Assessing the Wetlands of a Stage 0 River Restoration Project on Whychus Creek, Deschutes County, Oregon.

Thomas Goss

Prepared for: Upper Deschutes Watershed Council

Executive Summary:

The Upper Deschutes Watershed Council has worked closely alongside a number of partners, from academics of restoration science, such as Professor Colin Thorne of the University of Nottingham, to land owners, like the Deschutes Land Trust, to implement process-based, Stage 0 river restoration on a reach of Whychus Creek, Oregon. This project aims to restore habitat and ecosystem functions to the reach, in order to restore the numbers of Salmonids and Trout species, which are listed under the Endangered Species Act.

The outcomes of this restoration are being evaluated through post-project monitoring of the newly created wetlands and in channel heterogeneity, using wetland function assessments and bankfull modelling. This research compares restored and unrestored reaches of Whychus Creek and looks at the development of the wetlands between and between 2018 and 2019. T- tests on wetland function assessment scores imply that the restored reach functions better than the unrestored reach. Results are less conclusive when exploring wetland development between 2018 and 2019, as the wetland is still relatively underdeveloped. It is essential that more monitoring is completed in the future to assess the success of the project and inform future restoration schemes.

1: Introduction:

1.1. Background:

Over the last 5 decades there has been a concerted effort to restore degraded riverine environments (Katz et al., 2007; Powers et al., 2018). In the last decade, projects have begun to focus more on the processes underpinning river planform instead of focusing on river form itself (Beechie et al., 2013; Bernhardt and Palmer, 2011; Booth et al., 2016). One novel approach to river restoration is the concept of "Stage 0", which is a conceptual approach that involves reconnecting a stream to its floodplain and allowing the river to develop an anastomosed system (Powers et al., 2018). Stage 0 concepts seek to remove disturbances and restore reach baselevel as well as more granular, watershed-scale processes including the natural recruitment of wood into the stream (Powers et al., 2019). This idea was developed from Cluer and Thorne's (2013) Stream Evolution Model concept.

Usually, a restoration project seeks to restore the river back to a reference condition. While it may be possible to identify pre-disturbance reference conditions, it may not be feasible to restore a river to these conditions. Therefore, different scales of restoration intervention may be employed with the aim of reclaiming, restoring or rehabilitating the structure and, as aforementioned, function of ecosystems (Dobson et al., 1997; Abelson et al., 2015) (Figure 1.1).

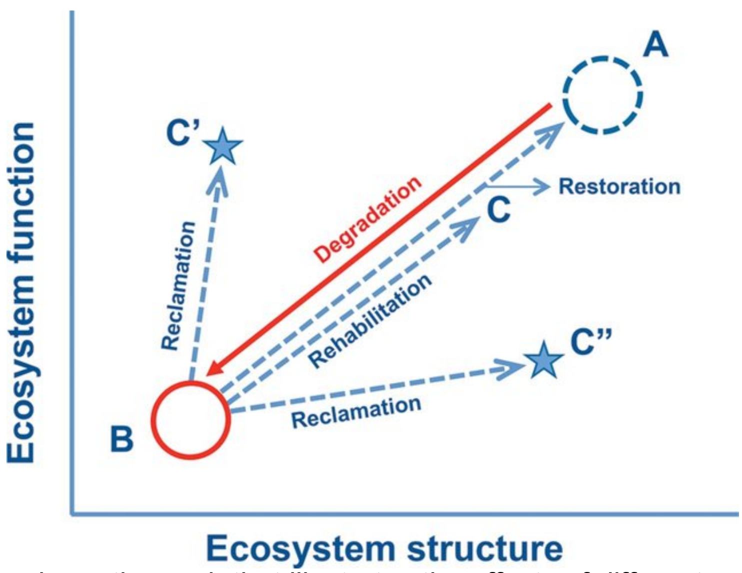

Figure 1.1.: *A schematic graph that illustrates the effects of different scales of restoration interventions (Abelson et al., 2015, adapted from Dobson, 1997).*

Stage 0 is most applicable to pre-disturbance states that were thought to be wetland, 'wet meadows' or inundated riparian areas. Reconnecting the channel to its floodplain and an elevated water table leads to recovery of wetland conditions and characteristics; these are synonymous with Stage 0 restoration (Powers et al., 2018). There are a number of habitat benefits associated with recovery of wetlands; for example, multiple channels, islands and broad floodplains offer a large diversity of habitats and refugia (Maltby and Acreman, 2011; Cluer and Thorne, 2013; Powers et al., 2018). Therefore, ecological restoration has taken place to attempt to recover the benefits of these wetland ecosystems (Moreno-Mateous *et al.,* 2012). Loss of such benefits is the result of a reduction in the number and size of wetlands, with estimations that the worlds land surface is covered by 6% wetlands (Maltby and Turner, 1983), around half the amount that existed prior to human disturbance (Maltby, 1986). This loss has often been attributed to a poor understanding of wetland functions and ecosystem services (Maltby and Acreman, 2011).

The functions of wetlands were first highlighted in the USA in the 1970's (Horwitz, 1978, Greeson and Clark, 1980, Adamus and Stockwell, 1983, Tiner, 1984, Sather and Smith, 1984). This increased prominence gave rise to a number of assessments of such wetland functions, known as 'Wetland Function Assessments', defined as assessments which "acknowledge that wetlands can perform work at a variety of scales in the landscape, which may result in significant direct and indirect benefits to people, wildlife and the environment" (Maltby, 2009: 87). In Oregon, Adamus (2001; 2016) has developed methodologies to quantify 13 functional benefits of wetlands.

With increasing knowledge of the numerous functions of wetlands came the realisation that they are among the most valuable ecosystems on the planet (Mitsch and Gosslink, 2015). This value is usually instrumental, associated with the benefits that nature brings to humans (Diaz *et al.,* 2015). The majority of these benefits are given without human interference (e.g. wetlands offering flood regulation) unlike other ecosystem benefits, which require co-production (e.g. the production of fuel wood from a tree) (Fischer and Eastwood, 2016).
At Whychus Creek, the wetlands were restored in 2016, and Wetland Function assessments are now being used to assess the success of restoration. Monitoring is vital when there is a need to determine whether a technique has worked effectively (Clark 2002; Bruce-Burgess and Skinner, 2002; Tompkins and Kondolf, 2007; England *et al.*, 2008) and so monitoring this novel restoration scheme is crucial. Of particular interest is modelling bankfull flows in the area as this will contribute to understanding of the functions of the restored reach of Whychus Creek, Oregon. The concept of bankfull flow was first introduced in a publication by Wolman and Leopold in 1957 and is defined as "the point where the river channel is full of

its capacity and the flow is just before entering the active floodplain" (Schneider et al., 2011, 235). Flows at bankfull are the most informative flows, as they are the most effective so tell us about the maximum potential of a river (Andrews, 1980), and they provide us with the most appropriate method to understand flows in a channel.

1.2. Aims and Objectives:

Aim:

The aim of this project is to assess the outcomes of restoration at Whychus Canyon Reach 4 on Whychus Creek (a tributary to the Deschutes River in Deschutes County, Oregon) from a single thread channel to a multi-threaded, Stage 0 river system.

Objectives:

1. A series of different river-based parameters are obtained from both primary data and secondary data. These parameters allow estimations for bankfull flow to be made, to infer a number of conclusions on the condition of Whychus Canyon.
2. Using exclusively primary data collected at Whychus Canyon on the Whychus Creek, statistical analysis is conducted the wetland function scores from an unrestored (Reach 3) and a recently restored section (Reach 4) of the creek.
3. A combination of the aforementioned wetland function assessments, conducted in August 2019, and wetland function assessments from secondary datasets held by the UDWC will be used for this particular objective. Through statistical comparison of data from August 2018 and 2019, an assessment will be made on the extent of development of the riparian and wider wetland ecosystem over a year period.

2: Methodology:

2.1. Study Area

2.1.1. Site Introduction:

This research will explore the successes of a recent Stage 0 restoration project that has been undertaken on Whychus Creek, Oregon. The creek is a spring-fed tributary to the Upper Deschutes River that flows down from the base of the Bend Glacier on Broken Top Mountain, through the subalpine environment of the Three Sisters Wilderness, through town of sisters and joins the Upper Deschutes just downstream of the city of Redmond Redmond (DeLorme Mapping Company, 1991). The course of Whychus Creek can be seen in Figure 2.1. The drainage basin has an area of around 162,000 acres (UDWC, 2009). Of the 40-mile course of the creek, 15.4 miles is designated as either 'wild' or 'scenic' (United States Fish and Wildlife Service, n.d.a). The land in the catchment of the creek has a number of different public (The United States Forestry Service), and private owners (Deschutes Land Trust). The creek was formerly known as 'Squaw Creek' but its name changed to Whychus as a result of the derogatory connotations of the word 'squaw' (McArthur and McArthur, 2003).

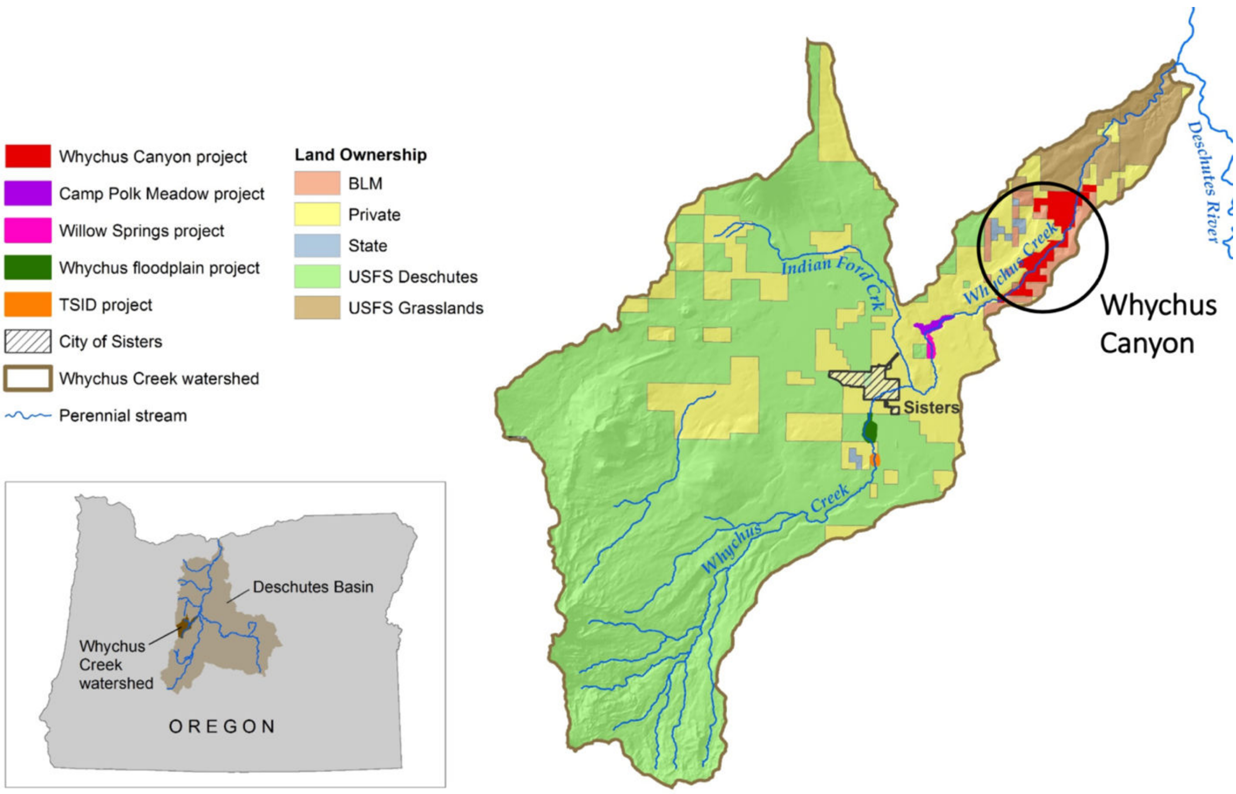

Figure 2.1.: *This illustration shows the course of the Whychus Creek, such as land ownership and the locations of the restoration projects that have been undertaken along the watercourse.*

Whychus Canyon has been split into a number of reaches, and this research will focus on a comparison between conditions in Reach 3 (unrestored) and Reach 4 (Restored in 2016). As aforementioned, this restoration seeks to change the channel from a single-threaded channel disconnected from its floodplain, to a multi-threaded dynamic channel system (Mork et al., 2018). The progress of this restoration can be seen through the images presented in Figure 2.2 (ibid).

Figure 2.2.: *This series of images displays the changes to the channel structure and riparian environment that have come out of the implementation of Stage 0 restoration techniques in Reach 4 at Whychus Canyon, on Whychus Creek, Oregon (Photos from Mork et al., 2018).*

As an effort to reduce flooding, an 18-mile section of channel along Whychus Creek was channelised in the 1960s (UDWC, n.d. a; b). Channelisation has reduced the creek's connectivity to its floodplain which supported the meadow and wetland ecosystems that were present (UDWC, a; Buijse et al., 2002; Beechie et al., 2010). One priority of the current restoration project is the reintroduction of salmonids. Another priority is to protect and restore the stream corridor through the restoration of wetlands and floodplain areas. Therefore, attempts to restore the meadow back to this pre-disturbance state began at Whychus Canyon in 2016 (UDWC, n.d. a) (Figure 2.2).

2.2. Geophysical, biological and hydrological site context:

2.2.1. Ecology:

Ecoregions delineate areas of general similarity in ecosystems and stratify the environment by its probable response to disturbance (Bryce et al., 1999). Whychus Creek flows through three different ecoregions. In its headwaters, it flows through the Cascade Crest Montane Forest, then down through a Ponderosa Pine/Bitterbrush Woodland environment, and then from Sisters to its confluence, the Deschutes River Valley. (Environmental Protection Agency, 2017).

There is one species listed as Endangered, under the Endangered Species Act, in the Lower Columbia Basin where Whychus Creek sits. The Chinook Salmon (*Oncorhynchus tshawytscha*) is the only one listed as endangered, while redband trout (*Oncorhynchus mykiss*) are listed as a species of concern (United States Fish and Wildlife Service, n.d.b; Gende et al., 2002; Gustafson et al., 2007). Recently, reintroduction programs have commenced in attempt to restore salmonid numbers (Temple et al., 2017; Johnson et al., 2019a). To date, over US$120million has been invested in the reintroduction program to bring fish back to this watershed (UDWC, n.d. c).

On top of these endangered species, there are a number of invasive species within the Upper Deschutes basin. Whychus Canyon contains known populations of Mullein (*Verbascum thapsis*), spotted knapweed (*Centaurea maculosa*), bull thistle (*Cirsium vulgare*) and cheatgrass (*Bromus tectorum*) (United Stated Forest Service, 2014).

2.2.2. Water Quantity and Quality:

Two gauges are used by the UDWC to monitor discharge and flow on Whychus Creek. Gauge 14076050 is situated at Sisters City Park but lies below a large irrigation diversion. This gauge is reflective of the flows seen at Whychus Canyon, whereas there is another gauge measuring a more natural flow prior to the irrigation diversion. (Oregon Water Resources Department, 2019). According to the hydrograph of the gauge at Sisters City Park, high flows occur in November and December.

For a creek largely fed by glacial meltwater, this would be against what is expected; however, as with most streams in Oregon, due to the water demands for irrigation, the lowest flows are experienced in the Summer months (Hall, 1988; UDWC, 2009). The mean daily flow from 1906 to 2018 has been 85.3 ft^3/s (cfs) above the irrigation canals, while below the irrigation canal, average flows are 23.7 ft^3/s (Oregon Water Resources Department, 2019). During the irrigation season, 90% of channel flow is diverted for irrigation, which has knock-on effects on stream temperature and dissolved oxygen levels; the creek is now listed as 'water quality limited' by the Oregon Department of Environmental Quality (UDWC, 2009).

2.2.3. Climate:

The Whychus Creek drainage basin is located on the eastern slopes of the Cascade Mountain Range; this results in very little precipitation as a result of a rain shadow effect. Figure 2.3 shows monthly climate normals from 1981-2010 from Redmond Municipal Airport, 15 miles from Whychus Canyon (National Weather Service, n.d.; Arguez et al., 2012). As a result of these low rainfall, very little surface runoff reaches the creek; instead it permeates the highly porous layers of basalt rock that is found commonly in Oregon (UDWC, 2009).

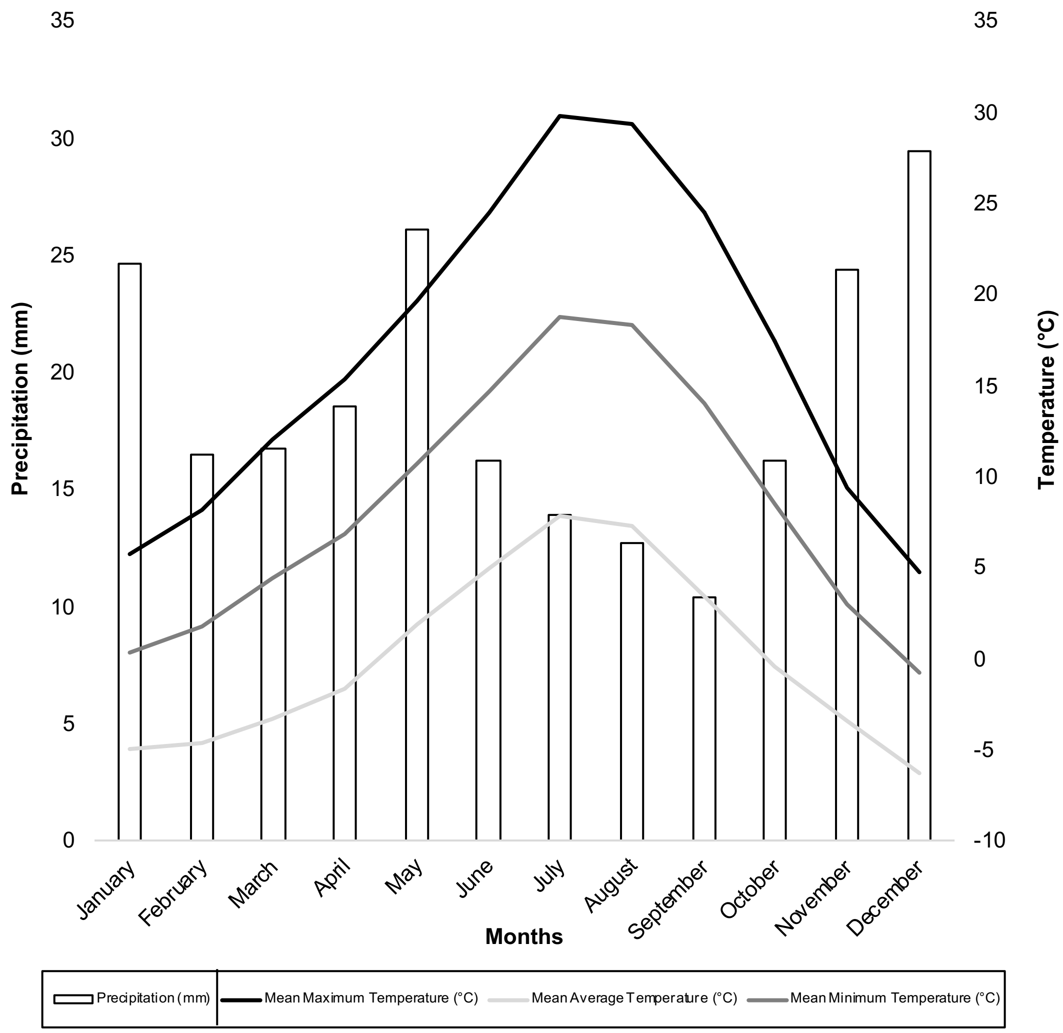

Figure 2.3.: *This graph displays the monthly climate normal temperature and precipitation values at Redmond Municipal Airport. The airport lies 15 miles away from Whychus Canyon. (Data sources: National Weather Service,n.d.; Arguez et al., 2012).*

2.2.4. Soils:

Due to volcanic activity, the upper 0.5-1 meter of soil in the Whychus canyon basin is largely composed of volcanic ash, cinder and pumice (Yake, 2003). This fine grain ash erodes easily without vegetation in place to stabilise the banks. Riparian soils along the creek will be more productive as a result of a higher water table and higher nutrient availability (Vought et al., 1994; Entry and Emmingham, 1996). The soil map for Whychus Canyon can be seen in Figure 2.4.

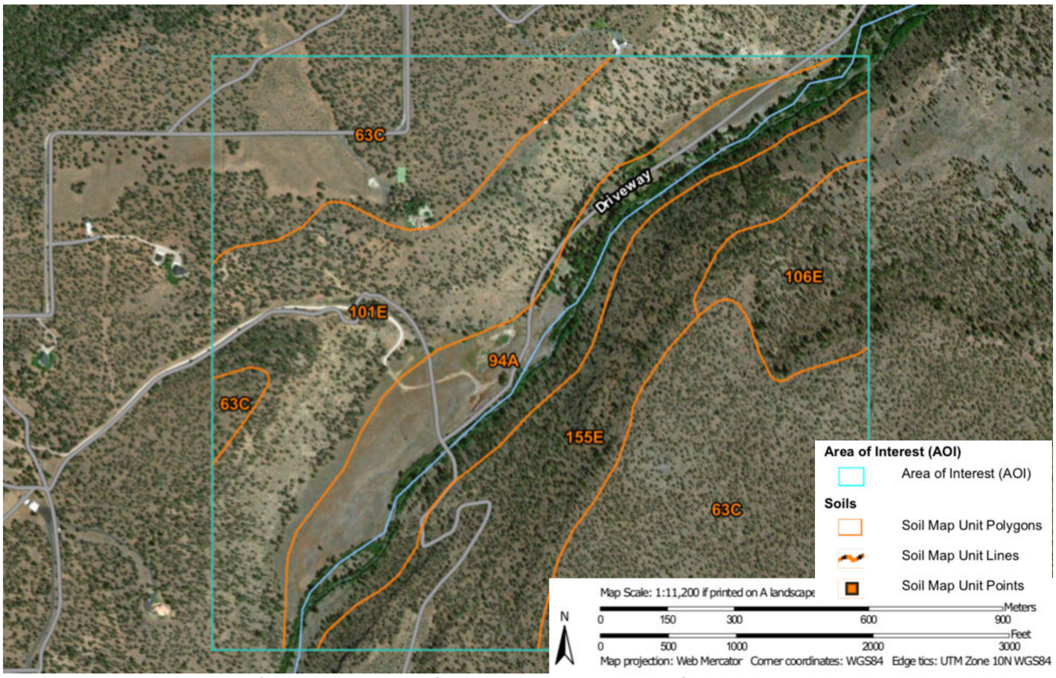

Figure 2.4.: *A soil Map for Whychus Canyon, Whychus Creek, Upper Deschutes River Area, Oregon. The river flows through parts of Deschutes, Jefferson and Klamath Counties.*

Table 2.1.: *Map Unit Legend accompanying the map above and outlining the different classifications of soil within the area of interest at Whychus Canyon.*

Unit Symbol	**Map Unit Name**	**Acres in AOI**	**Percent of AOI (%)**
63C	Holmzie-Searles complex, 0 to 15 percent slopes	173.1	35.9
94A	Omahaling fine sandy loam, 0 to 5 percent slopes	78.4	16.3
101E	Redcliff-Lickskillet-Rock outcrop complex, 30 to 50 percent south slopes	119.9	24.9
106E	Redslide-Lickskillet complex, 30 to 50 percent north slopes	28.9	6.0
155E	Wanoga sandy loam, 30 to 50 percent slopes	81.8	17.0
	Totals for Area of Interest	**482.2**	**100.00%**

2.3. Sites

As aforementioned in the introduction to the site, research has been conducted across two sites (Reach 3 and Reach 4) in the Whychus Canyon Preserve. Reach 3 is the stretch of river that has not been restored using stage 0 techniques, while Reach 4 underwent regrading and stage 0 restoration in the Summer of 2016 (Mork et al., 2018). To most effectively survey the site, polygons were created over both Reach 3 and Reach 4, in which data collection would take place. These were used in 2018 by Dr Colin Thorne and a team of students from the University of Nottingham, UK, who were conducting post-project monitoring on the Whychus Canyon site. The data collected during the fieldwork effort in August 2018 is the secondary data used in this report. This will be explored further in upcoming sections.

On arrival, as suggested by Rice and Toone (2010) the first day on site was spent conducting a fluvial audit of the site area, assessing accessibility to the polygons and becoming familiar with the sites. The main purpose of this exercise was to mark out the vertices of the polygons with rebar and tape for easy identification as well as the collection of GPS points for each one (Appendix A). For the wetland function assessments there are 8 sub-polygons over Reach 4 (each polygon was split into a downstream and upstream half) and 4 at Reach 3 (one large polygon was split into 4); these can be seen in Figure 2.5 and 2.6 respectively. The Program Managers at the UDWC chose to split the reaches up in this way as this was determined to be the best way to most effectively survey the heterogeneity in Reach 4. Reach 3 is more homogenous and therefore less complex, thus meaning larger spatial units could be used. To better map the wetland and riparian functions in each reach it was possible to use smaller spatial units than those 8 polygons used in 2018; however, the surveyors were conscious to use the same spatial units in 2019 as were used in 2018, for statistical analysis. Also, since the fieldwork period was only 10 days, the surveyors were restrained by the time available.

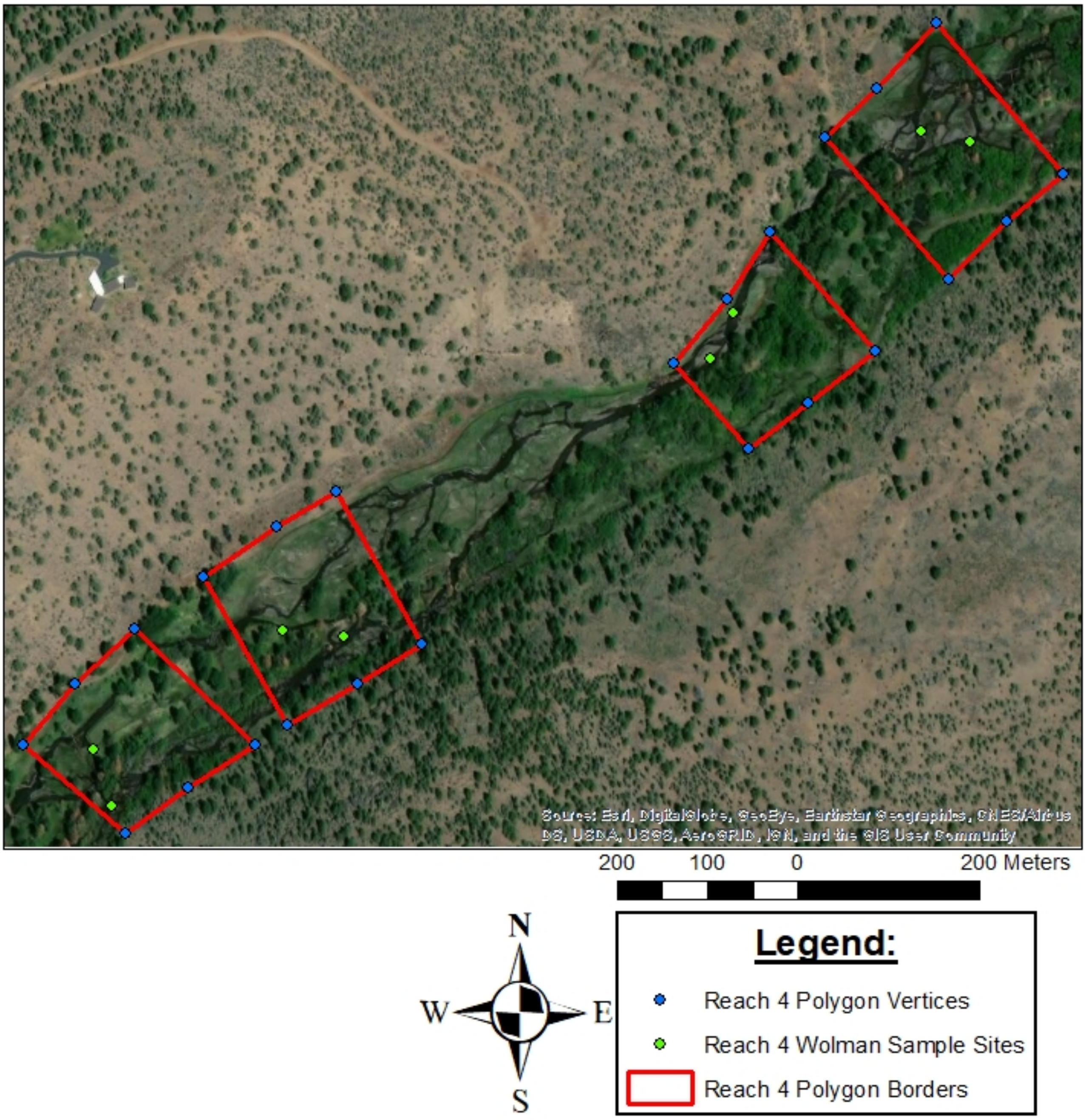

Figure 2.5.: *This map illustrates the 4 large polygons in Reach 4 of the Whychus Canyon Preserve on Whychus Creek. Each polygon was split into a downstream and an upstream section along the middle vertices of each polygon for the wetland function assessments. Two sites were identified in each polygon for the Wolman Samples.*

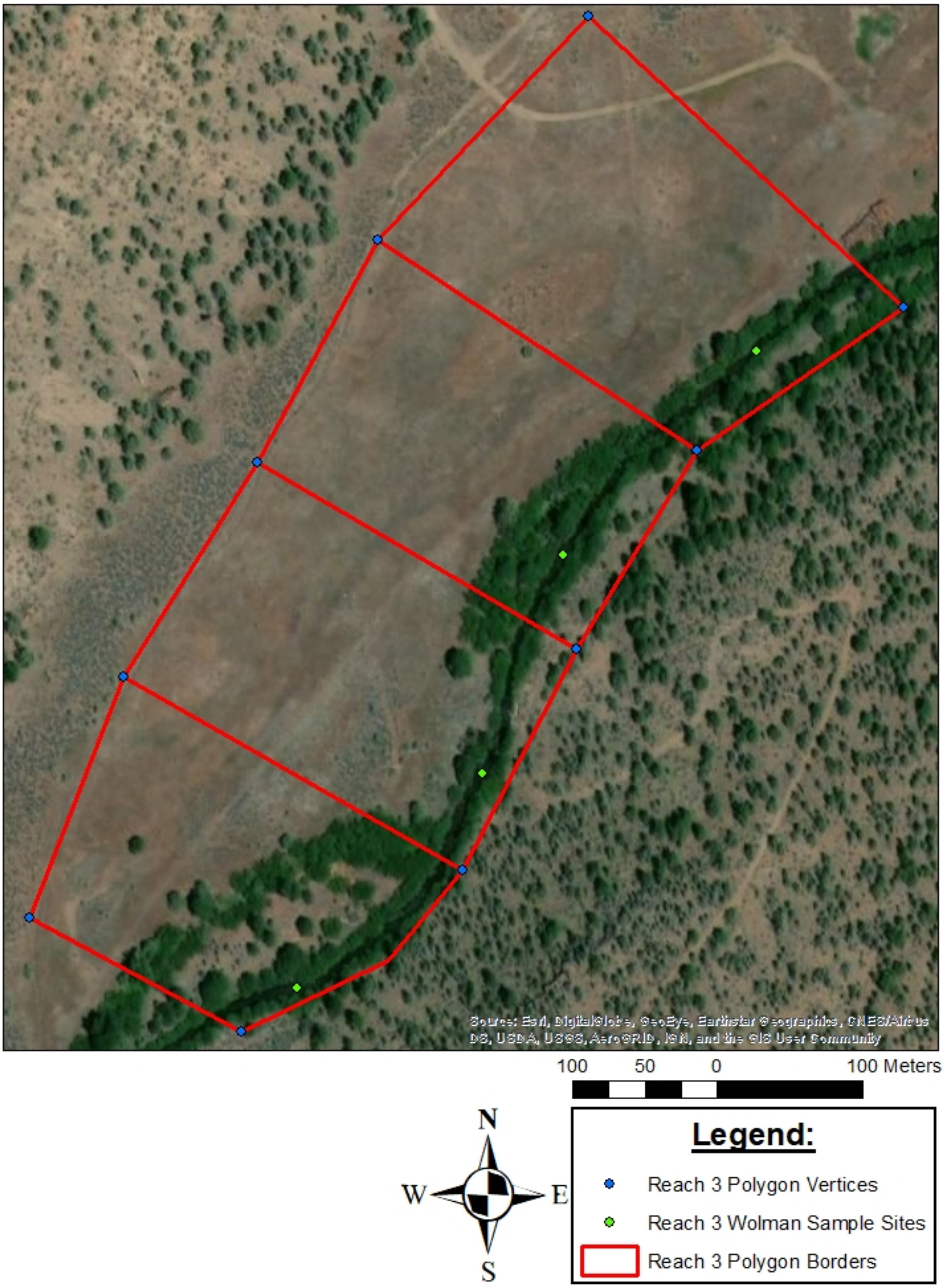

Figure 2.6.: *This map illustrates the 4 large polygons in Reach 4 of the Whychus Canyon Preserve on Whychus Creek. Each of the 4 polygons contains a site where 25 pebbles were randomly counted for a Wolman Sample.*

2.4. Modelling Bankfull Flow:

Depending on the equation used, particular parameters are used to estimate bankfull flow. For example, hydraulic radius is a measure of efficiency in a channel and is used consistently throughout the literature in equations to estimate bankfull discharge (Hey, 1979) and Froude and Reynolds numbers (Griffiths, 1981). From the literature, 3 different formulas are to be used: Manning (1891), Lacey (1929), and Hey, (1979). 5 variations will be used in modelling, as 3 different Manning's *n* values are obtained from Yochum et al., (2014) and Barnes (1967). Manning's n is the preferred prediction method to establish coefficient of roughness for many practitioners. However, The Darcy-Weisbach equation (Darcy 1854, Weisbach 1865) is an alternative that has been suggested to be more appropriate. This being said, it is rarely applied, and also varies by discharge, which would not be appropriate to use for bankfull discharge estimations (Comiti et al. 2007, Reid and Hickin, 2008, David et al., 2010, Yochum et al., 2012).

To get an estimate for bankfull flow, a combination of primary and secondary data has been collected for modelling. A number of parameters have been obtained for Reach 3 and 4 at Whychus Canyon; these are outlined in Table 2.2.

Table 2.2.: *This table outlines the different parameters required from primary and secondary sources to successfully complete bankfull modelling.*

Parameter	Abbreviation
Average depth (m)	d
Hydraulic radius (m)	R
Grain size (mm)	D50
Grain size (mm)	D84
Slope(m/m)	S
Cross-sectional area (m^2)	A
Manning's n calculated	*n*
Manning's n (Barnes, 1967)	*n*
Manning's n (Yochum et al., 2014)	*n*

2.4.1.: Bankfull Width (w):

Width measurements were taken at 10 transects in Reach 3 and 10 transects in Reach 4. These transects can be seen in Figure 2.7 and Figure 2.8 respectively. At Reach 3, 5 transects were on the polygon boundaries and the rest were spread equally along the reach. At Reach 4, 8 transects for depth were completed on the upstream and downstream polygon transects as they had previously been marked out, so for efficiency of time, this was the easiest option The other two were in the large gap between polygon 2 and 3. In Reach 3, width measurements were simple to take as water flows through a single-channel. However, in Reach 4, width was measured for all the threads across the transect; the maximum number of threads in the reach was 4, but some transects only had 1, 2, or 3 channels. It is important to note that bankfull width was measured from the top of bank, not water level (Thorne and Zvenbergen, 1985) Width is not required directly for the bankfull modelling analysis, but it is used to equate cross-sectional area.

2.4.2.: Average Depth (d):

At Reach 3, it was simple to collect the depth of the channel at each transect as it is a single-threaded channel. The width of the channel was measured and divided by 11 to get 10 points, equidistance from one another, within the channel at which depth was measured. Surveyors took care to ensure that depth was measured from bank-top, as oppose to water level for use in bankfull modelling (Thorne and Zvenbergen, 1985). However, due to the complex nature of the braided channel in Reach 4, it was much more difficult to obtain depth values. Therefore, based on work by Métivier et al. (2016), each thread of the braided channel along each transect was treated and measured individually based on wetted area at the time of measurement. Each thread of the braided channel was ranked in terms of width from largest to smallest. The largest thread along a transect was classed as the ‘main thread’; an average was formed for the main threads of each transect. This process was repeated for the other ranked threads. An average was then obtained for all the channels for the purposes of the Bankfull Flow calculations (Appendix B).

2.4.3.: Cross-Sectional Area (A):

Cross-sectional area was calculated for all transects in Reach 3 and Reach 4. Each channel is split into 11 segments using the depth values measured. Each segment’s area was calculated separately and then an aggregate value was calculated by adding all segment areas together. This gave a cross-sectional area value for each transect in Reach 3; an average for the reach was calculated for the purposes of bankfull modelling analysis. In Reach 4, the areas for the primary, secondary, tertiary and quaternary channels (if present) were aggregated together for all 10 transects (Métivier et al., 2016). Again, an average for the reach was calculated for the purposes of bankfull modelling analysis.

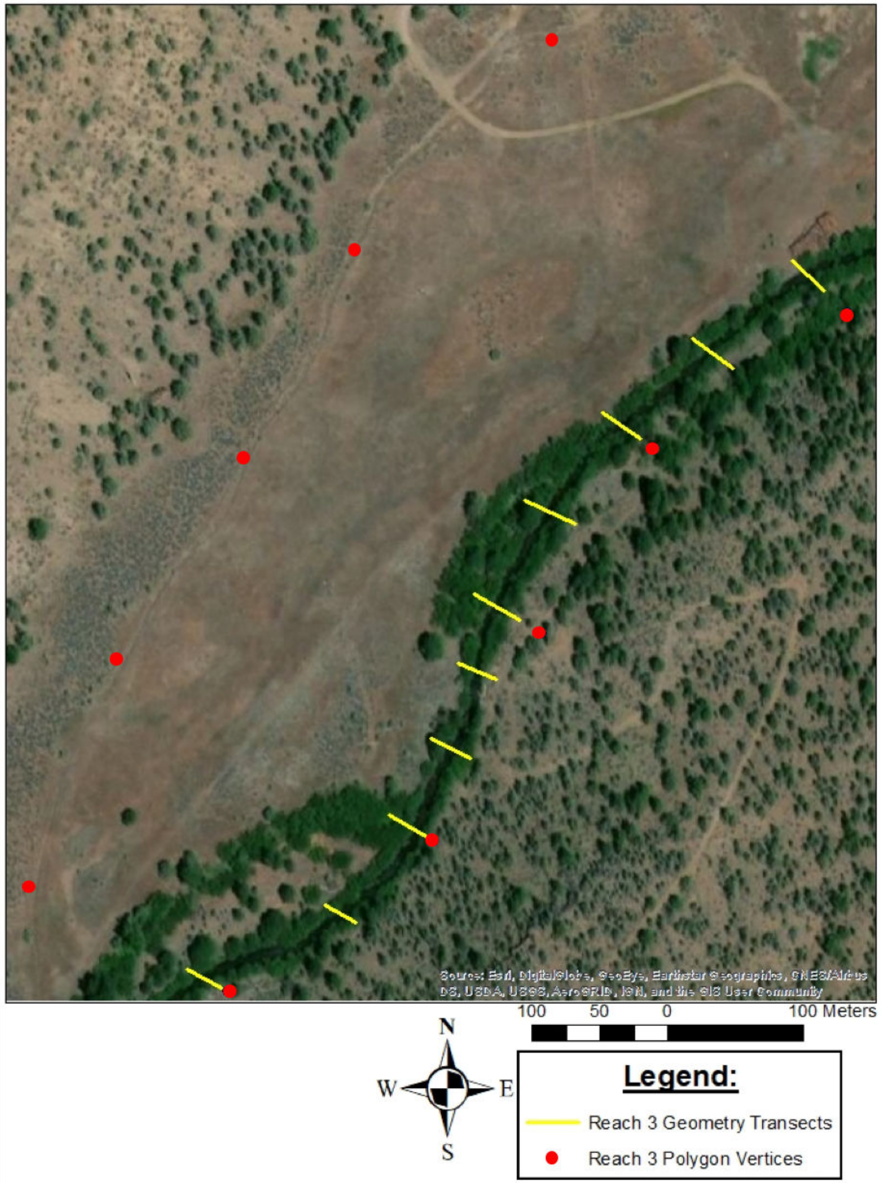

Figure 2.7.: *Map displaying the location of the ten transects along which channel dimensions (depth, width, and cross-sectional area) were measured in Reach 3 of the Whychus Canyon Preserve on Whychus Creek.*

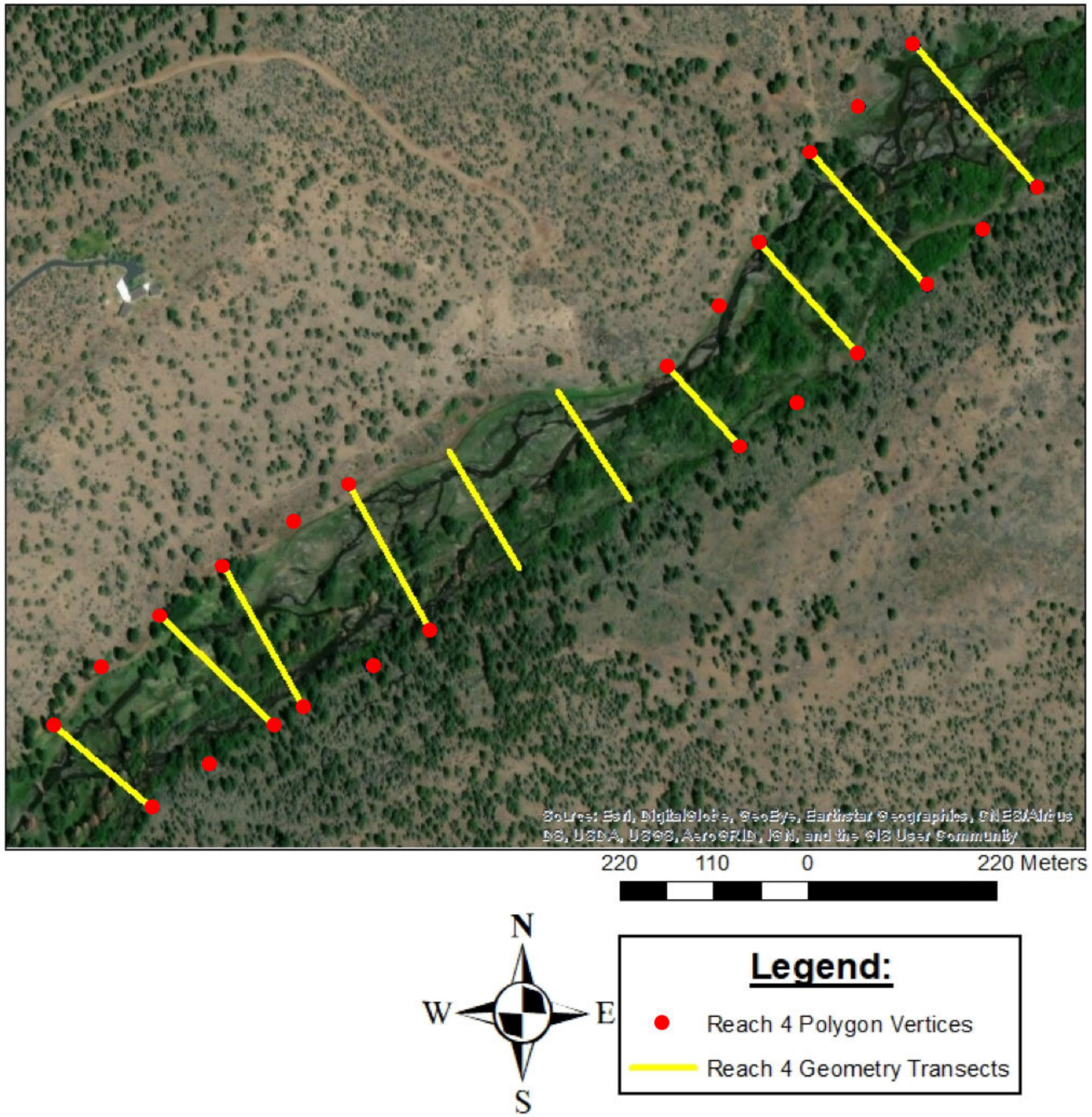

Figure 2.8.: *Map displaying the location of the ten transects along which channel dimensions (depth, width, and cross-sectional area) were measured in Reach 4 of the Whychus Canyon Preserve on Whychus Creek.*

2.4.4.: Hydraulic Radius (R):

Hydraulic radius is a measure of efficiency in a channel and is used consistently throughout the literature in equations to estimate bankfull discharge (Hey, 1979) and Froude and Reynolds numbers (Griffiths, 1981).Hydraulic radius is calculated by working out a ratio of cross-sectional area to wetted perimeter. Cross-sectional area values have been calculated previously, but wetted perimeter has also been calculated from the measured width and depth values. Like cross-sectional area, the wetted perimeter was calculated at all 10 transects in Reach 3 and all the channels across each transect in Reach 4. An average value was obtained in Reach 3 from the wetted perimeter value for each transect. In Reach 4, the areas for the primary, secondary, tertiary and quaternary channels (if present) were aggregated together for all 10 transects (Métivier et al., 2016). Again, an average for the reach was calculated for the purposes of bankfull modelling analysis.

2.4.5.: Wolman Sampling:

Pebble counts were conducted in Reach 3 and Reach 4 to sample bed-surface sediment (Appendix E). A Wolman Sample was conducted at Reach 3 and Reach 4 (Wolman, 1954). This method is applicable to coarse-bed rivers where the bed can be easily accessed by surveyors (Yuzyk, 1986). Pebble counts were the preferred method used as they enable a large sampling area to be covered and is most suitable for gravel and cobble bed channels (Bunte and Abt, 2001), such as Reach 3 and 4 of Whychus Creek. To get an accurate estimation for the grain size distribution, 12 or 13 pebbles were counted at 8 sites in Reach 4. 2 riffles in each polygon were selected to sample 25 pebbles per polygon, and a total of 100 pebbles in Reach 4. These sites can be seen in Figure 2.5. 4 sites in Reach 3 were sampled, pulling 25 pebbles from 4 riffles to sample a total of 100 rocks; this was because the riffle pool formation was less defined in Reach 3, than in Reach 4. At each of the riffle sites, the heel-to-toe walk method was employed to transverse the sampling area (Marcus et al., 1995; Bevenger and King, 1995; Kondolf, 1997; Bunte and Abt, 2001). From the samples in Reach 3 and 4, a frequency distribution is made; the desired size parameters are read from this (Wolman, 1954).

2.4.6.: Slope (S):

Slope values were extracted as another key parameter required to model bankfull flow. Digital Terrain Models (DTMs) were obtained from Joe Rudolph of Wolf Water Resources, partners of the UDWC (Rudolph, 2018) (Appendix G). Through GIS a number of tools and calculations, provided slope value for both reaches to be used in modelling.

2.4.7.: Manning's n:

The final values required for bankfull modelling were Manning's n values for 3 different equations. Firstly, the calculated Manning's n value was obtained using the grain size distribution from the Wolman Count. A second Manning's n came from Yochum et al.'s (2014) paper for the United States Department of Agriculture's Forest Service. The third was also obtained from the literature, by using the photographic evidence in Barnes' (1967) paper for the United States Geological Survey.

2.4.8.: Analysis

Once a pebble count has been undertaken, this data needs to be processed to produce a grain size distribution. Particle size by class is plotted against to the cumulative frequency percentage on a graph. From this graph, estimations can be made for D50 and D84. The D50 value represents the particle size that 50% of the samples are equal to or smaller than. The D84 value represents the particle size that 84% of the samples are equal to or smaller than (Wolman, 1954).

Once all the required values had been obtained for Reach 3 and 4, they were entered into calculations to get estimates for Bankfull Velocity, Bankfull Discharge, the Reynolds number and the Froude number. Formula's obtained from Hey (1979), Lacey (1929) (Savenije, 2003), Yochum et al., (2014) and Barnes (1967), were used to give estimate values for Bankfull conditions. The parameters used in each formula are listed in Table 2.3. This analysis then provides sufficient information to be able to answer objective number 1.

Table 2.3.: *The parameters used in each formula used to model bankfull flows.*

Method:	Parameters			
	Bankfull Velocity	Bankfull Discharge	Froude	Reynolds
Hey	R, D84	R, D84, A	R, D84, d	R, D84
Lacey	d, S	d, S, A	d, S	d, S, R
Mannings (Calculated)	R, S, n	R, S, n, A	R, S, n, d	R, S, n
Mannings (Barnes, 1967)	R, S, n	R, S, n, A	R, S, n, d	R, S, n
Mannings (Yochum et al., 2014)	R, S, n	R, S, n, A	R, S, n, d	R, S, n

2.5. Wetland Function Assessments:

To assess the value and function of the wetlands and their contribution to Ecosystem Services, a wetland and riparian function assessment was carried out on both Reach 3 and 4. The 'Guidebook for Hydrogeomorphic (HGM)-based Assessment of Oregon Wetland and Riparian Sites: Statewide Division and Profiles' was used to assess 13 functions of wetland environments(Adamus and Field, 2001). The reference-based method provides a numeric score for functions and is extensively referenced to technical literature and field data. An example of a complete survey can be found in Appendix C. The reference-based method used in this research uses similar concepts to Washington Department of Ecology's hydrogeomorphic methods (Hruby el al. 1999) and follows guidance issued by the U.S. Army Corps of Engineers (Smith et al. 1995). Other methods are offered in Adamus and Field's Assessment Protocol (2001) but the reference-based method is preferred (ibid); this will be assessed in the discussion.

2.5.1. Primary Data Collection:

When doing a walkover of the site, indicator species were used to build up a picture of conditions prior to the period of data collection. Five wetland indicator status ratings can be used to determine whether a species is hydrophytic (Lichvar et al., 2016); these are outlined in Table 2.4. *Pinus ponderosa* trees are known as Facultative Upland species; they are uncommon in wetland areas and grow across a 1,500m elevation gradient in a number of mountain ranges (Allen and Breshears, 1998; Allen et al., 2002). Both Reach 3 and 4 at Whychus Canyon have a number of Ponderosa pines. The trees in the recently restored Reach 4 show evidence that they are dying (Figure 2.7), while the trees in Reach 3 are still thriving. This is attributed to the elevated water table which is preventing enough oxygen reaching the roots of the trees (Mork, pers.comm.).

A 30-page survey was completed on each of the 8 polygons in Reach 4 and each of the 4 polygons in Reach 3 using a series of observations, estimations and calculations. Initially a site is assigned a subclass using the Key for Level-1 Hydrogeomorphic Classification of Willamette Valley Wetland/Riparian Systems. The reference-based method and the highest-functioning standard for assessing wetland functions was used for this research. This approach requires surveyors to estimate indicators of wetland function quantitatively selecting from numeric categories to standardize the estimate to a 0-1 scale. The standardized estimates are combined into a function capacity score using prespecified scoring models. A sketch map was also completed for each site (Appendix D). Scoring is based on direct comparison with indicator data from a large set of sites assessed in the Willamette Valley in 1999-2000.

Figure 2.9.: *This image was taken at Whychus Canyon on Whychus Creek. The image shows the dying trees at Polygon 2 in Reach 4 which were identified when walking the site and conducting wetland function assessments. Image from August 1st 2019.*

2.5.2. Secondary Data:

The assessment outlined in Section 2.5.1 is the same used by the students of the University of Nottingham in 2018. The same protocol was used at exactly the same time of year to ensure the reliability of the primary dataset when compared to the secondary dataset. While there will inevitably be sampling error due to different interpretations of the sites and indicators, training on how to fill out the methodology was delivered in the same way and, where possible, caution was taken to ensure the methods were carried out in the same manner. This dataset was obtained from the UDWC and has been combined with the primary dataset for statistical comparison between the sites in 2018 and 2019.

Table 2.4.: *Short qualitative descriptions and the frequency of which a species will occur in wetlands, given as a percentage (Adapted from Lichvar et al., 2012, using information from the UDWC, and Wright et al., 2002).*

Indicator Status	**Designation**	**Qualitative Description**	**Frequency in wetlands (%)**
Obligate (OBL)	Hydrophyte	Almost always occur in wetlands.	>99
Facultative Wetland (FACW)	Hydrophyte	Usually occur in wetland, but may occur in non-wetland areas.	67-99
Facultative (FAC)	Hydrophyte	Occur in wetland and non-wetland	34-66
Facultative Upland (FACU)	Non-hydrophyte	Usually occur in non-wetland areas, but may occur in wetlands	1-33
Upland (UPL)	Non-hydrophyte	Almost never occur in wetlands	0

2.5.3. Analysis

Once the function capacity scores had been determined for each section of the survey, the scores were input into a table. The data then underwent significant statistical testing in SPSS to answer the objectives of this report. To answer objective 2 independent t-tests were conducted to see if the mean score for each function in Reach 3 and 4 differs significantly. To answer objective 3, a paired samples t-test was conducted using the function scores from 2018 and 2019 for Reach 4. A paired sample t-test is preferred here as the relationship between sample sites dictates whether it is independent or paired; data collected at exactly the same sites must use a paired t-test to analyse the difference between years at the same site (Hsu and Lachenbruch, 2008). The α-value was 0.05.

The development of the hypotheses for objective 2 and 3 is outlined below:

Objective 2:

Research Question: Is the wetland more developed in Reach 4 than Reach 3?

Statistical Question: Do the mean scores for Reach 3 and Reach 4 differ significantly?

Null Hypothesis (H_0): The means in Reach 3 and Reach 4 don't differ significantly.

Alternative Hypothesis(H_A): The means of Reaches 3 and 4 don't differ significantly.

Objective 3:

Research Question: Is the wetland more developed in 2019 than in 2018?

Statistical Questions: Do the mean scores for Reach 4 differ between 2018 and 2019?

Null Hypothesis (H_0): The mean function scores of Reaches 3 and 4 differ significantly.

Alternative Hypothesis (H_A): The means of Reaches 3 and 4 don't differ significantly.

3: Results:

3.1.: Bankfull Modelling:

Bankfull modelling equations were used for both Reach 3 and 4. The values obtained from carrying out the methodology can be seen in Table 3.1.

Table 3.1.: *Parameters used to calculate the estimate values for bankfull velocity, bankfull discharge, Froude and Reynolds numbers. These parameters are for Reach 3 and Reach 4 at Whychus Canyon, on Whychus Creek, OR. The parameters that have been used are obtained from the papers from which the equations are published (Lacey, 1929; Barnes, 1967; Hey, 1979; Yochum et al., 2014).*

Parameter	Abbreviation	Value	
		Reach 3	Reach 4
Average depth (m)	d	0.48	0.23
Hydraulic radius (m)	R	0.47	0.82
Grain size (mm)	D50	52.36	48.51
Grain size (mm)	D84	102.42	69.81
Slope(m/m)	S	0.09	0.07
Cross-sectional area (m^2)	A	3.11	4.23
Manning's *n* calculated	*n*	0.09	0.05
Manning's *n* (Barnes, 1967)	*n*	0.06	N/A
Manning's *n* (Yochum et al., 2014)	*n*	0.06	0.38

The average depth in Reach 3 is more than double than that at Reach 4, as expected. The cross-sectional area is over 35% bigger in Reach 4 than Reach 3. Manning's *n* values have been obtained from Barnes (1967) and Yochum et al., (2014) for Reach 3, but there was no value in Barnes' paper that closely resembled Reach 4, so this was left blank. The Manning's n obtained from Yochum et al. (2014) in Reach 4 is 633% bigger than that of Reach 3; however, Reach 4 has a smaller Manning's n that Reach 3 for that calculated from grain size estimates. This raises questions over the accuracy of Manning's n for multi-threaded channels.

Table 3.2: *The results of the Wolman's sample on Reach 3 and Reach 4 are presented below as a distribution table.*

Size Class (mm)	Count	
	Reach 3	Reach 4
0-2	1	1
2-2.8	0	1
2.8-4	1	0
4-5.7	1	3
5.7-8	1	4
8-11.3	2	10
11.3-16	3	10
16-22.6	4	17
22.6-32	5	15
32-45.3	10	13
45.3-64	17	11
64-90.5	18	9
90.5-128	16	4
128-181	12	2
181-256	5	0
256-362	1	0
362-512	3	0
SUM	100	100

The distribution in Figure 3.2 shows that the grain size in Reach 3 is greater than in Reach 4. This can be visualised in Figure 3.1 and 3.2, where you can clearly see that more small rocks are found in the restored Reach 4. Slower, more heterogenous flow, has led to more small rocks being deposited.

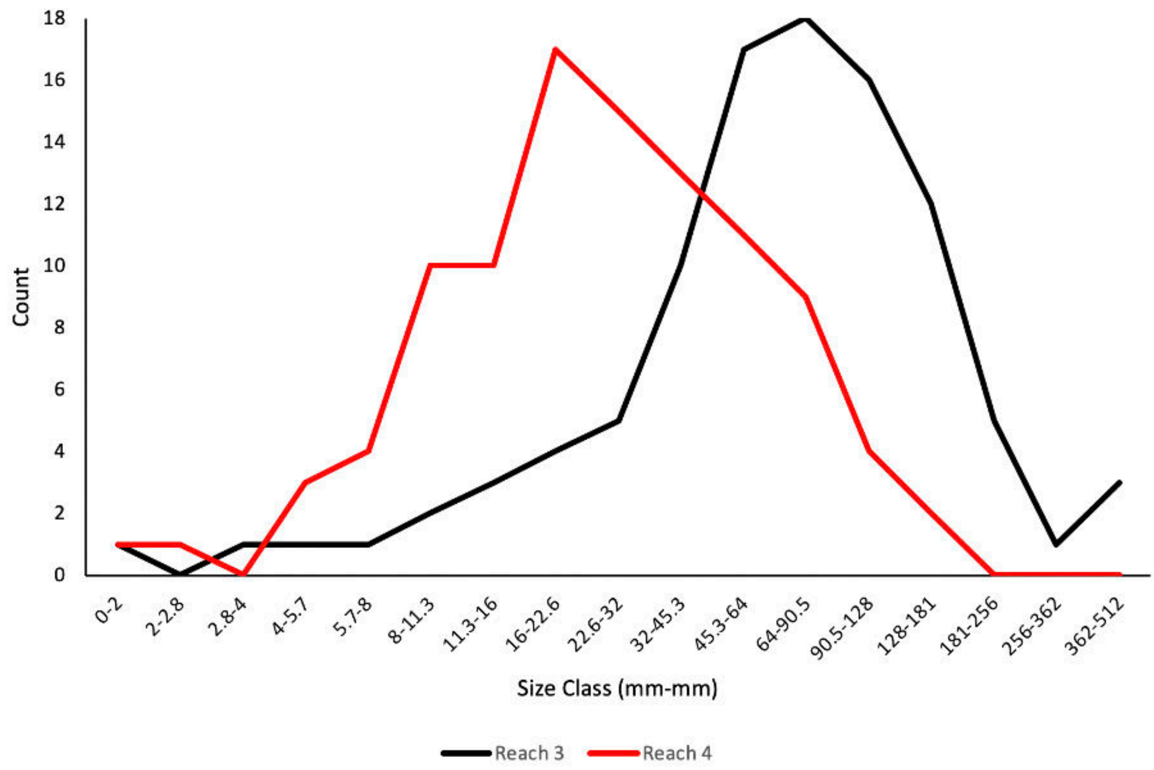

Figure 3.1: *A figure showing the distribution curves of the Wolman samples conducted in Reach 3 and 4.*

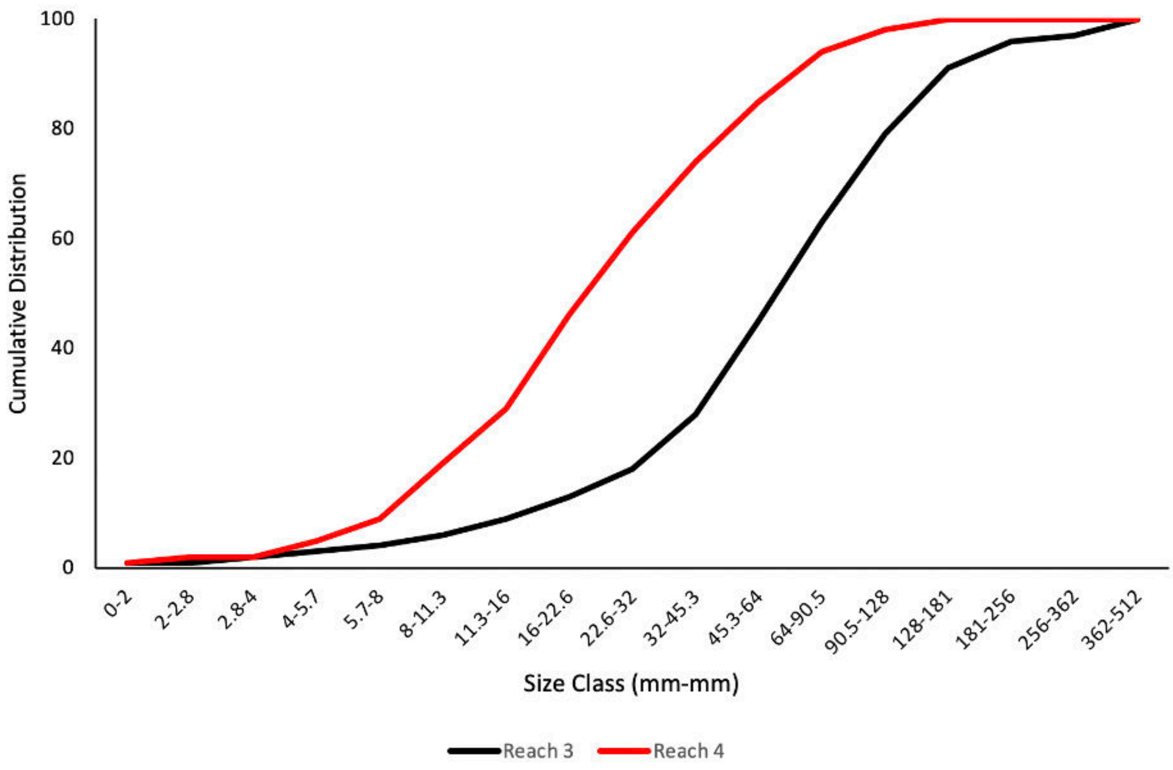

Figure 3.2: *A figure showing the cumulative distribution curves of the Wolman samples conducted in Reach 3 and 4.*

Table 3.3.: *This table displays the outputs from the bankfull modelling that was computed by inputting the parameter scores from Table 3.1 into the equations outlined in Section (2.1). An estimate Reynolds (Streeter, 1962) and Froude number are presented alongside bankfull velocity and Bankfull discharge values to give some more context to the river and its conditions based on the parameters measured.*

Method used		Bankfull Velocity (ms^{-1})		Bankfull Discharge (ms^{-3})		Froude Number (Fr)		Reynolds Number (Re)	
		Reach 3	Reach 4	Reach 3	Reach 4	Reach 3	Reach 4	Reach 3	Reach 4
Hey Equation		2.03	3.57	6.31	15.37	0.94	2.41	950088.76	2926633.65
Lacey Equation		2.96	1.65	9.21	7.08	1.37	1.11	1386673.20	1348534.36
Manning's Equation	Calculated	1.97	2.56	6.13	10.99	0.91	1.72	922443.58	2093915.02
	Barnes	3.17	N/A	9.87	N/A	1.46	N/A	1484759.64	N/A
	Yochum	3.07	0.61	9.53	2.62	1.41	0.41	1434428.81	499158.64

Table 3.3. gives information on the outputs from the Bankfull modelling computed on Reach 3 and Reach 4. Across the 5 estimations, the average bankfull velocity in Reach 3 is 2.64 ms^{-1} while in Reach 4, the average is only 2.10 ms^{-1}.

3.2.: Wetland Function Assessments:

Table 3.4 displays all of the function capacity scores from Reach 3 and Reach 4 in 2018 and 2019. Nitrogen Removal and Breeding Waterbird Support are shown as 'N/A' in the table, as Whychus Canyon did not meet the indicator criteria set for these sections. For Nitrogen Removal, the function can only be assessed where hydric soil features are present, of which there were none present in Whychus Canyon due to the maturity of the wetland (Vasilas et al., 2017). For Breeding Waterbird Support, the function is to be assessed where over 0.5 acres of stagnant water is present, which was not the case in Whychus Canyon. On top of this, a number of different functions are shown as N/A for Reach 3 in 2018, but this creates no problem as they are not used in any statistical comparison.

Reach 3 displays much less variance in its scores for each function, and this is reflective of the homogeneity of the conditions and environment in the reach. The standard error of means in is lower in Reach 3 for all 11 functions for which there are scores; for example, the standard error for primary production in Reach 3 is 0.009 and in Reach 4 is 0.035.

Table 3.4.: *This Table displays the function capacity scores from Adamus and Field's (2001) hydrogeomorphic-based wetland and riparian area function assessment. Using the 'Reference-based', 'Highest Functioning Standard' method, scores obtained from primary data collection in August 2019 were comparable to those collected in August 2018.*

Year	Reach Number	Site ID	Subclass	Water Storage & Delay	Sediment Stabilisation & Phosphorus Retention	Nitrogen Removal	Thermo-regulation	Primary Production	Resident Fish Habitat Support	Anadromous Fish Habitat Support	Invertebrate Habitat Support	Amphibian & Turtle Habitat	Breeding Waterbird Support	Wintering & Migratory Waterbird Support	Songbird Habitat Support	Support of Characteristic Vegetation	Site Area (Acres)
2018	Reach 4	P1 Upstream	RI	0.150	0.310	N/A	0.300	0.780	1.000	0.720	0.850	0.420	N/A	0.350	0.210	0.340	1.48
		P1 Downstream	RI	0.420	0.568	N/A	0.300	0.827	1.120	0.789	0.761	0.597	N/A	0.152	0.812	0.917	1.78
		P2 Upstream	RI	0.100	0.295	N/A	0.514	0.509	1.000	0.842	0.594	0.651	N/A	0.289	0.754	0.788	1.78
		P2 Downstream	RI	0.400	0.450	N/A	0.286	0.427	1.502	1.158	0.848	0.905	N/A	0.417	1.553	0.670	1.78
		P3 Upstream	RI	0.200	0.360	N/A	0.340	0.750	1.000	0.750	0.900	0.790	N/A	0.420	1.000	1.000	1.73
		P3 Downstream	RI	0.140	0.300	N/A	0.260	0.740	0.100	0.770	0.810	0.720	N/A	0.420	1.000	0.830	1.63
		P4 Upstream	RI	0.280	0.340	N/A	0.170	0.740	1.000	0.840	0.850	0.690	N/A	0.390	0.950	0.870	1.85
		P4 Downstream	RI	0.140	0.260	N/A	0.260	0.660	1.000	0.770	0.840	0.640	N/A	0.370	0.890	0.760	2.22
	Reach 3	Downstream	RFT	0.040	0.510	N/A	N/A	0.750	0.910	0.600	0.640	0.700	N/A	0.310	0.890	0.670	N/A
		Upstream	RFT	0.020	N/A	N/A	N/A	0.375	N/A	N/A	0.650	0.710	N/A	0.340	1.000	3.130	N/A
2019	Reach 4	P1 Upstream	RI	0.200	0.364	N/A	0.257	0.736	1.182	0.684	0.811	0.805	N/A	0.737	0.987	0.394	1.48
		P1 Downstream	RI	0.060	0.332	N/A	0.343	0.718	1.143	0.807	0.732	0.815	N/A	0.474	0.987	0.716	1.78
		P2 Upstream	RI	0.060	0.309	N/A	0.300	0.736	1.078	0.860	0.768	0.836	N/A	0.678	0.997	0.863	1.78
		P2 Downstream	RI	0.100	0.273	N/A	0.386	0.691	1.000	0.982	0.989	0.779	N/A	0.467	0.974	0.848	1.78
		P3 Upstream	RI	0.060	0.173	N/A	0.120	0.618	1.143	0.754	0.793	0.816	N/A	0.599	0.989	0.875	1.73
		P3 Downstream	RI	0.060	0.264	N/A	0.171	0.645	1.143	0.737	0.763	0.800	N/A	0.414	0.987	0.840	1.63
		P4 Upstream	RI	0.060	0.445	N/A	0.300	0.864	1.130	0.807	0.807	0.839	N/A	0.411	0.987	0.848	1.85
		P4 Downstream	RI	0.100	0.523	N/A	0.257	0.900	1.195	0.789	0.831	0.619	N/A	0.474	0.987	0.863	2.22
	Reach 3	P1	N	0.040	0.145	N/A	0.300	0.582	1.091	0.667	0.222	0.666	N/A	0.382	1.026	0.679	5.93
		P2	N	0.040	0.145	N/A	0.300	0.582	1.091	0.667	0.222	0.666	N/A	0.382	1.026	0.679	5.44
		P3	N	0.040	0.145	N/A	0.300	0.582	1.091	0.667	0.222	0.666	N/A	0.382	1.026	0.679	5.16
		P4	N	0.040	0.182	N/A	0.300	0.545	1.091	0.667	0.689	0.660	N/A	0.382	1.026	0.675	6.18

3.2.1. Objective 2:

Table 3.5 displays the results of the t-tests conducted on the function capacity scores from the hydrogeomorphic-based assessments. Of the 11 values tested, the mean scores between Reach 3 and 4 were significantly different in 7 functions. The independent t-test conducted on Anadromous Fish Habitat Support offered a high certainty of significant differences; the test suggested there was a significant difference in function score between Reach 3 (Mean=0.667, Standard Error=0.000) and Reach 4 (Mean=0.803, Standard Error=0.032), with a t-score of 2.945 and P-value of 0.015 (Degrees of Freedom=10). Therefore, the null hypothesis is rejected (i.e. H_0 - there is no statistical difference between the scores in Reach 3 and Reach 4) and the alternative hypothesis (i.e. H_A - the mean of function scores in Reach 4 is higher than in Reach 3) is accepted. This proposes that the means are statistically significant from one another, suggesting that the habitat in Reach 4 functions better as a wetland. This is also the case for Sediment Stabilisation & Phosphorous Retention, Primary Production, Invertebrate Habitat Support, Amphibian & Turtle Support, and Wintering & Migratory Waterbird Support.

However, of those functions that are proven to have statistically significant means, the function capacity scores for Songbird Habitat Support is the only one that suggests that Reach 3 (Mean=1.026, Standard Error=0.000) is better than Reach 4 (Mean=0.987, Standard Error=0.002). The t-value is-12.231 and the P-value is 0.000 (DF=10). For those scores that could not have their means proved to be statistically significant, 3 out of the 4 had higher mean score in the restored Reach 4. It is important to note that a P-value lower than the alpha (α) doesn’t equate to a 95% chance that the hypothesis is correct; it instead signifies that if the null is rejected, and all assumptions are valid, there is a 5% chance of obtaining a result less extreme than that observed (Baker, 2016). Assessment summary sheets and sketch maps for all primary fieldwork can be seen in Appendix D.

Table 3.5.: *This table displays the results of the independent t-tests conducted on data from Reach 3 and 4 at the Whychus Canyon Preserve, on Whychus Creek. The test compares the mean score between the two reaches from primary data collected in 2019 for each function along the reach.*

Function	Reach	N	Mean	Std. Error Mean	Levene's Test F	Levene's Test Sig.	Equal/Unequal Variances	t-test for Equality of Means t	t-test for Equality of Means DF	t-test for Equality of Means sig.	Accept or Reject Null
Water Storage & Delay	3	4	0.040	0.000	4.318	0.064	Equal	1.895	10	0.087	Accept
	4	8	0.088	0.017							
Sediment Stabilisation & Phosphorus Retention	3	4	0.154	0.009	3.898	0.077	Equal	3.206	10	0.009	Reject
	4	8	0.335	0.039							
Thermo-regulation	3	4	0.300	0.000	6.08	0.033	Unequal	-1.079	7	0.316	accept
	4	8	0.267	0.031							
Primary Production	3	4	0.573	0.009	3.326	0.098	Equal	3.263	10	0.009	Reject
	4	8	0.739	0.035							
Resident Fish Habitat Support	3	4	1.091	0.000	4.442	0.061	Equal	1.124	10	0.287	Accept
	4	8	1.127	0.022							
Anadromous Fish Habitat Support	3	4	0.667	0.000	3.853	0.078	Equal	2.945	10	0.015	Reject
	4	8	0.803	0.032							
Invertebrate Habitat Support	3	4	0.339	0.117	6.574	0.028	Unequal	3.942	3.341	0.024	Reject
	4	8	0.812	0.028							
Amphibian & Turtle Habitat	3	4	0.665	0.002	2.486	0.146	Equal	3.401	10	0.007	Reject
	4	8	0.789	0.025							
Wintering & Migratory Waterbird Support	3	4	0.382	0.000	14.856	0.003	Unequal	3.420	7	0.011	Reject
	4	8	0.532	0.044							
Songbird Habitat Support	3	4	1.026	0.000	1.454	0.256	Equal	-12.231	10	0.000	Reject
	4	8	0.987	0.002							
Support of Characteristic Vegetation	3	4	0.678	0.001	3.82	0.079	Equal	1.223	10	0.249	Accept
	4	8	0.781	0.058							

3.2.2.: Objective 3:

Table 3.6 displays the results of the paired t-tests conducted on function capacity scores from the wetland function assessment (Adamus and Field 2001). As with Objective 2, 11 values were tested to see if the mean scores in 2018 and 2019 in Reach 4 were statistically significant from one another. The means were significantly different in only 2 of the 11 functions tested. According to the results presented in the table, the means that are most statistically similar are those for the ‘Support of Characteristic Vegetation’ function. The test suggests that the function scores for 2018 (Mean=0.772, Standard Error=0.071) and 2019 (Mean= 0.781, Standard Error= 0.058) were not statistically different with a t-score of -0.206 and a P-value of 0.843 (Degrees of Freedom=7). The only two functions to have statistically significant means were Water Storage & Delay, and Wintering & Migratory Waterbird Support. However, the mean score for water storage and delay was higher in 2018 than 2019. Reasons for this will be debated in the discussion section.

The paired t-test does suggest that the mean scores for Wintering & Migratory Waterbird Support function are statistically different in 2019 (Mean=0.532, Standard Error= 0.044) compared to 2018 (Mean=0.351, Standard Error= 0.033). The t-value presented is -3.109 with a P-value of 0.017, lower than the specified alpha of 0.05. The mean is higher in 2019 than in 2018; the difference in the means illustrates that the function of this wetland feature was better in 2019 than in 2018.

Table 3.6.: *This table displays the results of the paired t-tests conducted on data from Reach 4 at the Whychus Canyon Preserve, on Whychus Creek. The test compares the mean score between 2018 and 2019 for each function along the reach.*

Function	Year	N	DF	Mean	Standard Error Mean	Mean Differences	95 % confidence intervals		t	Sig.	Accept/ Reject Null
							Lower	Upper			
Water Storage & Delay	2018	8	7	0.229	0.044	0.141	0.023	0.260	2.824	0.026	Reject
	2019	8	7	0.088	0.017						
Sediment Stabilisation & Phosphorus Retention	2018	8	7	0.360	0.036	0.025	-0.117	0.167	0.417	0.689	Accept
	2019	8	7	0.335	0.039						
Thermo-regulation	2018	8	7	0.304	0.035	0.037	-0.073	0.147	0.793	0.454	Accept
	2019	8	7	0.267	0.031						
Primary Production	2018	8	7	0.679	0.050	-0.059	-0.203	0.084	-0.978	0.361	Accept
	2019	8	7	0.739	0.035						
Resident Fish Habitat Support	2018	8	7	0.965	0.138	-0.162	-0.514	0.191	-1.083	0.315	Accept
	2019	8	7	1.127	0.022						
Anadromous Fish Habitat Support	2018	8	7	0.830	0.049	0.027	-0.027	0.082	1.193	0.272	Accept
	2019	8	7	0.803	0.032						
Invertebrate Habitat Support	2018	8	7	0.807	0.033	-0.005	-0.087	0.077	-0.147	0.887	Accept
	2019	8	7	0.812	0.028						
Amphibian & Turtle Habitat	2018	8	7	0.677	0.050	-0.112	-0.244	0.020	-2.002	0.085	Accept
	2019	8	7	0.789	0.025						
Wintering & Migratory Waterbird Support	2018	8	7	0.351	0.033	-0.181	-0.318	-0.043	-3.109	0.017	Reject
	2019	8	7	0.532	0.044						
Songbird Habitat Support	2018	8	7	0.896	0.131	-0.091	-0.403	0.221	-0.688	0.513	Accept
	2019	8	7	0.987	0.002						
Support of Characteristic Vegetation	2018	8	7	0.772	0.071	-0.009	-0.112	0.094	-0.206	0.843	Accept
	2019	8	7	0.781	0.058						

4: Discussion:

4.1.: Bankfull Modelling:

The bankfull modelling conducted in this research provides valuable insights into the state of the river currently, and the maintenance of a dynamic equilibrium between discharge, slope, sediment load and sediment size (Lane, 1955). Lane (1955) explores the relationship between the discharge and bed load transport rate; these ideas are portrayed in Figure 4.1- Lane's Balance. It suggests that alteration in one of these aspects of channel morphology will have a knock-on impact on the other characteristic variables. For example, an increase in discharge would pull the right-hand side of the scale down and cause the river to begin eroding laterally and vertically. This increased erosion will, over time, provide the river with a greater supply of sediment. As the sediment supply increases the scales become balanced again and dynamic equilibrium is reached (Wampler, 2012).

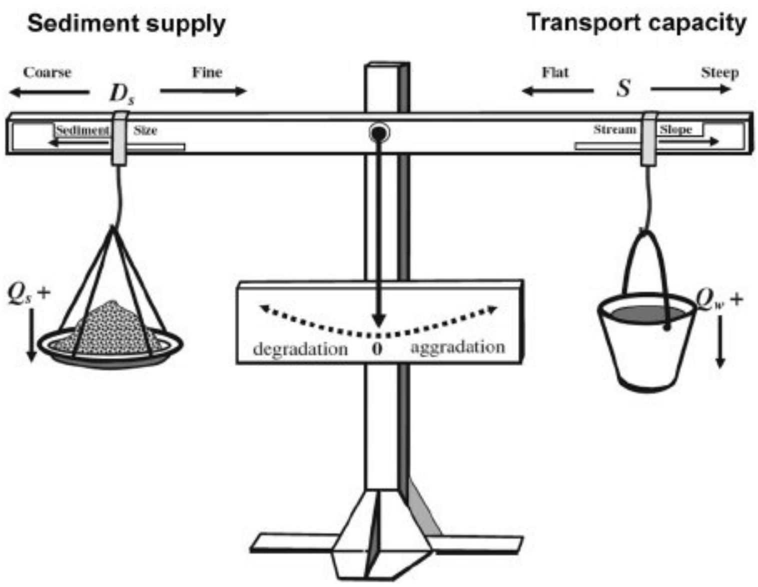

FIgure 4.1.: *Presentation of Lane's Balance, showing the interrelationship between transport capacity (discharge) and sediment supply in rivers and streams (Sourced from: Liro, 2014; Adapted from: Lane, 1955; Dust and Wohl, 2012).*

The principles outlined in Lane's balance make it possible to infer a number of conclusions on the condition of Whychus Canyon. The water in Reach 3 is running straight through a relatively homogenous environment with lacking heterogeneity in terms of flow and channel depth. Once water arrives in Reach 4, the cross-sectional area increases based on the results of this study, by 1.12 metres. The velocity therefore slows as this water reaches a much larger area and its energy dissipates. This is backed up by the results of the modelling; averaging the 5 modelling methods gives an average bankfull velocity in Reach 3 of 2.64 m s^{-1}. However, in Reach 4, the average is only 2.10 m s^{-1}.

As energy dissipates, particles being carried along in the water are deposited on the bed and banks in Reach 4. This is backed up by the result of the Wolman sample conducted in this research in the context of bed load transport literature. The median grain size in the plotted distribution is 3.85mm smaller in Reach 4 than in Reach 3. It is postulated that as flow velocity decreases (as modelled), the smaller the particle size that is deposited onto the bed. Filip Hjulström hypothesised this in 1935, and this can be seen in Figure 4.2- the Hjulström curve.

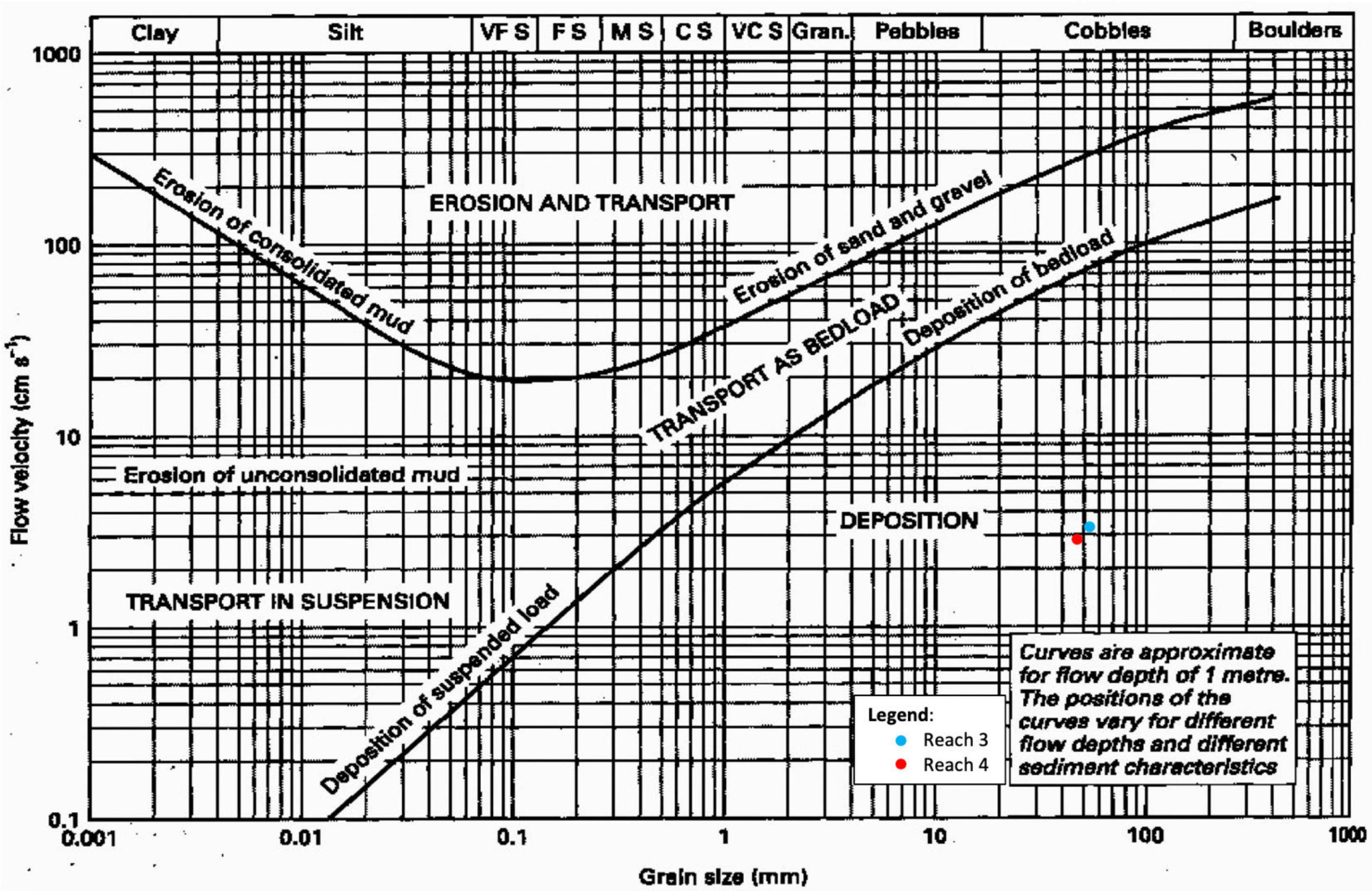

Figure 4.2.: *This graph shows the 'Hjulström Curve' as was first hypothesised by Filip Hjulström in 1935. It is a graph commonly used by hydrologists to determine entrainment, transport or deposition of fluvial sediment.*

Both Reach 3 and Reach 4 have been placed on Figure 4.2 to assess whether the dominant process impacting channel morphology is deposition, transportation or erosion (Werritty, 1997). According to the curve, both reaches are depositional environments. This is not what was expected from the results and field observations. Reach 3 is not a depositional stretch of river; it is fast flowing, stretch of river. Reach 4 exhibited similar conditions prior to restoration but was altered to create a more depositional reach (UDWC, n.d. a).

Exploring the data in Table 3.1 further, the slope in Reach 3 was calculated to be 2% steeper than in Reach 4. This may not seem like much, but over such long stretches of river this will contribute to greater deposition and lower velocities in Reach 4. This can be seen in Lane's Balance, where decreasing the slope causes aggradation (Lane, 1955). This leans towards producing environments synonymous with stage 0 environments (Powers et al., 2018). The slope map for Reach 3 and 4 can be seen in Figure 4.3.

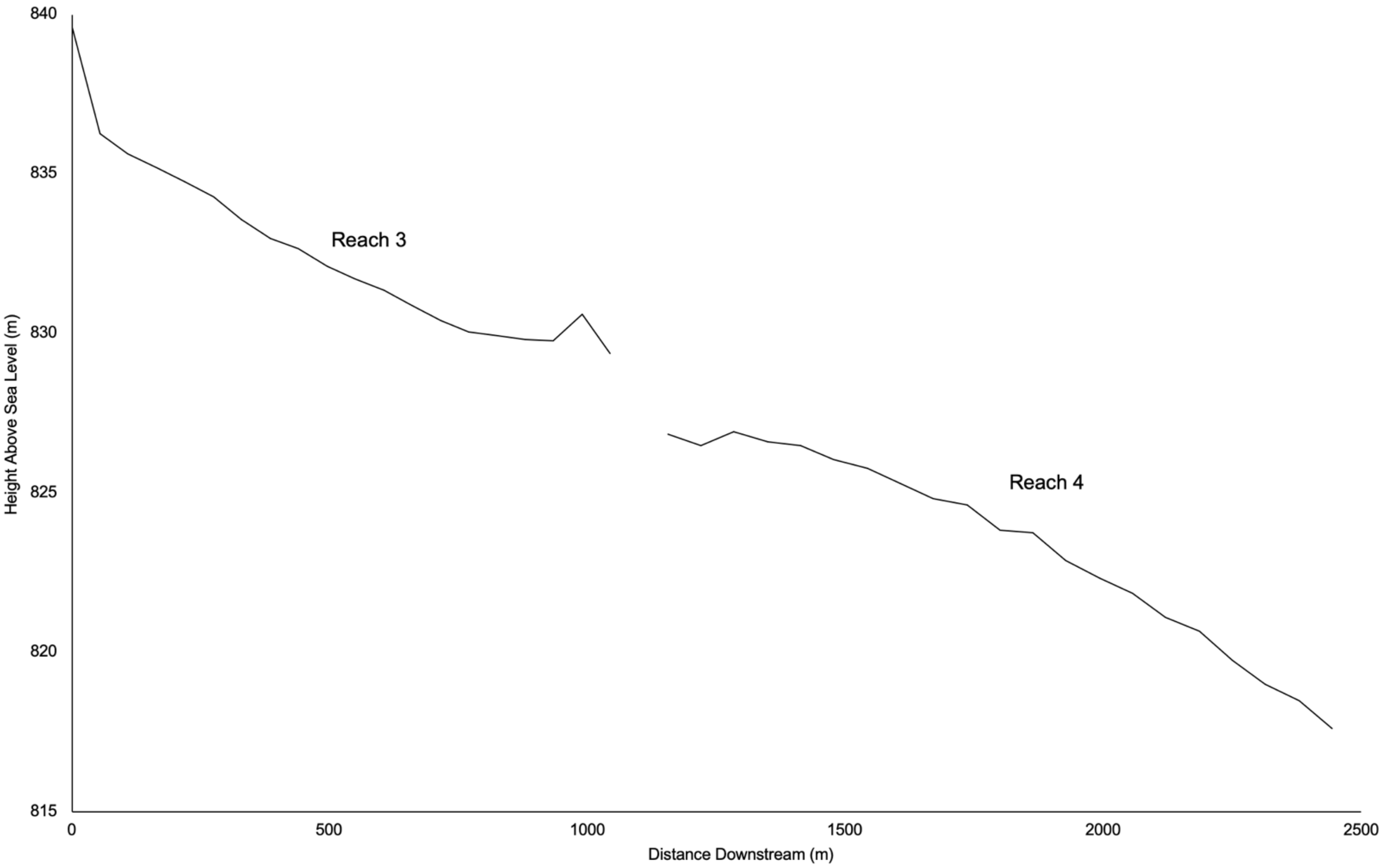

Figure 4.3.: *This graph shows the slope maps of Reach 3 and 4 at the Whychus Canyon Preserve on Whychus Creek. This slope graph was created using Digital Elevation Models obtained from Joe Rudolph of Wolf Water Resources (Rudolph, 2018).*

The hydromorphological conditions illustrated through analysis of the bankfull flow and sediment structure of Reach 4 explain why the channel now sits in a braided planform. The reach exemplifies the processes that create and maintain multi-thread channels (Bridge, 2003). Firstly, braiding requires a high supply of sediment (Knighton, 2014), which as illustrated by Lanes balance, is provided at Reach 4 due to erosion from increased discharge. Braiding results from a lack of capacity to transport the sediment supplied (ibid) and Reach 4 is predominantly deposition, as illustrated on the Hjulstrom Curve. This deposition, in the form of bars, is what separates the channel into threads. Furthermore, deposition diverts the flow against the channel banks and therefore contributes to the bank erosion for the development of the wide shallow channel commonly associated braided channels.

Furthermore, the highly dynamic and depositional conditions of Reach 4 contribute to the creation of habitat heterogeneity in streams (Yarnell et al., 2006). This can be attributed to the control that sediment and flow have on the channel morphology and substrate textures, two key physical habitat characteristics (ibid). Channel morphology provides the basis of the aquatic environment (Maddock, 1999) and channel morphology in Reach 4, due to the braided planform is extremely diverse (Mueller and Pitlick, 2014). This diversity creates a range of habitats in the channel, and on the bars created, increasing the habitat of the channel. This therefore illustrates the point that Reach 4, a multi-thread channel, will have higher habitat heterogeneity than Reach 3, a single-thread channel (Cluer and Thorne, 2013). Furthermore, Tockner et al. (2006) lists other processes that occur in braided channels such as; cut and fill alluviation, channel avulsion, production, entrainment and deposition of large wood (LW), and ground- and surface-water interactions, which further help to create a complex and dynamic array of aquatic, amphibious, and terrestrial habitats (Stanford, 1998; Poole et al., 2002; Ward et al., 2002; Lorang et al., 2005). This diversity in habitat not only provides a greater number of niches for species, but also provides habitats for species for breeding, foraging and refugia (Townsend et al., 1997; Ward et al., 1999; Ward and Tockner, 2001), as illustrated in the results of the wetland function assessment.

4.2.: Wetland Functions:

Analysing the scores for the independent t-tests between the scores in Reach 3 and Reach 4 shows that for the 6 of the 11 functions, Reach 4 has better wetland functions than Reach 3. They are:

- Sediment Stabilisation & Phosphorous Retention;
- Primary Production;
- Invertebrate Habitat Support;
- Amphibian & Turtle Support;
- Wintering & Migratory Waterbird Support; and
- Anadromous Fish Habitat Support.

We can say that the means differ significantly and the mean scores in Reach 4 are higher than Reach 3. In 3 of the other functions, the means are higher in Reach 4 than Reach 3, these are:

- Water Storage & Delay;
- Resident Fish Habitat Support; and
- Support of Characteristic Vegetation.

For two of the functions, the scores in Reach 3 were higher than in Reach 4. The reasons for this are due to some of the indicators used in the Songbird Habitat Support and Thermoregulation sections. For example, large proportions of the final standardised function capacity score are obtained through good scores on indicators such as "distance to nearest busy road' and 'Frequency of humans visiting on foot'; these don't actually reflect the habitats offered, just the remoteness of the site. This identifies a limitation of the method, but these will be expanded on further in Section 5.3.

It is possible to interpret variance (measured by standard error) in the restored reach as a good thing, as it suggests that there are areas better at certain functions than others. Not every function will score highly in a survey (Adamus and Field, 2001). It is important to get a variety of low and high scores for each function throughout a reach as this implies a heterogenous environment, which is better for a wide range of different flora and fauna (Willby et al., 2018)

When analysing the results from the paired t-tests assessing functions at Reach 4 in 2018 and 2019, there is less evidence on development and maturing of the wetland as was hypothesised in Objective 3. Of the 11 functions tested, the mean score was higher in 2019 in 7 functions, but only one of these was proved to be statistically different (Wintering and Migratory Waterbird Support). It is therefore sensible to assume that more time is required to allow the wetland to develop further to get observably better function capacity scores from this methodology. That being said, other, more recently released methods may have worked better at assessing methods (Section 5.3.) (Adamus et al., 2016).

To discuss the importance of these functions, it is important to think about the value that they offer. Using Mitsch and Gosslink's (2015) value classifications, the functions assessed in the wetland function assessment can be classified (Table 4.1). From the population values, 5 had higher mean scores in the restored Reach 4 than the unrestored Reach 3. This can be attributed the habitat heterogeneity of the restored reach. In terms of the value classes proposed by Mitsch and Gosslink (2015), 'Ecosystem Values' and 'Global Values' related most to human well-being and can therefore be assumed to offer Ecosystem Services. As evident in Table 4.1., none of the functions assessed are classified as 'Global Values', however it is expected that the restoration of wetlands will provide Ecosystem Services that have been lost. For example, many analyses discuss the role of wetlands in the hydrological cycle, often said to 'act like sponges', as they soak up water in wet periods and release it during high periods (Bucher et al., 1993). This is related to the 'Water Storage and Delay' function, which in Reach 4 is not significantly different to the reference site but is higher, therefore suggesting that it is a function but may not be fully developed yet, as suggested by the results of the 2018 and 2019 comparison. Furthermore, there is a substantial amount of literature relating to the role of wetlands in the protection and/or enhancement of water quality (Maltby, 2009). The wetland assessment suggests that Reach 4 offers this function, as the mean function score 'Sediment Stabilisation and Phosphorus Retention' was significantly different to the score at Reach 3. This way of analysing the functions of wetlands, in terms of the Ecosystem Services they offer, allows better communication with stakeholders and the public, by creating more direct links with human well-being, helping to increase support for such projects (Albert et al., 2016). Increased support can lead to greater funding towards the project being assessed, and other projects of similar types (Bullock et al., 2011).

Table 4.1.: *Table showing the functions assessed by the Wetland Function Assessment classified into Mitsch and Gosslink's (2015) classification of the values of wetland ecosystem services. Functions with ** were found to be significantly higher in Reach 4 and functions with * had a higher average in Reach 4, however it was not considered to be significant.*

Classification	Function
Population Values	Resident Fish Habitat Support*
	Anadromous Fish Habitat Support**
	Invertebrate Habitat Support**
	Amphibian and Turtle Habitat**
	Breeding Waterbird Support
	Wintering and Migratory Waterbird Support**
	Songbird Habitat Support
Ecosystem Values	Support of Characteristic Vegetation*
	Water Storage and Delay*
	Sediment Stabilisation and Phosphorus Retention**
	Thermoregulation
	Primary Production**

5: Conclusion:

In summary, Reach 4 is a highly depositional and dynamic environment which consequently lead to greater habitat heterogeneity in the channel. In the erosion and transport dominant Reach 3, this heterogeneity is not present. The results of the wetland function assessments tell us this. Certain functions score well in Reach 3 due to flaws in the methods but on the whole, the environmental conditions offered in Reach 4 are head and shoulder above Reach 3. Results are less conclusive when exploring wetland development between 2018 and 2019, as the wetland is still relatively underdeveloped. Improvements in wetland functions offer substantial environmental improvements in degraded reaches, and this can have huge positive effects on flora and fauna in the riparian corridor in particular.

At Whychus Canyon, and at a broader-scale, the need for further post-project monitoring is clear. Without more extensive monitoring programs on projects across the globe, the outcomes, whether positive or negative, will not be understood. The role of ecology is becoming increasingly important. This is becoming an increasingly common theme throughout the literature, for example with the introduction of concepts such as biomic river restoration (Johnson et al., 2019b).

Reference List:

Abelson, A., Halpern, B., Reed, D., Orth, R., Kendrick, G., Beck, M., Belmaker, J., Krause, G., Edgar, G., Airoldi, L., Brokovich, E., France, R., Shashar, N., de Blaeij, A., Stambler, N., Salameh, P., Shechter, M. and Nelson, P. (2015). Upgrading Marine Ecosystem Restoration Using Ecological-Social Concepts. *BioScience*, **66**(2), pp. 156-163.

Adamus, P.R. (2001). *Guidebook for Hydrogeomorphic (HGM)–based Assessment of Oregon Wetland and Riparian Sites I. Willamette Valley Ecoregion Riverine Impounding and Slope/Flats Subclasses. Volume IB. Technical Report*. Oregon Division of State lands: Salem, OR.

Adamus, P.R. (2016). *Manual for the Wetland Ecosystem Services Protocol (WESP)*. [online]. Available at: http://people.oregonstate.edu/~adamusp/WESP/Manual_WESP1.3_13Oct2016_Adamus.pdf [Accessed: 13th July 2019].

Adamus, P.R. and Field, D. (2001). *Guidebook for Hydrogeomorphic (HGM)-based Assessment of Oregon Wetland and Riparian Sites: Statewide Classification and Profiles.* Oregon Division of State lands: Salem, OR.

Adamus, P.R. and Stockwell, L.T., 1983. *A method for wetland functional assessment: volume 1 critical review and evaluation concepts* (No. FHWA-IP-82-83 Final Rpt.).

Adamus, P.R., Verble, K. and Rudenko, M. (2016). *Manual for the Oregon Rapid Wetland Assessment Protocol (ORWAP, revised)*. Oregon Department of State Lands: Salem, OR.

Albert, C., Galler, C., Hermes, J., Neuendorf, F., Von Haaren, C. and Lovett, A. (2016). Applying ecosystem services indicators in landscape planning and management: The ES-in-Planning framework. *Ecological Indicators*, **61**, pp. 100-113.

Allen, C. D. and Breshears, D.D. (1998). Drought-induced shift of a forest/woodland ecotone: rapid landscape response to climate variation. *Proceedings of the National Academy of Sciences*, **95**, pp.14839–14842.

Allen, C., Savage, M., Falk, D., Suckling, K., Swetnam, T., Schulke, T., Stacey, P., Morgan, P., Hoffman, M. and Klingel, J. (2002). Ecological restoration of southwestern ponderosa pine ecosystems: a broad perspective. *Ecological Applications*, **12**, pp.1418-1433.

Andrews, E.D. (1980). Effective and bankfull discharges of streams in the Yampa River basin, Colorado and Wyoming. *Journal of Hydrology*, **46**, pp. 311-330.

Arguez, A., Durre, I., Applequist, S., Vose, R.S., Squires, M.F., Yin, X., Heim, R.R., Jr. and Owen, T. W. (2012). NOAA's 1981-2010 U.S. Climate Normals: An Overview. *Bulletin of the American Meteorological Society*, **93**, pp.1687-1697.

Baker, M. (2016). Statisticians issue warning over misuse of *P* values: Policy statement aims to halt missteps in the quest for certainty. *Nature*, **531**, p. 151.

Barnes, H.H. (1967). *Roughness characteristics of natural channels*. U.S. Geological Survey: Reston, VA.

Beechie, T., Imaki, H., Greene, J., Wade, A., Wu, H., Pess, G., Roni, P., Kimball, J., Stanford, J., Kiffney, P. and Mantua, N. (2013). Restoring salmon habitat for a changing climate. *River Research and Applications*, ***29***(8), 939–960.

Beechie, T., Sear, D. A., Olden, J. D., Pess, G. R., Buffington, J. M., Mior, H., Roni, P. and Pollock, M. M. (2010). Process-based Principles for Restoring River Ecosystems. *Bioscience*, **60**, pp. 209-222.

Bernhardt, E. S. and Palmer M. A. (2011). River restoration: The fuzzy logic of repairing reaches to reverse watershed scale degradation. *Ecological Applications*, **21**, pp. 1926-1931.

Bevenger, G.S. and King, R.M. (1995). *A pebble count procedure for accessing watershed cumulative effects*. Research Paper RM-RP-319. US Department of Agriculture, Forest Service: Fort Collins, CO.

Booth, D., Scholz, J., Beechie, T. and Ralph, S. C. (2016). Integrating limiting factors analysis with process-based restoration to improve recovery of endangered salmonids in the Pacific Northwest, USA. *Water*, **8**, pp. 1-12.

Bridge, J. S. (2003). *Rivers and Floodplains.* Blackwell Publishing: USA.

Bruce-Burgess, L. and Skinner, K. S. (2002). *Appraisal: River restoration's missing link.* Held of the 27th November 2002 at the University of Nottingham.

Bryce, S.A., J.M. Omernik, and D.P. Larsen. 1999. Ecoregions: a geographic framework to guide risk characterization and ecosystem management. Environmental Practice, **1**,pp. 141-155.

Bucher, E. H., Bonetto, A., Boyle T., Canevari P., Castro G., Huszar P. and Stone, T. (1993). *Hidroviaan initial environmental examination of the Paraguay - Parana waterway*. Wetlands for the Americas Publication No. 10: Manomet MA, USA.

Buijse, A., Coops, H., Staras, M., Jans, L., Van Geest, G., Grifts, R., Ibelings, B., Oosterberg, W. and Roozen, F. (2002). Restoration strategies for river floodplains along large lowland rivers in Europe. *Freshwater Biology*, **47**, pp. 889-907.

Bullock, J.M., Aronson, J., Newton, A.C., Pywell, R.F. and Rey-Benayas, J.M. (2011). Restoration of ecosystem services and biodiversity: conflicts and opportunities. *Trends In Ecology & Evolution*, **26**(10), pp. 541-549.

Bunte,K. and Abt, S.R. (2001). *Sampling Surface and Subsurface Particle-Size Distributions in Wadable Gravel- and Cobble-Bed Streams for Analyses in Sediment Transport, Hydraulics, and Streambed Monitoring***.** Gen. Tech. Rep. RMRS-GTR-74. US Department of Agriculture, Forest Service: Fort Collins, CO.

Clark, M. J. (2002). Dealing with uncertainty: adaptive approaches to sustainable river management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **12**, pp. 347-363.

Cluer, B. and Pollock, M. (2018). Restoring to Stage Zero, Recent Innovations in Restoration Science: Reports from the Field. 36th Annual Salmonid Restoration Conference: California. [online] Available at: https://www.calsalmon.org/programs/events/restoring-stage-zero-recent-innovations-restoration-science-reports-field [Accessed 21st Mar. 2019].

Cluer, B. and Thorne, C. (2013). A Stream Evolution Model Integrating Habitat and Ecosystem Benefits. *River Research and Applications*, **30**(2), pp. 135-154.

Cluer, B. and Thorne, C. (2014). A stream evolution model integrating habitat and ecosystem benefits. *River Research and Applications*, **30**, pp.135-154.

Comiti, F., Mao, L. Wilcox, A., Wohl, E. and Lenzi, M.A. (2007). Field-derived relationships for flow velocity and resistance in high-gradient streams, *Journal of Hydrology* **340**, pp**.**48-62.

Darcy, H. (1854). Sur des recherches expérimentales relatives au movement des eaux dans les tuyaux. *Comptes Rendus des Séances de l'Academie des Sciences*, **38**, pp.1109-1121.

David, G. C. L., Wohl, E. Yochum, S. E. and Bledsoe, B.P. (2010). Controls on at-a-station hydraulic geometry of steep mountain streams. *Earth Surface Processes and Landforms*, **35**, pp. 1820-1837,

DeLorme Mapping Company. (1991). *Oregon Atlas and Gazetteer: Topo Maps of the Entire State*. Delorme Mapping Company: Maine.

Diaz, S., S. Demissew, J. Carabias, C. Joly, M. Lonsdale, N. Ash, A. Larigauderie, J. R. Adhikari, S. Arico, A. Baldi, A. Bartuska, I.A.Baste, A.Bilgin, E.Brondizio, K.M.A.Chan, V.E.Figueroa, A. Duraiappah, M. Fischer, R. Hill, T. Koetz, P. Leadley, P. Lyver, G. M. Mace, B. Martin-Lopez, M. Okumura, D. Pacheco, U. Pascual, E. S. Perez, B. Reyers, E. Roth, O. Saito, R. J. Scholes, N. Sharma, H. Tallis, R. Thaman, R. Watson, T. Yahara, Z. A. Hamid, C. Akosim, Y. Al-Hafedh, R. Allahverdiyev, E. Amankwah, S. T. Asah, Z. Asfaw, G. Bartus, A. L. Brooks, J. Caillaux, G. Dalle, D. Darnaedi, A. Driver, G. Erpul, P. Escobar-Eyzaguirre, P. Failler, A. M. M. Fouda, B. Fu, H. Gundimeda, S. Hashimoto, F. Homer, S. Lavorel, G. Lichtenstein, W. A. Mala, W. Mandivenyi, P. Matczak, C. Mbizvo, M. Mehrdadi, J. P. Metzger, J. B. Mikissa, H. Moller, H. A. Mooney, P. Mumby, H. Nagendra, C. Nesshover, A. A. Oteng-Yeboah, G. Pataki, M. Roue, J. Rubis, M. Schultz, P. Smith, R. Sumaila, K. Takeuchi, S. Thomas, M. Verma, Y. Yeo-Chang, and D. Zlatanova. (2015). The IPBES Conceptual Framework - connecting nature and people. *Current Opinion in Environmental Sustainability*, **14**, pp. 1-16.

Dobson, A.P., Bradshaw, A.D. and Baker, A.J.M. (1997). Hopes for the future: Restoration ecology and conservation biology. *Science*, **277**, pp.515–522.

Dust, D. and Wohl, E. (2012). Conceptual model for complex river responses using an expanded Lane's relation. *Geomorphology*, **139**, pp. 109-121.

England, J., Skinner, K. S. and Garter, M. G. (2008). Monitoring river restoration and the Water Framework Directive. Water and Environment Journal, **22**, pp. 227-234.

Entry, J.A. and Emmingham,W.H. (1996). Nutrient content and extractability in riparian soils supporting forests and grasslands. *Applied Soil Ecology*, **4**, pp.119-124.

Environmental Protection Agency. (2017). Level III and IV ecoregions of Oregon. [online] Available at: https://www.epa.gov/eco-research/ecoregion-download-files-state-region-10#pane-35 [Accessed 25th July 2019].

Fischer, A. and Eastwood, A. (2016). Coproduction of ecosystem services as human-nature interactions: an analytical framework. *Land Use Policy*, **52**, pp. 41-50.

Gende, S., Edwards, R., Wilson, M. and Wipli, M. (2002). Pacific Salmon in Aquatic and Terrestrial Ecosystems. *Bioscience*, **52**, pp.917-928.

Greeson, P.E. and Clark, J.R., 1980. *Wetland functions and values: the state of our understanding*. Technical publication series-American Water Resources Association (USA).

Griffiths, G.A., (1981). Flow resistance in coarse gravel bed rivers. *Journal of the Hydraulics Division*, **107**(7), pp. 899-918.

Gustafson, R., Waples, R., Myers, J., Weitkamp, L., Bryant, G., Johnson, O. and Hard, J. (2007). Pacific salmon extinctions: quantifying lost and remaining diversity. *Conservation Biology*, ***21***, pp.1009-1020.

Hey, R.D. (1979). Flow Resistance in Gravel-Bed Rivers. *Journal of Hydraulic Engineering*, **105**, pp.365-379.

Hjulstrom, F. (1935). Studies of the morphological activity of rivers as illustrated by the River Fyris. *Bulletin of the Geological Institute University of Uppsala*, **25**, pp. 221-527.

Horwitz, E.L., 1978. *Our nation's wetlands, An interagency task force report coordinated by the President's Council on Environmental Quality*. GPO: Washington, DC.

Hruby, T., Bruner, K., Cooke, S., Dublonica, K., Gersib, R., Granger, T., Reinelt, L., Richter, K., Sheldon, D., Wald, A. and Weinmann, F. (1999). *Methods for Assessing Wetland Functions. Volume 1: Riverine and Depressional Wetlands in the Lowlands of Western Washington. Ecology Publication 99-115.* Washington State Department of Ecology: Olympia, WA.

Hsu, H. and Lachenbruch, P. (2008). *Paired t-Test*. *Wiley Encyclopedia of Clinical Trials*: Hoboken, NJ.

Johnson, B., Johnson, M. and Thorgaard, G. (2019a). Salmon Genetics and Management in the Columbia River Basin. *Northwest Science*, ***92***, pp. 346-363.

Johnson, M., Thorne, C., Castro, J., Kondolf, G., Mazzacano, C., Rood, S. and Westbrook, C. (2019b). Biomic river restoration: A new focus for river management. *River Research and Applications*, pp. 1-10.

Katz, S. L., Barnas, K., Hicks, R., Cowen, J., and Jenkinson, R. (2007). Freshwater habitat restoration actions in the Pacific Northwest: A decade's investment in habitat improvement. *Restoration Ecology*, **15**, pp. 494–505.

Kondolf, G.M. (1997). Application of the pebble count: notes on purpose, method, and

Lacey, G. (1929). Stable channel in alluvium. *Minutes of the Proceedings of the Institution of Civil Engineers*, **229**, pp.259-285.

Lane, E.W. (1955). The importance of fluvial morphology in hydraulic engineering. *Proceedings of the American Society of Civil Engineers,* **81**, pp.1-17.

Lichvar, R.W., Banks, D.L., Kirchner, W.N. and Melvin, N.C. (2016). The National Wetland Plant List: 2016 Wetland Ratings. *Phytoneuron*, **30**, pp.1-17.

Lichvar, R.W., Melvin, N.C., Butterwick, M.L. and Kirchner, W.N. (2012). *National Wetland Plant List Indicator Rating Definitions*. U.S. Army Engineer Research and Development Center: Hanover, NH.

Liro, M. (2014). Conceptual model for assessing the channel changes upstream from dam reservoir. *Quaestiones Geographicae*, **33**, pp. 61-74.

Lorang, M. S., Whited, D.C., Hauer, F.R., Kimball, J.S. and Stanford, J.A. (2005). Using airborne multispectral imagery to evaluate the potential for geomorphic work across floodplains of gravel bed rivers. *Ecological Applications,* **15**, pp. 1209-1222.

Maddock, I. (1999). The importance of physical habitat assessment for evaluating river health. *Freshwater biology*, **41**, pp. 373-391.

Maltby, E. (1986). *Waterlogged wealth. Why waste the worlds wet places*. Earthscan: London.

Maltby, E., ed., (2009). *Functional assessment of wetlands: Towards evaluation of ecosystem services*. Cambridge: Woodhead Publishing.

Maltby, E. and Acreman, M. C. (2011). Ecosystem services of wetlands: pathfinder for a new paradigm, *Hydrological Sciences Journal*, **56**, pp. 1341-1359

Maltby, E. and Turner, R.E. (1983). Wetlands are not wastelands. *Geographical Magazine*, **55**, pp. 92-97.

Maltby, E., Hogan, D.V. and McInnes, R.J. (1996). *Functional analysis of European wetland ecosystems. Report to the European Commission*, EC DGXII STEP-CT90-0084.

Manning, R. (1891). On the flow of water in open channels and pipes. *Transactions of the Institution of Civil Engineers of Ireland*, **20**, pp.161-207.

Marcus, W., Ladd, S. and Stoughton, J. (1995). Pebble counts and the role of user-

McArthur, L.A. and McArthur, L.L. (2003). *Oregon Geographic Names*. 7th ed. Oregon Historical Society Press: Portland, OR.

Métivier, F., Devauchelle, O., Chauvet, H., Lajeunesse, E., Meunier, P., Blanckaert, K., Ashmore, P., Zhang, Z., Fan, Y., Liu, Y., Dong, Z. and Ye, B. (2016). Geometry of meandering and braided gravel-bed threads from the Bayanbulak Grassland, Tianshan, P. R. China. *Earth Surface Dynamics*, **4**, pp.273-283.

Mitsch, W. J. and Gosselink, J. G. (2015). *Wetlands*. 5th ed. John Wiley & Sons: Hoboken, NJ.

Moreno-Mateos, D., Power, M.E., Comín, F.A. and Yockteng, R. (2012). Structural and functional loss in restored wetland ecosystems. *PLoS biology*, **10**(1), p.e1001247.

Mork, L., Perle, M and Thorne, C. (2018). *Stage 0 Outcomes: Monitoring Results and Stakeholder Views*. Upper Deschutes Watershed Council: Bend, OR.

Mueller, E.R. and Pitlick, J. (2014). Sediment supply and channel morphology in mountain river systems: 2. Single thread to braided transitions. Jour*nal of Geophysical Research: Earth Surface*, **119**(7), pp. 1516-1541.

National Weather Service. (n.d.). NOWData - NOAA Online Weather Data. [online]. Available at: https://w2.weather.gov/climate/xmacis.php?wfo=pdt [Accessed 23rd August 2019].

Oregon Water Resources Department. (2019). OWRD Near Real Time Hydrographics Data. [online]. Available at: https://apps.wrd.state.or.us/apps/sw/hydro_near_real_time/display_hydro_graph.aspx?station_nbr=14076050 [Accessed: 12th June 2019].

Poole, G.C., Stanford J. A., Frissell, C.A. and Running, S.W. (2002). Three-dimensional mapping of geomorphic controls on food-plain hydrology and connectivity from aerial photos. *Geomorphology*, **48**, pp. 329-347.

Powers, P., Helstab, M. and Niezgoda, S. (2018). A process-based approach to restoring depositional river valleys to Stage 0, an anastomosing channel network. *River Research and Applications*, **35**(1), pp. 3-13.

Reid, D. E. and Hickin, E. J. (2008). Flow resistance in steep mountain streams. *Earth Surface Processes Landforms* **33**, pp. 2211-2240.

Rice, S. and Toone, J.A. (2010). *Fluvial Audit of the Upper Dove Catchment, Derbyshire and Staffordshire,* UK. Natural England: Buxton, Derbyshire.

Rudolph, J. (2018). *Technical Memorandum: Whychus Creek Monitoring 2018*. Wolf Water Resources: Portland, OR.

Sather, J.H. and Smith, R.D. (1984). *An overview of major wetland functions and values*. US Fish and Wildlife Service: Washington, D.C.

Savenije, H. (2003). The width of a bankfull channel; Lacey's formula explained. *Journal of Hydrology*, **276**, pp.176-183.

Schneider, C., Flörke, M., Eisner, S. and Voss, F. (2011). Large scale modelling of bankfull flow: An example for Europe. *Journal of Hydrology*, **408**, pp. 235-245.

Smith, R.D., Ammann, A., Bartoldus, C. and Brinson, M.M. (1995). An Approach for Assessing Wetland Functions Using Hydrogeomorphic Classification, Reference Wetlands and Functional indices. US Army Corps of Engineers: Vicksburg, MS.

Stanford, J.A. (1998). Rivers in the landscape: introduction to the special issue on riparian and groundwater ecology. *Freshwater Biology*, **40**, pp. 402-406.

Streeter, V.L. (1962). *Fluid Mechanics (3rd edition)*. McGraw-Hill: New York, NY.

Temple, G., Newsome, T., Webster, T. and Coil, S. (2017). Evaluation of Rainbow Trout Abundance, Biomass, and Condition Following Coho Salmon Reintroduction in Taneum Creek, Washington. *Northwest science*, ***91***, pp.54-69.

Thorne, C.R. and Zvenbergen, L.W. (1985). Estimating mean velocity in mountain rivers. *Journal of Hydraulic Engineering*, **111**(4), pp. 612-624.

Tockner, K., Paetzold, A., Karaus, U.T.E., Claret, C. and Zettel, J.(2006). Ecology of braided rivers. *Special Publication-International Association of Sedimentologists*, **36**, p. 339.

Tompkins, M. R. and Kondolf, G. M. (2007). Systematic post-project appraisals to maximise lessons learned from river restoration projects: case study of compound channel restoration projects in northern California. *Restoration Ecology*, **15**, pp. 524-537.

Townsend, C., Doledec, S. and Scarsbrook, M. (1997). Species traits in relation to temporal and spatial heterogeneity in streams: a test of habitat templet theory. *Freshwater Biology*, **37**, pp. 367-387.

UDWC. (2009). *Whychus Creek Restoration Monitoring Plan: Upper Deschutes Model Watershed Program*. Upper Deschutes Watershed Council: Bend.

UDWC. (n.d. a). Deschutes Land Trust's Whychus Canyon Preserve. [online] Available at: https://www.upperdeschuteswatershedcouncil.org/restoration/whychus-creek/whychus-canyon-restoration/ [Accessed: 27 Jun. 2018].

UDWC. (n.d. b). Camp Polk Meadow Preserve Restoration Project. [online] Available at: https://www.upperdeschuteswatershedcouncil.org/restoration/whychus-creek/camp-polk-meadow/ [Accessed: 27 Jun. 2018].

UDWC. (n.d. c) Whychus Creek. [online] Available at: https://www.upperdeschuteswatershedcouncil.org/restoration/whychus-creek/ [Accessed: 27 Jun. 2018].

United States Fish and Wildlife Service. (n.d.). *Whychus Creek, Oregon*. [online]. Available at: https://www.rivers.gov/rivers/whychus.php [Accessed 25th July 2019].

Vasilas, L.M., Hurt, G.W. and Berkowitz, J.F. (2017). *Field Indicators of Hydric Soils in the United States: A Guide for Identifying and Delineating Hydric Soils, Version 8.1*. United States Department of Agriculture, Natural Resources Conservation Service: Washington, DC.

Vought, L.B.M., Dahl, J., Pedersen, C.L. and Lacoursiere, J.O. (1994). Nutrient retention in riparian ecotones. *Ambio*, **23**, pp.342-348.

Wampler, P. J. (2012). Rivers and Streams: Water and Sediment in Motion. *Nature Education Knowledge*, **3**, p. 18

Ward, J. V., Tockner, K. and Schiemer, F. (1999). Biodiversity of floodplain river ecosystems: ecotones and connectivity. *Regulated Rivers: Research and Management*, **15**, pp. 125-139.

Ward, J., Tockner, K., Arscott, D. and Claret, C. (2002) Riverine landscape diversity. *Freshwater Biology*, **47**, pp. 517-539.

Ward, J.V. and Tockner, K. (2001). Biodiversity: towards a unifying theme for river ecology. *Freshwater Biology*, **46**, pp. 807-820.

Weisbach, J., (1865). *Lehrbuch der Ingenieur-und Mashchinenmechanik*. Brunswick: Germany.

Willby, N., Law, A., Levanoni, O., Foster, G. and Ecke, F. (2018). Rewilding wetlands: beaver as agents of within-habitat heterogeneity and the responses of contrasting biota. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **373**(1761), pp.1-8.

Wolman, G.M. (1954). A method of sampling coarse river-bed material. *Transactions of the American Geophysical Union*, **35**(6), pp. 951-956.

Wolman, M.G. and Leopold, L.B. (1957). River flood plains: some observation on their formation. *US Geological Survey Professional Papers*, **282**, pp. 87-109.

Wright, J., Jones, C. and Flecker, A. (2002). An ecosystem engineer, the beaver, increases species richness at the landscape scale. *Oecologia*, **132**, pp.96-101.

Yake, K.E. (2003). *Upper Deschutes subbasin assessment*. [online]. Upper Deschutes Watershed Council: Bend, OR. Available at: https://www.upperdeschuteswatershedcouncil.org/wp-content/uploads/2013/12/Upper-D-Assessment-with-Maps.pdf [Accessed: 28th July 2019].

Yarnell, S.M., Mount, J.F. and Larsen, E.W. (2006). The influence of relative sediment supply on riverine habitat heterogeneity. *Geomorphology*, **80**, pp. 310-324.

Yochum, S. E., Bledsoe, B. P., David, G. C. L. and Wohl, E. (2012). Velocity prediction in high-gradient channels. Journal of Hydrology, **424**, pp. 84-98.

Yochum, S. E., Francesco, C., Wohl, E., David, G.C.L. and Luca, M. (2014). *Photographic Guidance for Selecting Flow Resistance Coefficients in High-Gradient Channels*. US Department of Agriculture Forest Service: Fort Collins, CO.