaches**

The four reaches I sampled in this project were Camp Polk Reach 2 (CP-R2), Whychus Canyon Reach 3 (WC-R3), and Whychus Canyon Reach 4 split into upper and lower sections (WC-R4 Forest and WC-R4 Delta). CP-R2 is the oldest restoration project reach with the last major work ending in 2012. CP-R2 was chosen because it represented a desired future condition for the other reaches based on physical (e.g. geomorphology, sediment routing, physical habitat, etc.) and biological (e.g. riparian vegetation, macroinvertebrates, etc.) conditions. WC-R4 was chosen because it represents a range of physical and biological conditions since major restoration work ended only two years before in 2016. WC-R3 is an untreated reach and was chosen because it represents the pre-restoration condition of the other reaches and acts as a control reach in which to compare the restoration projects. I established one 500-m valley-length sampling reach at CP-R2, one at WC-R3, and two at WC-R4. The last reach was split into two sections to better characterize the variability within this ~1.6-km stream restoration project.

3.1.2 **Transect layout**

Sampling reaches were approximately 50 to 150 meters wide depending on the width of the active floodplain. I split each 500-m reach into four groups of three transects each (12 transects total) that ran perpendicular to the valley. Each of the three transects within a group were placed 20 meters apart so that each grouping was 40 meters wide. I spaced the middle transects of the four groups 125 meters apart throughout the reach. A shapefile of these transect parameters was created and randomly overlaid on aerial photos of four study reaches. The transects spanned the width of the active floodplain (figure 9) which I defined as the area that is expected to be inundated on a two-year recurrence interval. Transects included the active floodplain because the entire area may provide habitat during high flows from late spring runoff. Additionally, given the dynamic nature of late-stage streams, channels may shift, close off, widen or narrow as they evolve and it was important to establish a monitoring protocol that captures those changes.

I designed a grouped layout of nested sampling scales because it permitted more freedom in the analysis than using equidistant transects. A grouped design allowed me to calculate patch diversity at both the meso-habitat and reach scales. In addition, it was necessary to include a

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3 The floodplain of WC-R3 is hydrologically disconnected from the creek and does not fit my definition based on a two-year recurrence interval. The transects were set in what is anticipated to be the active floodplain after the reach is treated.
grouped layout when analyzing spatial diversity indices because they rely on the sequence of values between defined and regular spatial intervals. By comparing the combined transect results in each of the four groups within a reach, I increased the sample sizes being compared and therefore the probability that the sampling scheme in each group accurately represented the condition of the stream.

3.1.3 Field methods for locating transects

I used aerial-image maps with georeferenced transects to delineate each 500-m reach so that they can be found again with a GPS unit for future monitoring. In addition, I ‘monumented’ the outside boundaries of each transect with capped rebar and fiberglass rods to ensure that the same area will be measured and results can be accurately compared with future substrate monitoring results. To improve the accuracy of remaining in-line with the transects, I temporarily placed several pieces of flagging along intermediate points between the outside edges of the sampling area. I used a GPS unit and georeferenced maps of each site to determine the placement of the intermediate flagging along the transects. This ensured that at least two pieces of flagging were always visible to the surveyors which proved to be more accurate and timely than using a leveling line between end-points.

Figure 9: 500-m aerial image of CP-R2 with the transect layout. The black line runs parallel to the valley, the thick red outline delineates the approximate active floodplain boundary of the reach and the thin red lines are the transects that run perpendicular to the valley.
3.2 Data collection

3.2.1 Pebble count

Using a point-intersect method from the crosshairs of a 0.5 by 1 meter plot (figure 10), I selected a pebble sample every 0.5 meters along the entire width of each transect. I placed the plot lengthwise along the transect (perpendicular to the flow) so that two samples could be selected per placement. I blindly reached under the two upstream and outermost crosshairs (figure 10) and selected the first particle touched. After two particles were selected, measured, and recorded, the sampling frame was flipped along its shortest axis and two more samples taken. Because of the way the frame was designed, this ensured that one particle was selected every 0.5 meters. I repeated this process along all non-vegetation dominant segments of each transect. I remained downstream of the plot during all pebble counts so as not to disturb the substrate being sampled. I measured the intermediate axis (i.e. neither the shortest nor longest axis) of each particle by placing it through the smallest hole it could fit through on a gravel card (figure 11). Larger cobbles and boulders that could not fit through the largest hole were measured along their intermediate axis with a metric ruler. I determined small, immeasurable substrate classes by feel – each selection of silt was universally marked as 0.5mm when it was smooth between fingers and each selection of sand was universally marked as 1mm when it had a gritty feeling. Only mineral substrates were sampled. Once recorded, I later ‘binned’ the data by size classes. The size classes can be broken up into a simple distribution of broad size classes of silt, sand, gravel, cobble, boulder and bedrock or they can be segregated into finer detail of smaller ranges (e.g. small, medium or large cobble). After preliminary data analysis, I chose the simple distribution as the input data for the diversity indices because 1) it represented a more parametric distribution of size classes, 2) so it could be easily compared with the other two sampling methods implemented in this study, and 3) because biota likely show clearer trends between broad size classes (e.g. gravel, cobble, boulder) than small-range classes (e.g. small, medium or large gravel).
3.2.2 Plot method

Using the same 0.5 by 1 meter plot (figure 10), I conducted ocular estimates to determine the total patch area within the plot. Patches were characterized by areas of a dominant size class and patch borders were delineated by distinct changes in the dominant cover of a particular size class. The photo of the plot (figure 10) would be characterized as 100% gravel. Though there are

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**Figure 10:** The 1 X 0.5 meter plot used to select particles for the pebble count as well as estimate patch cover in the plot method.

**Figure 11:** Gravel card with 13 size ranges and a metric ruler for measuring larger substrata (Bunte and Abt 2001)
individual particles that would qualify as cobble, there are no distinct cobble patches and the dominant size class present is gravel. I did not count patches that made up less than 10% of the plot area. The 16 quadrants within the plot improved the accuracy of delineating patch areas by counting the number of 12.5 x 25 cm segments that contained the $i^{th}$ size class. The patch classes and determinations I used were:

*Silt:* Smooth between fingers: < 0.5 mm  
*Sand:* Gritty between fingers: 0.5 - 4 mm  
*Gravel:* BB to tennis ball sized: 4 - 45 mm  
*Cobble:* Tennis ball to basketball sized: 45 - 256 mm  
*Boulder:* Larger than a basketball: > 256 mm  
*Vegetation:* Live vegetation including riparian vegetation, macrophytes and periphyton  
*Detritus:* Dead and decaying plant material including significant log jams, debris piles and dead/decaying algae colonies

Each transect consisted of three semi-randomized plot placements for a total of 36 plot placements per reach. Since each transect spanned the active floodplain and the majority of that area (approximately 70%) was dominated by vegetation, completely randomized placements would have similarly been dominated by vegetation and would not have captured channel diversity. To mitigate this, I assessed all the areas not dominated by vegetation and then used a random number generator that ranged from 0-100 to determine at what percentage of the width of each segment to place a plot. For example, if a transect crossed three channels (flowing or dry) and the random number generator produced 10, 90 and 70, then I placed plots at 10% across the non-vegetation-dominant area of one channel, 90% across another and 70% across the third channel. If there were more or less than three channels, I prioritized larger areas of mixed substrata over narrower ones.

3.2.3 Transect-wide patches

At the middle transect of each group, I used a 60-meter tape to measure the one-dimensional width of each patch class across the active floodplain. I determined the width of each individual patch by marking and measuring the boundaries where the dominant class was replaced by another dominant class. For example, along a given transect, 0 – 5m might be marked as vegetation, 5 - 6.1m as sand, 6.1 – 6.8m as gravel etc. I included all of the same substrate classes in this method as in the plot method – silt, sand, gravel, cobble, boulder, vegetation and detritus. I sampled four transects per reach rather than the 12 transect samples of the other two methods for two reasons. First, the high dominance of vegetation along the reach negatively skewed the diversity indices and therefore, the index outputs could not be accurately compared to the other two methods. Second, this method was the most time consuming of the three, with an estimated four days required to measure all 48 transects, whereas the other two methods required less than three days combined. Since this study was meant to develop a replicable and timely monitoring protocol, sampling all 12 transects with this method did not fit within the UDWC goals.
3.3 Method justification

Each of the three methods used in this study encompassed different aspects of the creek’s substrata. The three methods were intended to be used in concert so that the strengths of each strategy would counteract the weaknesses of another (table 3).

Table 3: Strengths and weaknesses of each method of data collection

<table>
<thead>
<tr>
<th>Method</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pebble count</td>
<td>Most objective</td>
<td>Assumes results of each transect mirrors general patch makeup</td>
</tr>
<tr>
<td></td>
<td>Point-intersect particle selection &amp; gravel card measurements reduce bias</td>
<td>Some selections are anomalous &amp; not representative of dominant patch class</td>
</tr>
<tr>
<td></td>
<td>Captures conditions of the entire transect</td>
<td>Only captures mineral substrates</td>
</tr>
<tr>
<td></td>
<td>Support a large variety of statistical analyses</td>
<td></td>
</tr>
<tr>
<td>Plot method</td>
<td>Measures the two-dimensional patch makeup</td>
<td>More subjective than other methods</td>
</tr>
<tr>
<td></td>
<td>Quadrants within the plot improve accuracy &amp; consistency of ocular estimates</td>
<td>Does not capture the condition of the entire transect</td>
</tr>
<tr>
<td></td>
<td>Includes more classes of substrata than the pebble count</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Most time efficient method</td>
<td></td>
</tr>
<tr>
<td>Transect patches</td>
<td>Measures large patches</td>
<td>Most time-intensive method</td>
</tr>
<tr>
<td></td>
<td>Captures the condition of entire transect</td>
<td>Measures only one-dimensional patch size</td>
</tr>
<tr>
<td></td>
<td>Includes more classes of substrata than pebble count</td>
<td>Continuous data limits statistical analyses</td>
</tr>
</tbody>
</table>

3.4 Statistical analysis

3.4.1 Indices of heterogeneity

Each of these indices can be more or less responsive to changes in the input data so they were meant to be interpreted in the context of each other – any individual indicator of diversity was too simplistic and could not accurately represent the status of the creek.

Simpson’s Diversity Index (SDI):

\[
\sum_{i=1}^{c} \frac{n_i(n_i - 1)}{N(N - 1)}
\]

Where \( n \) is the frequency or area of the \( i \)th class and \( N \) is the total frequency of all classes. The output range is \( 0 < \text{SDI} < 1 \), with higher values indicating higher diversity. SDI Responds to number of patches and proportions but is most the responsive to class richness (Brown 2003).

Shannon’s Evenness Index (SEI):

\[
\sum_{i=1}^{n} -\frac{p_i \ln p_i}{\ln N}
\]

Where \( P_i \) is the percent composition of the \( i \)th class and \( N \) is the total of all classes. The output range is \( 0 < \text{SEI} < 1 \), with higher values indicating a more even composition of classes and lower values indicating a reach with a few dominant classes. This responds most to changes in proportionality between classes (Brown 2003).

Lloyd’s Index of Patchiness (LIP):

\[
\frac{(\bar{x} + \sigma^2)/\bar{x} - 1}{\bar{x}}
\]

Where \( \bar{x} \) is the mean frequency of each substrate class between transect groups and \( \sigma^2 \) is the variance of the frequency of each class between transect groups. Rather than providing a single number as an output that represents the entire reach, this index indicates how congregated or dispersed each substrate class is within the reach. A value >1 indicates dispersed occurrences of a particular class and <1 indicates that a class is congregated in specific regions [appendix D (Xiao, Hao and Subbarao 1997)].

Fortin’s Spatial Diversity Index (Spl.DI):

\[
\sum_{i=1}^{n} -\frac{p_i \log p_i}{\log N}
\]

Where \( P_i \) is the percent composition of the \( i \)th class and \( N \) is the total of all classes. Rather than providing a single value as the output that represents the entire reach, this index indicates how widespread and proportional each class is throughout the reach. The output values are \( 0 < \text{Spl.DI} < 1 \), with higher values indicating more spatially diverse spread [appendix E (Fortin and Marineau 1999)].
3.4.2 Analyzing diversity index values

SDI and SEI scores combine reach-wide proportions of all substrate classes and their proportions for a single value output that represents the whole reach. Conversely, LIP and Spl.DI take into account spatial distribution between group samples and the output is individual substrate class values throughout a reach. For example, a gravel frequency of 11, 3, 20, and 0 between transect groups would result in different values for both LIP and Spl.DI than would 7, 8, 9 and 10 - even though the total abundance and mean are the same for both samples. However, both of those distributions would have the same value for SDI and SEI.

For Spl.DI and LIP, I quantified the differences between samples at the group level (N=4) for each substrate class type. For this reason, the tables and figures for each reach in my results show the Spl.DI and LIP value for each substrate class as well as a combined mean value. To combine the Spl.DI values of individual substrate classes into a single score, I calculated the mean score among classes to represent overall spatial diversity for the reach. To combine LIP scores into a single reach-wide value, I counted all scores where LIP < 1.0 and divided by the total number of possible substrate classes. For example, CP - R2 had four substrate classes as scoring less than 1.0 under the plot method so the overall output value for the reach was 4/7 = 0.57. Converting these values to a 0 < x < 1 spectrum allowed for more standardized comparisons between reaches and methods.

I determined the confidence interval (CI) for these values based on formulas that calculate the variance of the scores. However, after considerable research, I found equations for only SDI and SEI – likely because these are widely used and well known indices whereas LIP and Spl.DI have a narrower field of use. This was one of the weaknesses associated with using LIP and Spl.DI to determine patch heterogeneity. The variance formulas for SDI and SEI are:

\[
\text{VAR}_{\text{SDI}} = \frac{\sum_{i=1}^{s} \left( \frac{n_i}{N} \right)^3 - \left[ \sum_{i=1}^{s} \left( \frac{n_i}{N} \right) \right]^2}{N/4}
\]

\[
\text{VAR}_{\text{SEI}} = \frac{\sum_{i=1}^{s} n_i \ln(n_i)^2 - \left[ \sum_{i=1}^{s} n_i \ln(n_i) \right]^2}{N^2}
\]

Where \( s \) is the number of classes, \( n_i \) is the frequency of the \( i \)th class and \( N \) is the total sample (Statsdirect 2018).

3.4.3 Testing for significance between reaches and methods

I used a chi-square test of independence of both the plot method and pebble count to test whether reach totals for substrate classes were significantly different between reaches. For the chi-square test of independence, data must be in whole-number integers and not continuous data. For this
reason, the areal plot method data was converted to the frequency of occurrence of 12.5 by 25 cm quadrants within each plot. The plot had a total of 16 segments of this size for a total sample size of N=576 per reach. I could not test the data from the transect patch method because it included continuous data. While the chi-square test indicates whether the reaches can be said to be significantly different from each other, or more specifically, whether substrate distributions are independent (accepting the null) or dependent (rejecting the null) on a reach, it does not indicate how strong the relationship between these variables is. However, Cramer’s V does test the strength of associations between the reach and substrate composition so I used this test to determine how different the reaches were from each other.
4. Results and Discussion

4.1 Summary of substrate distributions

4.1.1. Pebble count summary and comparison

Pebble count results show that there was more non-vegetated habitat available for aquatic biota in the restoration project reaches than the untreated WC-R3. The largest sample, and therefore greatest non-vegetated area of the active floodplain was WC-R4 Delta with 617 samples taken, followed by WC-R4 Forest with 555 samples, CP-R2 with 519 samples and finally WC-R3 with 174 samples. These values cannot be explicitly compared because the floodplain widths varied somewhat between and within reaches but these values nevertheless point to several trends. First and most obvious is that WC-R3 had significantly less mineral and by inference, aquatic habitat available than the other three reaches. Additionally, WC-R3 was dominated by cobble (49%), making it the only reach with this dominant substrate class. This is an expected outcome since a smaller sample size indicates that the flow is confined to a smaller area and has more energy to entrain smaller particles. Conversely, the largest majority of the samples in the three project reaches fell in the ‘gravel’ class with 45% in CP-R2, 41% in WC-R4 Delta and 35% in WC-R4 Forest (figure 12), indicating that the project reaches likely disperse much of the hydraulic energy, resulting in smaller size class distributions.

Comparison of the reaches also indicates that CP-R2 class composition most closely resembled a parametric distribution of size classes while the two WC-R4 sections displayed higher rates of finer material. The distributions in the two WC-R4 sections may begin to mirror CP-R2 in the coming years as riparian and hydrophytic vegetation have a chance to recolonize areas of finer sediments. CP-R2 has likewise had more time for vegetation to become established which may also indicate why there were less mineral substrata present than the recently completed projects in Whychus Canyon. Under the detailed frequency distribution of smaller size ranges (figure 13), there are high rates of fine sediments (silt and sand) and comparatively low frequencies of the other size classes. This is because the size bins of the fine sediment classes remained the same but larger mineral classes were split into smaller range bins. These non-fine sediment classes in the three restoration reaches all resemble parametric distributions with the highest frequencies of the middle size classes – medium gravel, coarse gravel and very coarse gravel.

CP-R2 shows a relatively even spread of its interquartile range (figure 14) which indicates that the sizes from 25% above and below the median (the 25-75% range of substrata) were relatively evenly distributed throughout the reach. Conversely, the two WC-R4 reaches had smaller median diameters and size distributions skewed towards smaller particles. WC-R4 Forest had the widest interquartile range (1–45mm) as well as the widest overall range (0.5 to 1,200 mm) of the three project reaches. The WC-R3 size distribution had a median substrate size of 64 mm which qualifies the median size as “cobble” under the simple distribution (table 4) or “very coarse cobble” – “small boulder” under the detailed distribution (table 5).
Table 4: Simple size class distributions – pebble count

<table>
<thead>
<tr>
<th>Substrate class</th>
<th>Bin (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silt</td>
<td>0.5</td>
</tr>
<tr>
<td>Sand</td>
<td>1 – 4</td>
</tr>
<tr>
<td>Gravel</td>
<td>5 – 45</td>
</tr>
<tr>
<td>Cobble</td>
<td>46 – 256</td>
</tr>
<tr>
<td>Boulder</td>
<td>257 – 1200</td>
</tr>
</tbody>
</table>

Table 5: Detailed size class distributions – pebble count

<table>
<thead>
<tr>
<th>Substrate class</th>
<th>Size class</th>
<th>Bin (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silt</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Sand</td>
<td></td>
<td>1-2</td>
</tr>
<tr>
<td>Gravel</td>
<td>very fine</td>
<td>3-4</td>
</tr>
<tr>
<td></td>
<td>fine</td>
<td>5-8</td>
</tr>
<tr>
<td></td>
<td>medium</td>
<td>9-16</td>
</tr>
<tr>
<td></td>
<td>coarse</td>
<td>17-32</td>
</tr>
<tr>
<td></td>
<td>very coarse</td>
<td>33-64</td>
</tr>
<tr>
<td>Cobble</td>
<td>small</td>
<td>65-128</td>
</tr>
<tr>
<td></td>
<td>large</td>
<td>129-256</td>
</tr>
<tr>
<td>Boulder</td>
<td>small</td>
<td>257-512</td>
</tr>
<tr>
<td></td>
<td>large</td>
<td>513-1200</td>
</tr>
</tbody>
</table>

Figure 12: Substrate class distribution comparison between reaches – pebble count
Table 6: Substrate intermediate axis diameters (mm)

<table>
<thead>
<tr>
<th></th>
<th>CP-R2</th>
<th>WC-R4 Delta</th>
<th>WC-R4 Forest</th>
<th>WC-R3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minimum</strong></td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>1st quartile</strong></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>22.6</td>
</tr>
<tr>
<td><strong>Median</strong></td>
<td>16</td>
<td>11</td>
<td>8</td>
<td>64</td>
</tr>
<tr>
<td><strong>3rd quartile</strong></td>
<td>32</td>
<td>32</td>
<td>45</td>
<td>170</td>
</tr>
<tr>
<td><strong>Maximum</strong></td>
<td>340</td>
<td>310</td>
<td>1200</td>
<td>900</td>
</tr>
</tbody>
</table>

Figure 13: Detailed substrate class distribution compared between reaches – pebble count
Figure 14: Modified box-whisker plot of mineral substrate diameter distributions between reaches in (mm) This input data was not binned into classes but it displays the gross size distributions with the lowest whisker indicating the minimum size and first quartile, the bottom box indicating the second quartile range, the orange line indicating the median size and the upper box indicating the third quartile range. The fourth quartile cannot be displayed because the maximum diameter found in each reach is orders of magnitude larger than the rest of the distribution (table 6). WC-R3 contained much larger diameters so it is displayed on a separate scale.
4.1.2 Plot method summary and comparison

Under this method, CP-R2 once again had a strong dominance of gravel (49%) over other substrates while WC-R3 had a strong, though slightly lower dominance of cobble (43%). Similar to the results from the pebble count, both WC-R4 reaches had a more moderated spread of substrate classes (figure 15), indicating that there was a higher diversity of substrata in these reaches than WC-R3 or CP-R2. When comparing only mineral substrates from the plot method to the pebble count, the four reaches had similar distributions (table 7).

Though there are noticeable differences in percent-cover ratios between the two methods, there is only one difference in intra-reach substrate rank between the two methods. Under the pebble count method in WC-R3, boulders were the fourth most abundant substrate (7.5%) and in the plot method, they were the third most abundant (8.1% excluding biotic substrata). Though the percentage is similar, the rank in the pebble count indicates that there was more cover of sand than boulders in WC-R3. This is unsurprising since a pebble count only counts a boulder as a single occurrence in the overall makeup whereas the plot method takes into account its size - a single boulder may dominate an entire plot area. For this reason, the plot method shows that on average, there was 45% more coverage of boulders throughout all reaches than the pebble count.

Figure 15: Substrate class distribution between reaches – plot method
4.1.3 Transect patches summary and comparison

A comparison of the qualitative transect patch data among reaches indicates that WC-R4 Delta had a more complex and varied lateral profile than the other reaches – especially WC-R3 (figures 17 and 18). WC-R4 Delta and WC-R4 Forest also contained a relatively high amount of detritus (45.3 m and 24.3 m respectively) throughout the reach compared to Camp Polk R2 (11.5 m) and WC-R3 (6 m). WC-R3 had a significantly less complex geomorphic form than the project reaches (figures 16-19) as seen by the relatively narrow area of non-vegetated substrate classes. Indeed, this can also be seen by the number of data points or patch transitions collected in each reach:

CP-R2 N= 69
WC-R3 N= 28
WC-R4 Delta N= 87
WC-R4 Forest N= 64

Higher or lower complexity resulted from the abundance of wet and dry channels, large log jams, off-channel pools and hydraulic complexity. The relatively simple layout shown for WC-R3 was likely more homogenous than shown here. This is due to the fact that my sample included a dry relic channel within the floodplain that is hydrologically disconnected from the stream except during extreme runoff events. The diversity indices of all three methods may likewise overestimate heterogeneity of this reach.

Table 7: Mineral substrate distribution comparison between two methods.

<table>
<thead>
<tr>
<th>Pebble count</th>
<th>Silt</th>
<th>Sand</th>
<th>Gravel</th>
<th>Cobble</th>
<th>Boulder</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP-R2</td>
<td>14.8%</td>
<td>24.5%</td>
<td>45.5%</td>
<td>14.1%</td>
<td>1.2%</td>
</tr>
<tr>
<td>WC-R3</td>
<td>0.6%</td>
<td>15.5%</td>
<td>27.0%</td>
<td>49.4%</td>
<td>7.5%</td>
</tr>
<tr>
<td>WC-R4 Delta</td>
<td>11.2%</td>
<td>32.1%</td>
<td>40.8%</td>
<td>15.7%</td>
<td>0.2%</td>
</tr>
<tr>
<td>WC-R4 Forest</td>
<td>11.0%</td>
<td>35.0%</td>
<td>35.3%</td>
<td>17.7%</td>
<td>1.1%</td>
</tr>
<tr>
<td>Plot method</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CP-R2</td>
<td>18.3%</td>
<td>21.3%</td>
<td>48.9%</td>
<td>11.5%</td>
<td>0.0%</td>
</tr>
<tr>
<td>WC-R3</td>
<td>0.8%</td>
<td>7.8%</td>
<td>31.7%</td>
<td>43.6%</td>
<td>16.1%</td>
</tr>
<tr>
<td>WC-R4 Delta</td>
<td>7.8%</td>
<td>36.9%</td>
<td>30.5%</td>
<td>24.8%</td>
<td>0.0%</td>
</tr>
<tr>
<td>WC-R4 Forest</td>
<td>4.9%</td>
<td>34.8%</td>
<td>45.5%</td>
<td>12.8%</td>
<td>2.0%</td>
</tr>
</tbody>
</table>
Figure 16: Lateral substrate profile of CP-R2 measured in meters
Figure 17: Lateral substrate profile of WC-R3 measured in meters
Figure 18: Lateral substrate profile of WC-R4 Delta measured in meters
Figure 19: Lateral substrate profile of WC-R4 Forest measured in meters
4.2 Statistical testing between reaches

For the pebble count, the chi-squared test of independence indicates that the four reaches were significantly different from each other in terms of substrate class distribution. This test of independence was: \( X^2 (18, N = 1865) = 210.23, \ p < .001 \). However, for the boulder size class in WC-R3 (5% of the total) I was not able to reject the null hypothesis of independence, indicating this size class in this reach was too similar to the expected frequency and therefore could not be said to be dependent on the reach. This is likely due to the fact that the sample size for WC-R3 was relatively small (N=174) because of the small and confined area of mineral substrates throughout the reach. To reject the null hypothesis in the chi-square test of independence, \( X^2 \) must be greater than 5, but for the boulder class in WC-R3, \( X^2 = 2.4 \). This suggests that larger sample sizes are required in WC-R3 for future years. However, the results for the reach were still significantly different than the other three. The critical value for \( X^2 \) \( df = 18 \) at \( p < .001 \), is 42.31 so the given value of 210.23 shows strong independence between all reaches.

For the plot method, \( X^2 (18, N = 2306) = 836.57, \ p < .001 \). In this case, none of the classes in any reach had an expected count <5 which indicates that the sample size was indeed large enough for this method. Once again, the critical value at \( p < .001 \) is 42.31, therefore the given score of 836.57 indicates strong independence among reaches.

The Cramer’s V value for the pebble count method was \( V=0.19, \ p < 0.001 \) which shows that there was a weak - moderate relationship whereas with the plot method, \( V= 0.35, \ p <0.001 \) which indicates that there was a strong to very strong relationship between reach and substrate composition. This means that there is a more significant relationship between substrate compositions and a specific reach under the plot method than the pebble count method.
4.3 Quantifying patch heterogeneity

4.3.1 Pebble count

Under the pebble count, the heterogeneity metrics indicate that WC-R3 scored lowest on all four index values with an average score of 0.67 (table 16 and figure 20). The indices also illustrate that WC-R4 Forest was the most heterogeneous reach on three of the four outputs with an average score of 0.76. There was a relatively large disparity in scores from the two spatial-specific indices (LIP and Spl.DI) between WC-R3 and the three project reaches with a mean difference of 0.15 (24%). Conversely, there was a relatively small difference between WC-R3 and the others from the two indices based on reach totals (SDI and SEI) with a mean difference of 0.05 (8%). However, when the average group-level scores of SDI and SEI were compared between the project reaches and WC-R3 (i.e. meso-habitat diversity), the project reaches scored 0.08 higher (12% more diverse). Both the spatial-specific diversities as well as the group-level SDI / SEI indices showed greater disparities between the project reaches and the untreated reach than did reach-wide SDI / SEI scores. This indicates that there was more spatial diversity among more substrate classes in the project reaches than WC-R3 (figure 21).

Table 8: Diversity scores between reaches – pebble count

<table>
<thead>
<tr>
<th></th>
<th>SDI</th>
<th>SEI</th>
<th>LIP</th>
<th>μ (Spl.DI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP-R2</td>
<td>0.69 ± 0.03</td>
<td>0.82 ± 0.05</td>
<td>0.80</td>
<td>0.74</td>
</tr>
<tr>
<td>WC-R3</td>
<td>0.66 ± 0.05</td>
<td>0.75 ± 0.1</td>
<td>0.60</td>
<td>0.65</td>
</tr>
<tr>
<td>WC-R4 Delta</td>
<td>0.69 ± 0.05</td>
<td>0.79 ± 0.04</td>
<td>0.80</td>
<td>0.73</td>
</tr>
<tr>
<td>WC-R4 Forest</td>
<td>0.71 ± 0.02</td>
<td>0.83 ± 0.04</td>
<td>0.80</td>
<td>0.75</td>
</tr>
</tbody>
</table>
Figure 20: Pebble count diversity indices – all reaches

Table 9: Spatial distribution indices by substrate class - pebble count

<table>
<thead>
<tr>
<th></th>
<th>CP-R2</th>
<th>WC-R3</th>
<th>WC-R4 Delta</th>
<th>WC-R4 Forest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silt</td>
<td>0.13</td>
<td>0.82</td>
<td>2.67</td>
<td>0.07</td>
</tr>
<tr>
<td>Sand</td>
<td>0.23</td>
<td>0.95</td>
<td>0.95</td>
<td>0.73</td>
</tr>
<tr>
<td>Gravel</td>
<td>0.25</td>
<td>1.02</td>
<td>0.24</td>
<td>0.99</td>
</tr>
<tr>
<td>Cobble</td>
<td>0.18</td>
<td>0.78</td>
<td>0.08</td>
<td>0.97</td>
</tr>
<tr>
<td>Boulder</td>
<td>9.56</td>
<td>0.12</td>
<td>1.85</td>
<td>0.50</td>
</tr>
</tbody>
</table>
Note that some values under the Spl.DI were slightly over 1.0 which is likely due to rounding errors since the values are combinations of several separate formulas. However, they should be viewed as having a Spl.DI value of 1.0 which indicates a consistent, even dispersal across the entire reach.

*Figure 21: Breakdown of Spl.DI by substrate class – pebble count*
4.3.2 Plot method

Under this sampling method, WC-R4 Delta was on average 5% more diverse than the Forest reach—a reversal of the Delta reach being an average of 2% more diverse than the Forest reach under the pebble count method. The plot method illustrates generally higher scores for the two WC-R4 reaches than the pebble count while simultaneously indicating lower scores in CP-R2 and WC-R3. This method also displays a more distinct substrate signature for each reach than the pebble count. This is illustrated by comparing the wider range of index values in table 10 to the index values in table 6 which show more moderated scores (smaller ranges). This difference in index value range was also supported by the significant differences in Cramer’s V test values where under the pebble count, \( v = 0.19 \) and under the plot method, \( v = 0.35 \) which suggests a more distinct signature for each reach when measured with plots.

Table 10: Diversity scores between reaches – plot method

<table>
<thead>
<tr>
<th></th>
<th>SDI</th>
<th>SEI</th>
<th>LIP</th>
<th>( \mu ) (Spl. DI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP-R2</td>
<td>0.67 ± 0.02</td>
<td>0.66 ± 0.03</td>
<td>0.57</td>
<td>0.54</td>
</tr>
<tr>
<td>WC-R3</td>
<td>0.68 ± 0.01</td>
<td>0.65 ± 0.03</td>
<td>0.43</td>
<td>0.51</td>
</tr>
<tr>
<td>WC-R4 Delta</td>
<td>0.76 ± 0.01</td>
<td>0.81 ± 0.03</td>
<td>0.86</td>
<td>0.74</td>
</tr>
<tr>
<td>WC-R4 Forest</td>
<td>0.74 ± 0.01</td>
<td>0.80 ± 0.04</td>
<td>0.71</td>
<td>0.77</td>
</tr>
</tbody>
</table>
Table 11: Spatial distribution indices by substrate class - plot method

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Silt</td>
<td>0.08</td>
<td>0.98</td>
<td>5.82</td>
<td>0.00</td>
<td>0.50</td>
<td>0.79</td>
<td>1.48</td>
<td>0.50</td>
</tr>
<tr>
<td>Sand</td>
<td>0.19</td>
<td>0.95</td>
<td>1.01</td>
<td>0.69</td>
<td>0.43</td>
<td>0.87</td>
<td>0.07</td>
<td>0.98</td>
</tr>
<tr>
<td>Gravel</td>
<td>0.02</td>
<td>1.00</td>
<td>0.27</td>
<td>0.92</td>
<td>0.45</td>
<td>0.85</td>
<td>0.20</td>
<td>0.94</td>
</tr>
<tr>
<td>Cobble</td>
<td>0.60</td>
<td>0.86</td>
<td>0.09</td>
<td>0.98</td>
<td>0.24</td>
<td>0.92</td>
<td>0.69</td>
<td>0.81</td>
</tr>
<tr>
<td>Boulder</td>
<td>0.00</td>
<td>0.00</td>
<td>0.24</td>
<td>0.94</td>
<td>0.00</td>
<td>0.00</td>
<td>1.69</td>
<td>0.50</td>
</tr>
<tr>
<td>Detritus</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.65</td>
<td>0.82</td>
<td>0.79</td>
<td>0.73</td>
</tr>
<tr>
<td>Vegetation</td>
<td>5.25</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.43</td>
<td>0.89</td>
<td>0.22</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Figure 22: Plot method diversity indices – all reaches
Figure 23: Breakdown of Spl.DI by substrate class – plot method
4.3.3 Transect patch method

The transect patch method shows comparatively lower values than the other two methods. This is likely due to the fact that it was the only method that sampled the large areas of vegetation within the active floodplain and the resulting proportions negatively skewed the diversity indices. For example, the CP-R2 transects contained 80.4% vegetation and the other 19.6% of the area was split between six other classes. Nevertheless, it served as an important sampling strategy because the data included the entire transect and did not rely on chance and randomization to represent stream group conditions. In general, the results mirror what the other two methods indicate – that substrata in the two WC-R4 segments were more heterogeneous while WC-R3 remained the most homogenous (table 12 and figure 24).

Table 12: Diversity scores between reaches – transect patch method

<table>
<thead>
<tr>
<th></th>
<th>SDI</th>
<th>SEI</th>
<th>LIP</th>
<th>Spl.DI</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP-R2</td>
<td>0.34 ± 0.03</td>
<td>0.36 ± 0.09</td>
<td>0.43</td>
<td>0.62</td>
</tr>
<tr>
<td>WC-R3</td>
<td>0.19 ± 0.02</td>
<td>0.22 ± 0.08</td>
<td>0.29</td>
<td>0.58</td>
</tr>
<tr>
<td>WC-R4 Delta</td>
<td>0.54 ± 0.03</td>
<td>0.60 ± 0.09</td>
<td>0.57</td>
<td>0.71</td>
</tr>
<tr>
<td>WC-R4 Forest</td>
<td>0.43 ± 0.03</td>
<td>0.64 ± 0.11</td>
<td>0.43</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Figure 24: Transect patch method diversity indices – all reaches
4.4 Combined methods

Average scores between all methods and indices (table 13) show that WC-R4 Delta was the most diverse reach with a mean score of 0.72 and WC-R3 was the least diverse with an mean score of 0.52 – a 38% difference. CP-R2 shows only a 15% more heterogeneous score than WC-R3 despite the fact that it was hypothesized that it would be the most diverse reach. Though averaging scores among indices and methods offers an overly simplistic view of each reach, it does provide an overall summary of reach conditions and it allows for a convenient ranking system that includes all types of collected data.

Table 13: Mean diversity scores between methods and reaches. Values for each method are the mean score of SDI, SEI, LIP and Spl.DI for each reach and the mean score among the three methods is again averaged to get a single value for each reach that includes all diversity indices and all methods.

<table>
<thead>
<tr>
<th></th>
<th>Pebble Count</th>
<th>Plot</th>
<th>Transect Patches</th>
<th>Mean score</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP-R2</td>
<td>0.76</td>
<td>0.61</td>
<td>0.44</td>
<td>0.60</td>
</tr>
<tr>
<td>WC- R3</td>
<td>0.67</td>
<td>0.56</td>
<td>0.32</td>
<td>0.52</td>
</tr>
<tr>
<td>WC - R4 Delta</td>
<td>0.76</td>
<td>0.79</td>
<td>0.61</td>
<td>0.72</td>
</tr>
<tr>
<td>WC - R4 Forest</td>
<td>0.77</td>
<td>0.76</td>
<td>0.52</td>
<td>0.68</td>
</tr>
</tbody>
</table>
4.5 Correlations between indices and reaches

To test correlations between the data collection method used and diversity indices, I ran a simple Pearson’s correlation test. With testing all indices, $r = 0.57$, $N= 16$, $p < 0.05$ which is a moderate correlation. However, since LIP tends to be interpreted on a dichotomous scale ($\text{LIP} = <1$ or $>1$) to indicate congregation or dispersal, and it is not generally interpreted on a continuum, I ran a separate correlation on only SDI, SEI and $\mu(\text{Spl. DI})$. The results show a closer relationship with $r = 0.65$, $N=12$, $p < 0.05$ which is considered a strong relationship (figure 25). Finally, I ran a correlation on all of the mineral Spl.DI scores (biotic classes were dropped from the plot method) for each class and reach – rather than using the mean Spl.DI used in preceding correlations (figure 26). This resulted in the strongest relationship with $r = 0.89$, $N=20$, $p <0.01$. This strong relationship indicates that the two methods were more robust in determining spatial distribution between groups of transects than they were when data was summarized by reach. It also indicates that the two methods captured similar proportions of each substrate class on the group-level. However, as the summary statistics indicate, the pebble count attenuated differences in the between reaches while the two ocular estimate method tended to accentuate them.

![Diversity index comparison between methods w/o LIP](image.png)

Figure 25: Scatterplot and trendline showing the relationship between pebble count diversity indices and plot method diversity indices without LIP scores. In this example, $r = 0.65$. 
Figure 26: Scatterplot and trendline showing the relationship between pebble count Spl.DI values and plot method Spl.DI values (mineral only). In this example, $r = 0.89$. 
5. Conclusion

5.1 Reach conditions

The methods used for determining substrate patch heterogeneity exhibit clear trends among the four study reaches of Whychus Creek. Quantitative and qualitative data indicate that both WC-R4 sections were the most heterogeneous reaches. This is somewhat contrary to the original hypothesis that CP-R2 would have the most heterogeneous substrate patches, WC-R4 (both sections together) would have slightly less and WC-R3 would have the most homogeneous distribution of patches. It is encouraging that the most recent restoration project shows the most diverse mosaic of substrata because this should encourage strong rates of post-disturbance recolonization by riparian vegetation, macroinvertebrates, fish and other species at higher trophic levels (Milesi, Doledec and Melo 2016). However, it is important not to deduce that one reach is necessarily a ‘healthier’ system than another based solely on these results. To illustrate this, WC-R4 had instances of head-cuts, terraced banks, cut banks and other features characteristic of a dynamic stream system progressing through stream evolutionary stages. Conversely, CP-R2 was consistently valued as having a slightly less heterogeneous patch mosaic than WC-R4, even though it has had more time to progress towards a late-evolutionary-stage system. It is therefore important to analyze the findings of this project in the context of other ongoing monitoring efforts throughout Whychus Creek. Whether the geomorphic profile of WC-R4 is and continues to be inherently more diverse or whether its diversity will be attenuated by vegetation recolonization and increased sediment sorting remains to be seen.

There was a clearer distinction between Whychus Canyon reaches 3 and 4. This is especially relevant because the entire canyon resembled WC-R3 prior to the completion of the major restoration activities in 2016. The results presented here clearly illustrate that there was greater substrate heterogeneity in the post-project than pre-project condition. Since WC-R3 can act as a control site, one can infer that the quantitative and qualitative outputs of this protocol determine how much the restoration activities have created a more diverse landscape. Since the Whychus Canyon restoration reaches are downstream, they do not directly influence WC-R3. The results of this project can also act as a baseline measurement for a before-after (BA) design of evaluating future restoration activities on WC-R3. However, the data for WC-R3 likely indicate a more diverse habitat than was actually available for aquatic and riparian biota since the transects in this reach extend into a floodplain that is hydrologically disconnected from the creek except during extreme flood events. Specifically, data collected from a relic channel and a discontinued irrigation canal within the boundary of the sample area likely increased the values of heterogeneity.

5.2 Data collection and analysis

Based on the results of the chi-square tests, the Cramer’s V tests and the diversity indices themselves, it is apparent that the plot method achieved the most accurate quantifiable representation of patch diversity in each reach. The plot method showed stronger relationships between distinct substrate compositions in each reach as well as more significant discrepancies in diversity index scores between reaches. However, the other two methods are useful in other
contexts. The pebble count allows for a host of additional analytical tools not used in this study (see: Bunte and Abt 2001). In addition, tracking the substrate sizes over time and analyzing size distributions from box-whisker plots can be important indicators of changes in fluvial processes that other two methods will not necessarily capture. The transect patch method produces useful qualitative charts that can indicate how diverse the large patches are in the lateral profiles of the stream. In short, though the plot method seems to exhibit the most accurate representation of patch heterogeneity, all three methods taken together provide a fuller picture of overall conditions that the plot method cannot reproduce in isolation (appendix F).

5.3 Implications

This substrate monitoring protocol has proven to be an informative tool that allowed me to assess the conditions and evolution of fluvial geomorphic processes on Whychus Creek. Stream substrate patchiness and heterogeneity holds important implications for both aquatic and terrestrial biota through niche diversification, ecosystem resilience, post-disturbance recovery and ontogenetic migration (Milesi, Doledec and Melo 2016). By increasing hydraulic, geomorphic and topographic heterogeneity, the restoration projects in Camp Polk and Whychus Canyon are enhancing these benefits and restoring these reaches to highly productive ecosystems.

Substrate conditions are among the first factors to change within a watershed and tracking such changes can signal large-scale shifts within the basin. Such changes in land use, water management or natural cycles in the hydrograph are important factors track for the restoration partners. Whereas biotic variables tend to have a longer lag time in responding to such input variables, substrate conditions change on a much shorter timescale, allowing for more immediate assessment and management response. Therefore, by using this pilot project as a baseline, further annual monitoring will be able to quantify geomorphic conditions in future years and may help inform restoration-related decision making for other projects.
6. **Recommendations**

This pilot project proved to be a robust means of determining the geomorphic response to restoration projects on Whychus Creek. I strongly encourage continued monitoring based on these methods for future years to be able to analyze how the various reaches are responding to the restoration efforts. If this monitoring protocol is able to continue, I have several suggestions to improve the process.

1. If there are sufficient funds and time, conducting all three methods described here would be useful to be able to compare results between years. If there is limited time, the pebble count should be dropped from the protocol. As seen from the these results, it is the least useful in determining patch heterogeneity because the method can muddle the differences in patch distribution by selecting anomalous samples in distinct patches of a particular substrate class. However, a pebble counts conducted every two or three years can be informative since it useful for determining changes in the median and interquartile size distributions throughout the reaches (figure 14). Additionally, it allows for a variety of different analyses that can be used to detect changing stream conditions.

2. I recommend an increased sample size for the plot method in future years. Rather than the three samples per transect (36 per reach) collected in the pilot project, I propose using six per transect (72 per reach) to more accurately capture the conditions in each group. The transect patch method charts indicate higher diversity of substrate classes and patchiness than reflected in the diversity indices under the plot method so a higher sample size per transect may be able to narrow that difference. Specifically, I recommend using the same randomization process as with the original three-placement strategy but instead, each placement would sample two contiguous plots. To reduce bias, the surveyor would sample and record one plot placement then consistently flip the plot along the transect always to river right or always river left to sample again. Under this design, each of the three placements would sample a 2 x 0.5-m area with 32, 12.5 x 25-cm quadrants counted.

3. If time is very limited to and only one method can be conducted, the plot method is the most useful for quantifying patch heterogeneity, accurately determining significant differences between reaches and efficiently sampling each transect. Two surveyors can gather the 36 samples from each reach in approximately three hours per reach – one hour for WC-R3 in its current state.

4. I recommend that future surveyors read the protocol carefully and review this report before collecting official data. There are multiple strategies that the surveyor can implement to improve accuracy and replicability – included in the separate protocol document. I also highly suggest that only one surveyor conducts each method, as adding more surveyors increases bias discrepancies. Finally, each surveyor should practice each method along an entire transect before officially gathering data, as this has been shown to improve accuracy.
5. I also recommend that future data analysis include more detailed statistical tools than I used here. There are more options available to draw stronger conclusions when there are multiple samples taken from the same sites. Since pre-formatted excel sheets and analytical instructions are included with this pilot project, analyzing the results at the level presented here should not require a large time commitment, and more work can be done to expand upon the groundwork laid out in this report. This is especially true if the UDWC is going to do a BA design analysis of future restoration on WC-R3. This is because it would be important to understand how consistent or inconsistent the monitoring protocol is between years before the baseline analysis is compared to the post-restoration response.

6. If another similar pebble count is conducted, the surveyor should collect more samples in WC-R3 while it is in its current condition. The chi-square test of independence suggested that the sample size was slightly too small for that reach. If using the sampling frame, each frame placement should sample four pebbles rather than two as was done in 2018. This can easily be done by using the point intersect method of the four outermost crosshairs on the frame.

7. The findings of this project could be compared within a larger context of other sampling protocols such as macroinvertebrate abundances and diversities. It would be interesting to run regression analyses between patch diversity and macroinvertebrate diversity to see if and how they respond to patch heterogeneity.
References


Appendix A: Stream Evolution Model

The design of the most recent restoration projects and the realization of the importance of quantifying substrate heterogeneity arose largely out of Cluer and Thorne’s Stream Evolution Model (2014). Below is a basic table and graphic representation of the various stages this model.
<table>
<thead>
<tr>
<th>SEM</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0. Anastomosing</td>
<td>Pre-disturbance, dynamically meta-stable network of anabranching channels and floodplain with vegetated islands supporting wet woodland or grassland. $Q_{in} &gt; Q_{out}, h &lt;&lt; h_c$</td>
</tr>
<tr>
<td>1. Sinuous</td>
<td>Dynamically stable and laterally active channel within a floodplain complex. Flood return period 1-5 yr range. $Q_{in} \geq Q_{out}, h &lt;&lt; h_c$</td>
</tr>
<tr>
<td>2. Channelized</td>
<td>Re-sectioned land drainage, flood control, or navigation channels. $Q_{in} \leq Q_{out}, h &gt; h_c$</td>
</tr>
<tr>
<td>3. Degrading</td>
<td>Incising and abandoning its floodplain. Featuring head cuts, knick points or knick zones that incise into the bed, scour away bars and riffles and removes sediments stored at bank toes. Banks stable geotechnically. $Q_{in} &lt; Q_{out}, h &gt; h_c$</td>
</tr>
<tr>
<td>3a. Arrested degradation</td>
<td>Stabilized, confined or canyon-type channels. Incised channel in which bed lowering and channel evolution have been halted because non-erodible materials (bed rock, tight clays) have been encountered. $Q_{in} \sim Q_{out}, h &gt; h_c$</td>
</tr>
<tr>
<td>4. Degradation and widening</td>
<td>Incising with unstable, retreating banks that collapse by slumping and/or rotational slips. Failed material is scoured away and the enlarged channel becomes disconnected from its former floodplain, which becomes a terrace. $Q_{in} &lt; Q_{out}, h &gt; h_c$</td>
</tr>
<tr>
<td>4-2. Renewed incision</td>
<td>Further head cutting within Stage 4 channel. $Q_{in} &lt; Q_{out}, h &gt;&gt; h_c$</td>
</tr>
<tr>
<td>5. Aggrading and widening</td>
<td>Bed rising, aggrading, widening channel with unstable banks in which excess load from upstream together with slumped bank material build berms and silts bed. banks stabilizing &amp; berming. $Q_{in} &gt; Q_{out}, h \sim h_c$</td>
</tr>
<tr>
<td>6. Quasi-equilibrium</td>
<td>Inset floodplain re-established. quasi-equilibrium channel with two-stage cross-section featuring regime channel inset within larger, degraded channel. Berms stabilize as pioneer vegetation traps fine sediment, seeds and plant propagules. $Q_{in} \sim Q_{out}, h &lt; h_c$</td>
</tr>
<tr>
<td>7. Laterally active</td>
<td>Channel with frequent floodplain connection develops sinuous course, is laterally active and has asymmetrical cross-section promoting bar accretion at inner margins and toe scour and renewed bank retreat along outer margins of expanding/migrating bends. $Q_{in} \geq Q_{out}, h &lt;&lt; h_c$</td>
</tr>
<tr>
<td>8. Anastomosing</td>
<td>Meta-stable channel network. Post-disturbance channel featuring anastomosed planform connected to a frequently inundated floodplain that supports wet woodland or grassland that is bounded by set-back terraces on one or both margins. $Q_{in} \geq Q_{out}, h &lt;&lt; h_c$</td>
</tr>
</tbody>
</table>
Appendix B: Map of the DLT-managed lands along Whychus Creek

Source: (Deschutes Land Trust n.d.)
Appendix C: Detailed sampling protocols

Plot method

1. Starting from the downstream most transect, use a tablet with the relevant georeferenced map of the reach and a GPS unit to find the monumented transect endpoints.

2. Using the GPS and map as a guide, walk along the transect and place several pieces of flagging on trees or bushes along intermediate points between the two transect endpoints.
   a. The goal is to be able to see two points at all times along a transect.

3. On MS Excel, use random number function to generate 3 random numbers 1-100
   a. Type: =randbetween(1,100)
   b. Drag formula down 2 cells.

4. Use these as percentages to determine where along the transect to place the plot from river left bank (0%) to the far river-right bank (100%).
   a. Exclude regions dominated by vegetation (>90%).
   b. If there are multiple channels, split the 3 samples between those channels – ex: 12% across 1 channel, 39% across another and 91% across the a third channel.

5. Lay the 1 X 0.5 m plot parallel to transect (perpendicular to the flow) with the center of the plot located approximately at the given percentage point.

6. Once plot is placed, one surveyor visually identifies major substrate classes and patch boundaries within the plot.
   a. Patches are identified by the dominant class within a given patch.

7. Size classes are as follows:
   a. clay/silt: smooth between fingers (not gritty)
   b. sand: < BB
   c. gravel: BB – tennis ball
   d. cobbles: tennis ball – basketball
   e. boulders: > basketball,
   f. bedrock: very large with flat surface
   g. Detritus: dead/decaying plant material including large woody debris only if it is on the ground, not suspended above the stream bed.

8. Once patches and boundaries are identified, count the number of 12.5x25 cm quadrants (N=16) that a particular patch underlays.
   a. If a quadrant has two distinct patches in it, determine which covers more area and count that class as 1/16 of the plot.
   b. Do NOT search for small patches within each of the 16 quadrants – first find major patches within the plot, THEN count the corresponding quadrants. Most plot placements will have 1 – 3 distinct patch classes.
9. Call out to the second surveyor the number of quadrants of each class in the plot and they record it on the data sheet (digital or paper).

10. If the transect bisects a deep pool that prevents ocular estimates, select 5 particles from 5 random crosshairs, measure them with the gravel card and use the median size to classify the entire plot.

11. On the data sheets, include reach I.D., grouping #, transect # and plot #.
   a. Group numbers range from 1-4 from downstream to upstream
   b. Transect numbers range from 1-3 downstream to upstream within a group
   c. Plot numbers range from 1-3 in each transect

12. Remove intermediate flagging between endpoints.

Example 1A: An abnormally complex patch mosaic with many distinct patches

![Image of a patch mosaic with grid lines and various patches]

Scagliotti

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Example 1B: Delineated patch boundaries

Example 1C: Table representing the dominant substrate class per quadrant

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Gravel</th>
<th>Gravel</th>
<th>Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>Gravel</td>
<td>Gravel</td>
<td>Gravel</td>
</tr>
<tr>
<td>Sand</td>
<td>Gravel</td>
<td>Sand</td>
<td>Sand</td>
</tr>
<tr>
<td>Sand</td>
<td>Sand</td>
<td>Gravel</td>
<td>Gravel</td>
</tr>
</tbody>
</table>

Example 1D: Resultant substrate class counts

<table>
<thead>
<tr>
<th>Silt</th>
<th>Sand</th>
<th>Gravel</th>
<th>Cobble</th>
<th>Boulder</th>
<th>Vegetation</th>
<th>Detritus</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>7</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
Example 2A: A homogenous sample that would be qualified as 100% (N=16) gravel. While there are several individual pieces that may qualify as cobble, there are no obvious patches within the plot and therefore, these anomalous individuals are not the dominant category.

Example 2B: Resultant substrate class counts

<table>
<thead>
<tr>
<th>Silt</th>
<th>Sand</th>
<th>Gravel</th>
<th>Cobble</th>
<th>Boulder</th>
<th>Vegetation</th>
<th>Detritus</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>16</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Pebble Count Method

1. Starting from the downstream most transect, use a tablet with the relevant georeferenced map of the reach and a GPS unit to find the monumented transect endpoints.

2. Using the GPS and map as a guide, walk along the transect and place several pieces of flagging on trees or bushes along intermediate points between the two transect endpoints.
   a. The goal is to be able to see two points at all times along a transect.

3. Starting at one end of the transect, place the plot parallel to transect (perpendicular to the valley).
   a. Always stand downstream of the plot so as not to disturb the sample.

4. At the intersection of the upstream and outermost crosshairs, reach down with one finger and select the first object your finger touches.
   a. Do NOT look at the substrate before you select a sample.

5. Measure sample by finding the smallest hole on gravel card that the sample will fit through and record that the corresponding number labeled on the card.
   a. If sample is larger than the gravel card holes, use the metric ruler on the side to measure intermediate axis (not the longest, not the shortest axis, but the middle axis)
   b. If you touch fine particles and you cannot accurately measure an individual particle, define that sample as either sand (1-mm) if it is gritty between fingers or silt (0.5-mm) if it is smooth between fingers.
      i. However, note that the gravel card can measure particles as small as 2 and 4-mm so be careful not to record small particles as 1-mm when they would actually closer resemble 2 or 4-mm size classes.
   c. For substrate that is too embedded to remove, use a loose ruler to measure intermediate axis

6. Call out to second surveyor the particle size and they record the diameter on the data sheet.
   a. Only sample mineral substrates, if biotic substrates are encountered, simply do not record that sample. Do NOT dig under vegetation or detritus to find an underlying mineral substrate.

7. First surveyor repeats sample selection on the next outside crosshair along the transect.

8. After two samples have been collected for each plot placement (1 sample every 0.5 m), flip the plot over along short axis to continue measuring along the transect.
   a. For areas of >90% vegetation as would be measured by a single plot-placement, the surveyors may walk to the next patch of mineral substrates where non-vegetated substrates would constitute at least 10% or more of the plot area.
b. Be sure to remain in line with the transect by continually checking your position between flagging tape.

9. Areas that exhibit predominantly upland vegetation (e.g. bitterbrush, rabbitbrush, juniper, ponderosa) should NOT be recorded. However, if there are some facultative riparian plants (equisetum, willows, sedges etc.) mixed with some upland vegetation, then sample that area.

10. Remove intermediate flagging between endpoints.

11. Only one surveyor should sample a single reach. If possible only one surveyor should do all pebble counts on all reaches in a given year.
Transect Patch Method

1. Starting from the downstream most transect, use a tablet with the relevant georeferenced map of the reach and a GPS unit to find the monumented transect endpoints.

2. Using the GPS and map as a guide, walk along the transect and place several pieces of flagging on trees or bushes along intermediate points between the two transect endpoints.
   a. The goal is to be able to see two points at all times along a transect.

3. Starting from the river-left endpoint of a transect, use a 60 or 100m metric tape and measure the width of the immediate substrate class (typically vegetation) from the monumented rebar to the boundary of the next distinct substrate class.
   a. Second surveyor typically holds the end of the tape.

4. The second surveyor records the substrate class and width in meters to the nearest tenth (e.g. 9.4 m of vegetation).

5. The first surveyor places a pole or survey flag on the border between substrate classes and that marks the starting point for the next measurement.
   a. Be sure to remain in line with the transect by continually checking your position between flagging tape.

6. Size classes are as follows:
   a. clay/silt: smooth between fingers (not gritty)
   b. sand: < BB
   c. gravel: BB – tennis ball
   d. cobbles: tennis ball – basketball
   e. boulders: > basketball,
   f. bedrock: very large with flat surface
   g. Detritus: dead/decaying plant material including large woody debris only if it is on the ground, not suspended above the stream bed.

7. Continue measuring substrate patch widths until you have reached the far endpoint of the transect.

8. If the transect bisects a deep pool that limits visual identification, select 1 particle from the toe of your boot at 5 different locations along the transect, measure the intermediate axis with the gravel card and use the median size to classify the area that you cannot see.

9. Remove intermediate flagging between endpoints.
Improving surveyor accuracy

For future substrate monitoring, the surveyor should review this report as well as the detailed written procedures document to ensure that they understand the protocols. They should also do several practice passes of each method to assess any unforeseen challenges. To reduce inter-surveyor bias, only one surveyor should perform each protocol and this person should also review training materials as seen below to improve their accuracy.


https://www.pifsc.noaa.gov/cred/survey_methods.php
Equipment list

- 60m or 100m tape
- 2 gravel cards
- iPad – charged
- GPS unit
- Field chargers as backups
- Uploaded data sheets
- Printed data sheets as backup
- Write-in-the-rain notebook and pencils
- Waders and boots
- Sampling frame / plot square
- Laminated procedures instructions
- First aid kit
- Wading/trekking pole
- Multi-tool (for tightening collars on the plot)

Safety considerations

- Rattlesnakes
  - Whyhus Canyon has a healthy population of Great Basin Rattle Snakes
  - Walk Slowly, stomp loudly, listen for their rattles and wear long pants
  - A trekking pole can add a buffer between you and the snake
- Weather related illness
  - The canyons can regularly range 90-100+ degrees in the summer so carry plenty of water (minimum 2 liters), take breaks and snack regularly
  - Shoulder season sampling can also include below-freezing temperatures – plan accordingly
- Musculoskeletal injuries
  - Wading/trekking poles can help one safely navigate fast-flowing water and climbing in and out of steep toe-slopes.
- Wader accidents
  - Walk slowly and test the depth as you go
  - Wear a wading belt
  - Stay within eyesight of the other surveyor
Appendix D: Graphic representation of LIP

A sample representation of Lloyd’s Index of Patchiness that measures how congregated or separated samples of a particular substrate class are. This example below is the occurrence of a fungus in soil but can be applied to substrate classes (Xiao 1997). Values >1 indicate dispersed, non-congregated occurrence and values <1 indicate a congregated, patchy distribution.

Source: (Xiao, Hao and Subbarao 1997)
Appendix E: Graphic Representation of Spl.DI

A sample representation of the Spatial Diversity Index which determines how widely dispersed a substrate class is throughout the reach. Values range between 0 and 1 with higher values indicating a more widely dispersed substrate class.

Source: (Yabuki 2009)