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RESEARCH ARTICLE

A process-based approach to restoring depositional river valleys to Stage 0, an anastomosing channel network

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Abstract

Stream restoration approaches most often quantify habitat degradation, and therefore recovery objectives, on aquatic habitat metrics based on a narrow range of species needs (e.g., salmon and trout), as well as channel evolution models and channel design tools biased toward single-threaded, and "sediment-balanced" channel patterns. Although this strategy enhances perceived habitat needs, it often fails to properly identify the underlying geomorphological and ecological processes limiting species recovery and ecosystem restoration. In this paper, a unique process-based approach to restoration that strives to restore degraded stream, river, or meadow systems to the premanipulated condition is presented. The proposed relatively simple Geomorphic Grade Line (GGL) design method is based on Geographic Information System (GIS) and field-based analyses and the development of design maps using relative elevation models that expose the relic predisturbance valley surface. Several case studies are presented to both describe the development of the GGL method and to illustrate how the GGL method of evaluating valley surfaces has been applied to Stage 0 restoration design. The paper also summarizes the wide applicability of the GGL method, the advantages and limitations of the method, and key considerations for future designers of Stage 0 systems anywhere in the world. By presenting this ongoing Stage 0 restoration work, the authors hope to inspire other practitioners to embrace the restoration of dynamism and diversity through restoring the processes that create multifaceted river systems that provide long-term resiliency, meta-stability, larger and more complex and diverse habitats, and optimal ecosystem benefits.

KEYWORDS

ecological uplift, Geomorphic Grade Line, relative elevation model, resilience, river restoration, Stage 0 anastomosing/anabranching, stream evolution, wetland restoration

1 | INTRODUCTION

Over the past five decades, there has been a concerted and prominent effort applied toward restoring degraded river systems throughout the USA (Bernhardt et al., 2005; Bernhardt & Palmer, 2007; Katz, Barnas, Hicks, Cowen, & Jenkinson, 2007; Wohl et al., 2005; Wohl, Lane, & Wilcox, 2015), Europe (Brookes, 1990; Clifford, 2012; Szalkiewicz, Jusik, & Grygoruk, 2018; Zockler, Wenger, & Madgwick, 2000), and Australia (Brierley & Fryirs, 2005; Brooks & Lake, 2007). Rivers exhibit variability in form and process as a result of their history and imposed disturbances and are quite diverse and dynamic. In the past 10 years, there has been a strong call from the scientific community to embrace the restoration of diversity and prioritize river process in restoration to improve project effectiveness (e.g., Beechie et al., 2010, 2013; Bernhardt & Palmer, 2007, 2011; Booth, Scholz, Beechie, & Ralph,

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2016; Kondolf, 1998; Roni et al., 2002; Wohl et al., 2005; Wohl et al., 2015). Process-based restoration efforts to restore physical connectivity among channel, floodplain, and hyporheic zone and restore the natural diversity and variability in flow and sediment regimes are being shown to be more effective in restoring ecological function (Szalkiewicz et al., 2018; Wohl et al., 2015), as predicted by Cluer and Thorne (2013).

Most restoration projects begin with the identification of predisturbance channel or reference condition to which a given river should be restored (Miller, Pruitt, Theiling, Fischenich, & Komlos, 2012; Rosgen, 1996; Wohl et al., 2015). Recent work shows that the assumed "stable" single-threaded river planform that has long been seen as a reference template in restoration projects is not actually the predisturbance condition but the product of adjustments from prior anthropogenic manipulation, such as drainage, damming, deforestation, and agriculture (e.g., Gendaszek, Magirl, & Czuba, 2012; Gordon & Meentemeyer, 2006; Polvi & Wohl, 2013; Walter & Merrits, 2008; Woelfle-Erskine, Wilcox, & Moore, 2012). There is now evidence being presented worldwide that in unconfined, depositional valleys, a multithreaded channel configuration that has broad floodplain inundation better represents the predisturbance condition (Brown & Sear, 2008; Cluer & Thorne, 2013; Sear & Arnell, 2006). Cluer and Thorne (2013) have introduced this predisturbance channel configuration as a Stage 0 anastomosing channel network as part of their stream evolution model (SEM; see Figure 1). Table 1 summarizes the key hydrogeomorphic attributes that maximize habitat and ecosystem benefits in a typical Stage 0 system. Stage 0 systems are highly complex and resilient multithreaded systems with shallow alluvial aquifers and an abundance of roughness elements that allow them to respond to perturbations through natural physical and biological adjustments and continue to function in response to first-order system drivers such as climate change (Beechie et al., 2010, 2013; Cluer & Thorne, 2013; Woelfle-Erskine et al., 2012; Wohl et al., 2005; Wohl et al., 2015). There is mounting evidence to support the restoration of predisturbance stream processes using Stage 0 multichannel patterns that once dominated the landscape as reference conditions (Polvi & Wohl, 2013; Slowik, 2014; Woelfle-Erskine et al., 2012).

The restoration of a river to Stage 0 requires a firm understanding of the process-based approach to restoration. Process-based restoration focuses on removing imposed disturbances, restoring watershed and reach-scale processes (e.g., deposition, lateral migration, and natural recruitment of wood), and allowing the river system to develop dynamically in response to the restoration or to future conditions (Beechie et al., 2010, 2013). Figure 2 illustrates the key linkages that connect processes with habitat formation and biological and ecological response. As is shown in Figure 2, the method presented in this paper focuses on the restoration of reach-scale stream processes in depositional or unconfined valleys, which allows for anabranching and/or discontinuous channels that are dynamic and resilient in response to changing watershed processes (Beechie & Imaki, 2014; Fryirs & Brierley, 2013).

In depositional valley reaches, the aim is to construct a valley surface that is connected at base flow. In so doing, stream power is distributed longitudinally and laterally across a large portion of the valley rather than concentrated in a high capacity channel, shifting energy dissipation from channel boundaries to roughness elements throughout the connected valley bottom. The efficiency or competence of the river is then reduced; rather than transporting the mean annual sediment load rapidly through a project area, the goal is to promote the deposition and temporary storage of mobilized sediments, organic material, nutrients, and species. With the restoration of these processes, habitat is then naturally formed with the passage of floods, sediments, and nutrients over time. The formation of habitat then supports instream biological processes and creates a significant ecological response, all with little human intervention. It is apparent that the potential benefits of Stage 0 valley restoration are abundant; however, the design of such a system can seem daunting and has rarely been considered in the restoration practice, until now. The goal of this paper is to present a novel process-based approach to restoration, the Geomorphic Grade Line (GGL) method, which restores degraded depositional rivers and alluvial fans to highly dynamic and highly diverse conditions.

2 | GGL STAGE 0 RESTORATION APPROACH

The development of the Stage 0 restoration approach began in incised streams flowing through degraded meadows. As can be seen in an example unconfined, depositional valley (Figure 3a), anthropogenic manipulation, coupled with the loss of beaver and their associated grade control and wetland maintenance activities, resulted in head cutting and channel incision followed by a lowering of the shallow groundwater and a transition from wetland (SEM multithread Stage 0) to arid terrace (SEM single-thread Stage 3). With a firm understanding of natural processes that occur in unconfined, depositional valleys, designers on these projects attempted to work at the valley scale and recover the predisturbance anastomosing pattern (return the valley to the SEM Stage 0). The incised channel (Figure 3b) was completely filled with native materials (gravels, soil, and large wood), and the entire valley floor was treated as the flow surface, with large wood distributed across valley surfaces to provide short-term roughness and habitat complexity until riparian vegetation could establish. As shown in Figure 3c, recovery of wetland characteristics, including the shallow groundwater elevation and the rapid recolonization of riparian dependent vegetation, generally occurred in less than 2 years. These initial results provided strong evidence that the restoration to Stage 0 was possible and had great potential to create significant biological and ecological uplift. Encouraged by these early project results, designers continued to work at the valley scale and developed a repeatable method for designing Stage 0 systems, presented here as the GGL method. The sections below describe the GGL methodology and a user's guide on the methodology is provided as supplemental material (https://github.com/helstab/GGLREM).

Figure 4 illustrates the GGL methodology for the design of any Stage 0 system. The discussion here focuses on the general application of the GGL methodology for a site that has a LiDAR digital elevation model (DEM) available for the project valley. LiDAR data at varying resolutions can be obtained commercially or through online sources such as Open Topography, DOGAMI, USGS Earth Explorer, or LiDAR Online (among others). Fortunately, it is getting easier to obtain high quality LiDAR DEMs for most areas; however, the

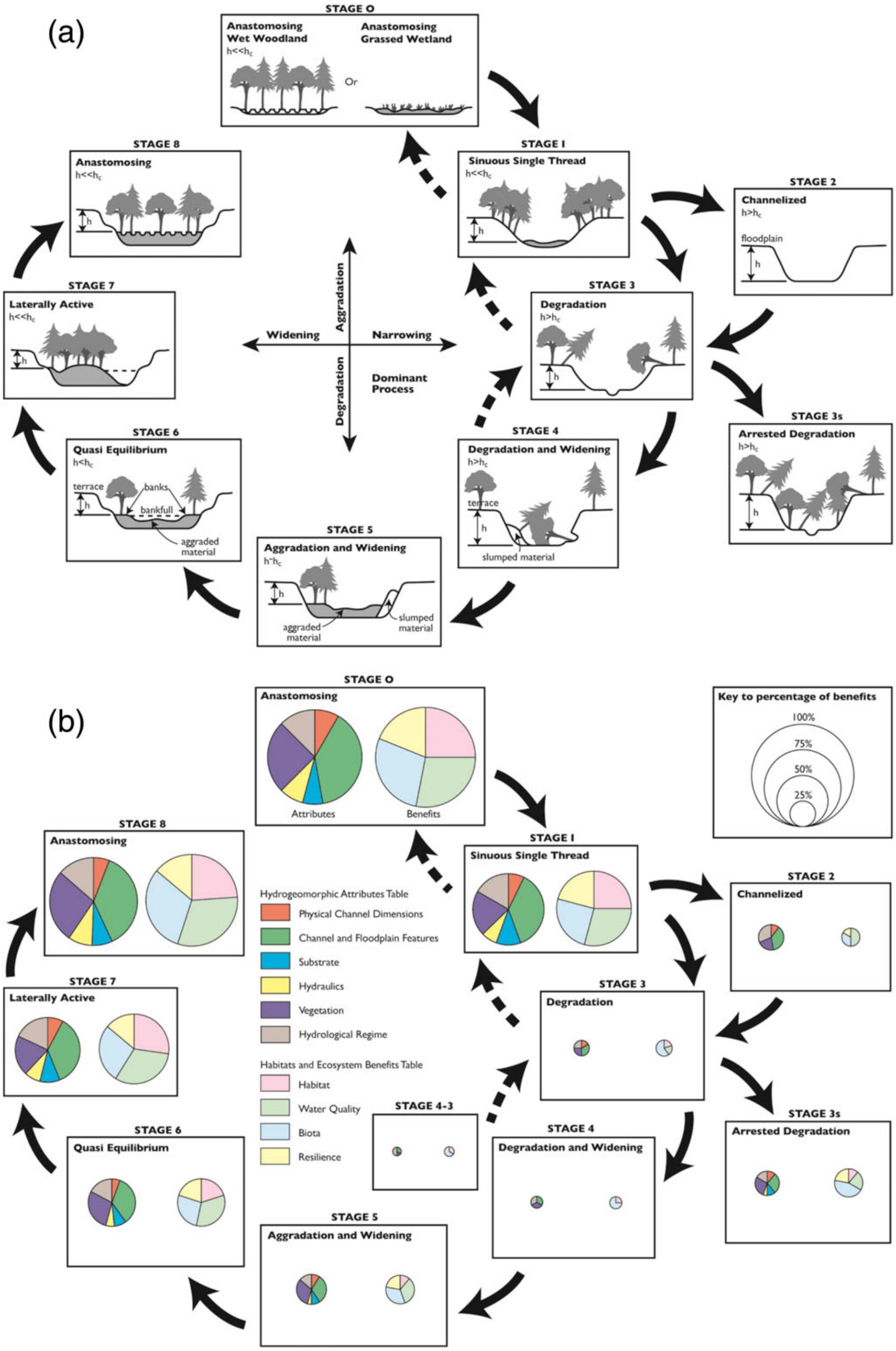


FIGURE 1 (a) Cluer and Thorne's (2013) stream evolution model, (b) habitat and ecosystem benefits provided by each stage of the stream evolution model (reprinted with permission from Wiley Publications) [Colour figure can be viewed at wileyonlinelibrary.com]

supplemental user's guide provides a discussion on other ways to apply the GGL methodology using any high density DEM.

The foundation of the Stage 0 project is to first identify an unconfined, depositional valley that has been disturbed and then set the upstream and downstream extents of the project to match the valley length based on identifying geomorphic controls (Steps 1 and 2). It is critical to determine both the location and elevation of the geomorphic controls. These controls can be the confluence with another river channel, an alluvial fan area, or a geologic control that denotes a change in valley type, typically showing deposition upstream of the control and transport downstream of the control.

The development of the GGL in Step 3 relies on displaying the DEM, drawing a centreline down the valley (extending beyond project valley control), adding valley stations and elevations along the centreline, and identifying key relic/historic features and their elevations. Key surfaces might include relic channels, or historic

TABLE 1 Summary of the hydrogeomorphic attributes and habitat and ecosystem benefits of Stage 0 systems (adapted from Cluer & Thorne, 2013)

Hydrologic regime	Hydraulics and substrate	Dimensions and morphology	Vegetation attributes
• Floods and flood pulses diffused and subdued. • High water table and close connection with groundwater ensuring reliable baseflow and continuous hyporhesis. • Flow in smaller anabranches may be ephemeral.	• Multiple channels provide maximum in-channel hydraulic diversity through partition of discharge that widens range of in-channel depth/velocity combinations. • Anabranches create multiple, marginal deadwaters. • Wide range of substrate grain sizes, numerous, well-sorted bed patches.	• Multiple anabranches, islands, and side channels. • Morphological features abound in-channel, on floodplain providing high capacity to store sediment and wood. • Bank heights are low with stability enhanced by riparian margins • Network and floodplain are highly resistant to disturbance, buffering the system.	• Frequent, small channel adjustments and high water table create proliferation and succession of aquatic plants. • Wet woodlands on islands and floodplain supply and retain wood, widespread vegetation proximal to channels produces abundant leaf litter.

Habitat	Biota	Resilience and Persistence	Water Quality
• Multiple channels, islands, and broad floodplain with diverse habitats and refugia. • High water table, deep pools, and continuous hyporhesis provide drought refugia. • Channel margins evolve semicontinuously expose tree roots.	• Multiple, complex, dynamic channels connected to an extensive floodplain and interact with groundwater to support large numbers of different species. • Highest possible biodiversity, proportion of native species, and 1st- and 2nd-order productivity.	• Physical and vegetative attributes and functions stemming from their complexity, connectivity, and diversity act to attenuate floods and sediment pulses, making habitat and biota persistent and highly resistant to disturbances including flood, drought, and wild fire.	• High capacity multichannel network stores sediment, cycles nutrients, and produces exceptional water clarity. • Dense, diverse proximal vegetation provides abundant shade, which ameliorates temperatures.

(premanipulation) wetland/floodplain surfaces, those features that provide strong indicators of the predisturbance valley. Centreline elevation data are then plotted along the valley stationing, and a best-fit trendline is added to describe the GGL and valley slope at different points along the valley length.

Step 4 involves the expansion of the centreline GGL elevations valley-wide to create the target restored GGL valley surface. The GGL trendline equation is used to set target elevations in valley-spanning cross sections that are spaced 1 m apart (or matching DEM resolution) along the valley centreline within the project extent. The result is the identification of a target restored valley surface that represents or mimics the valley before significant disturbance, which is verified by matching target GGL elevations with any key relic/historic features present on site. The novelty here is that instead of attempting to identify a reference condition from nearby assumed undisturbed reaches, this method actually finds and exposes the historic valley surface as determined directly from persistent relic valley and channel features and valley morphology. The target valley surface is the predisturbance surface and if implemented will allow for restoration of Stage 0 processes valley-wide.

The determination of the target valley surface in Step 4 allows for the development of a relative elevation model (REM, Step 5, see Jones, 2006; Coe, 2016) that is used to evaluate, design, and construct the Stage 0 restored valley. The REM is developed by subtracting the target valley surface (developed in Step 4) from the existing valley surface. Essentially, the existing surface elevations are compared with the target elevations; where areas located above the target are identified as potential cut, and areas located below the target elevation are identified as potential fill. A GIS based toolkit (GGL/REM toolkit) that automates the process of developing the GGL and associated REM maps is provided as supplemental material.

The final grading plan comes from evaluating the REM (developed in Step 5) in the field and identifying what high and low surfaces should actually be cut or filled based on the type of material and features that are present. Evaluation is made based on whether high or low surfaces appear to be natural features such as former wetlands, terraces, or vegetated islands or if they appear to be anthropogenic features such as berms or roads. Incised channels (Stages 3–4) are identified as fill zones. After field evaluation, the REM is edited to create the final grading plan (cut/fill areas) as polygons, with final cut/fill volumes determined from polygon areas and the average elevation in each polygon that is above/below the zero elevation. The final step (Step 6) is to develop the final grading plan (cut/fill maps) for construction of the Stage 0 system. Construction layout then utilizes georeferenced REM maps exported to mobile devices with submetre Global Positioning System (GPS), along with standard survey equipment (laser level or total station) and previously established monuments to stake out the project. The target restoration GGL surface is marked on the ground throughout the project indicating the zero elevation for identifying cut and fill.

3 | APPLICATION OF THE GGL METHOD TO DESIGN STAGE 0 VALLEYS IN WESTERN OREGON, USA

The GGL methodology has been developed through implementation of nearly 20 projects spaced throughout the Pacific Northwest, USA. Projects have been implemented across a wide range of landscapes,

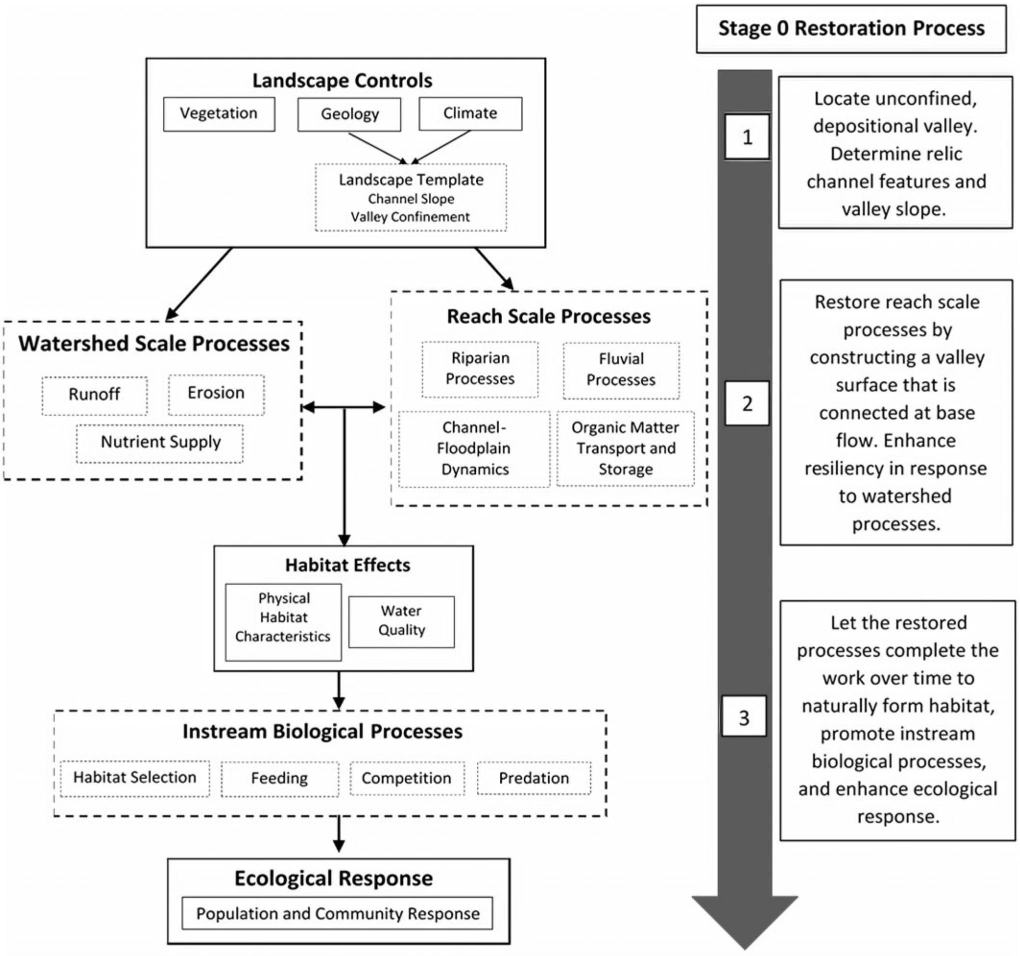


FIGURE 2 Illustration of the Stage 0 restoration process-based approach that utilizes the linkages between landscape controls (unconfined, depositional valleys), watershed-processes, and reach-scale processes to restore and enhance biological- and ecological-processes (adapted from Beechie & Bolton, 1999, Beechie et al., 2010, and Roni & Beechie, 2012). Dashed lines indicate processes that can dynamically change over time and space. Solid lines indicated static controls and effects and responses to changing processes

ranging from small streams in arid environments to West Cascades rivers. Figure 5 provides the location of six (the most diverse) of these, and Table 2 summarizes climate, watershed-scale characteristics, valley-scale characteristics, and project details important to understanding the drivers, processes, and restoration of each system. As can be seen in Table 2, the Stage 0 restoration process has been applied to a wide variety of geologic, climatic, and valley settings and on a range of channel sizes, with the only common factor among all the completed projects is the depositional valley type. Although all of these projects are located in the Pacific Northwest region of the USA, the characteristics of each project presented may be found anywhere in the world. As such, it is the intent to illustrate the diversity of environments and range of conditions where this approach has been successfully applied to encourage that it be applied outside the Pacific Northwest, USA. To better illustrate the application of the GGL method, the following section describes the GGL Stage 0 design process for Staley Creek, OR, USA.

Staley Creek is a fourth-order (Strahler, 1952) headwater tributary to the Middle Fork Willamette River (MFWR; see Table 2) located approximately 40-km south of Oakridge, Oregon, USA (Figure 5). Starting in the mid-1950s, extensive upland and riparian clear-cut harvesting, stream cleaning, road construction and maintenance, and fire suppression impaired many watershed and reach-level stream processes. From its confluence with MFWR through the lower 5.6 km of unconfined valley/confluence fan, Staley Creek was intensively clear-cut harvested within the riparian area, and as much as 75% of downed large woody debris was salvaged following the 100-year flood events of 1964.

LiDAR Digital Terrain Model (DTM's) and field investigations were employed to describe the potential range of lateral, longitudinal, and vertical connectivity throughout the project reach. Specifically, relic surfaces, such as undisturbed areas that correspond with historic aerial imagery, geomorphic features, and vegetation patterns representative of frequent inundation, were identified throughout the entire unconfined valley and alluvial fan of Staley Creek. Evaluation of both the watershed processes and the reach processes occurring within the entire valley bottom indicated that Staley Creek evolved over time from a Stage 0 valley system to a Stage 3's channel where it was then arrested. The goal was established to restore the Staley Creek valley from a Stage 3's, counterclockwise through the SEM, back to a Stage 0 from which was originally disturbed, as described below:

- Step 1—The lower Staley Creek unconfined valley/confluence fan reach that extends 4,000-m upstream from the confluence with the MFWR was selected for restoration.

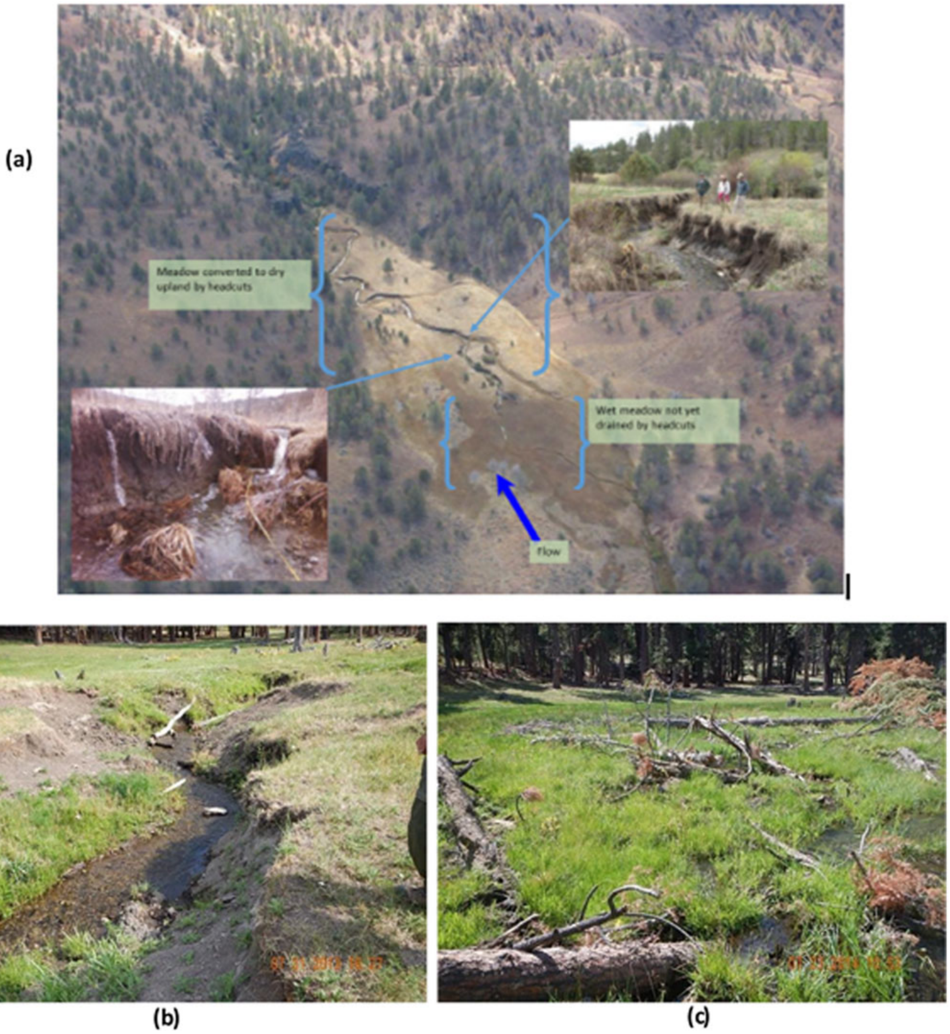
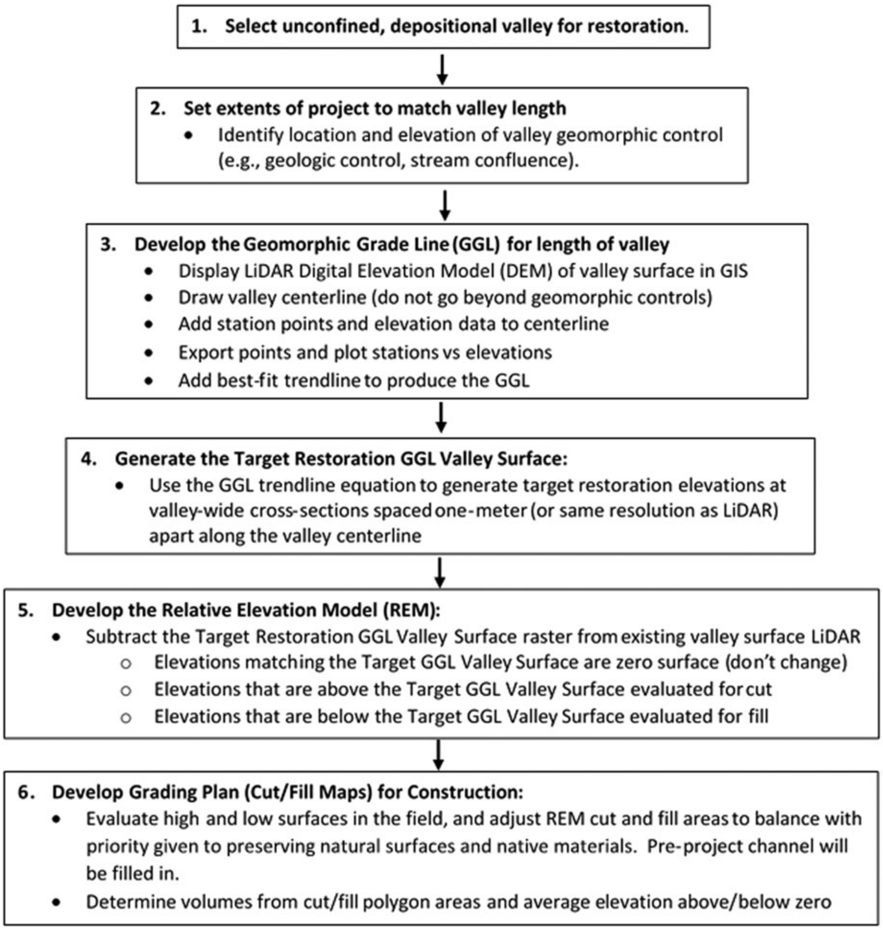


FIGURE 3 (a) Aerial view of preproject conditions (Neilsen-Pincus, 2005) at a typical East Cascade degraded meadow system. Advancing headcuts are draining the upstream wetland. Downstream of the headcuts a single incised channel has developed, dewatering a historic wetland and converting it to an upland terrace; (b) pre-Stage 0 restoration (July 2013) and (c) post-Stage 0 restoration (July 2014) photos. Views are looking upstream and taken from same location [Colour figure can be viewed at wileyonlinelibrary.com]

- Step 2—The downstream extent of the project was the confluence with the MFWR, and the upstream extent of the project was at a geologic valley constriction located approximately 1,000-m upstream of the confluence.
- Step 3—One-metre resolution LiDAR DEM was obtained and a valley centreline was drawn on the DEM in ArcGIS and extended approximately 1,000-m downstream of the lower project extent (along the MFWR) and approximately 2,000-m upstream of the upper project extent. Elevation data for each relic surface were extracted from the LiDAR DEM and attached to each 1-m spaced station along the centreline. Figure 6 shows the LiDAR DEM, the valley centreline, and the plot of the best-fit trendline (fifth-order polynomial) that was modelled and used to represent the GGL for Staley Creek.
- Step 4—Perpendicular cross sections that extended to the valley toe slope were added to each 1-m station along the project centreline. GGL elevations from the trendline were added to these cross section points, and the target valley surface was created. The target valley surface was then validated by comparing with the relic/historic features on the DEM and surveyed at Staley Creek. Figure 7a shows the target valley surface, with all of the areas highlighted in blue matching the target elevation (the predisturbance elevation). Figure 7a shows that this valley supported an anastomosing network of channels (Stage 0) predisturbance and illustrates the reference condition to which the valley will be restored.
- Step 5—The Staley Creek REM was then produced in GIS by subtracting a raster created from the target restoration GGL valley surface from a raster created from the existing valley surface. The resulting 1-m resolution raster displays the REM (Figure 7b) and includes relative elevations bound against the GGL elevations. The REM was then exported to a mobile device as a georeferenced map and target elevations were ground-truthed against established survey grade monuments in the field.
- Step 6—The validated REM for Staley Creek was then used in the field to evaluate and develop the final cut and fill areas, volumes, and maps with precision and accuracy similar to the LiDAR DEM



1. **Select unconfined, depositional valley for restoration.**

2. **Set extents of project to match valley length**
    - Identify location and elevation of valley geomorphic control (e.g., geologic control, stream confluence).

3. **Develop the Geomorphic Grade Line (GGL) for length of valley**
    - Display LiDAR Digital Elevation Model (DEM) of valley surface in GIS
    - Draw valley centerline (do not go beyond geomorphic controls)
    - Add station points and elevation data to centerline
    - Export points and plot stations vs elevations
    - Add best-fit trendline to produce the GGL

4. **Generate the Target Restoration GGL Valley Surface:**
    - Use the GGL trendline equation to generate target restoration elevations at valley-wide cross-sections spaced one-meter (or same resolution as LiDAR) apart along the valley centerline

5. **Develop the Relative Elevation Model (REM):**
    - Subtract the Target Restoration GGL Valley Surface raster from existing valley surface LiDAR
        - Elevations matching the Target GGL Valley Surface are zero surface (don't change)
        - Elevations that are above the Target GGL Valley Surface evaluated for cut
        - Elevations that are below the Target GGL Valley Surface evaluated for fill

6. **Develop Grading Plan (Cut/Fill Maps) for Construction:**
    - Evaluate high and low surfaces in the field, and adjust REM cut and fill areas to balance with priority given to preserving natural surfaces and native materials. Pre-project channel will be filled in.
    - Determine volumes from cut/fill polygon areas and average elevation above/below zero

FIGURE 4 Diagram illustrating the Geomorphic Grade Line methodology for designing a Stage 0 system

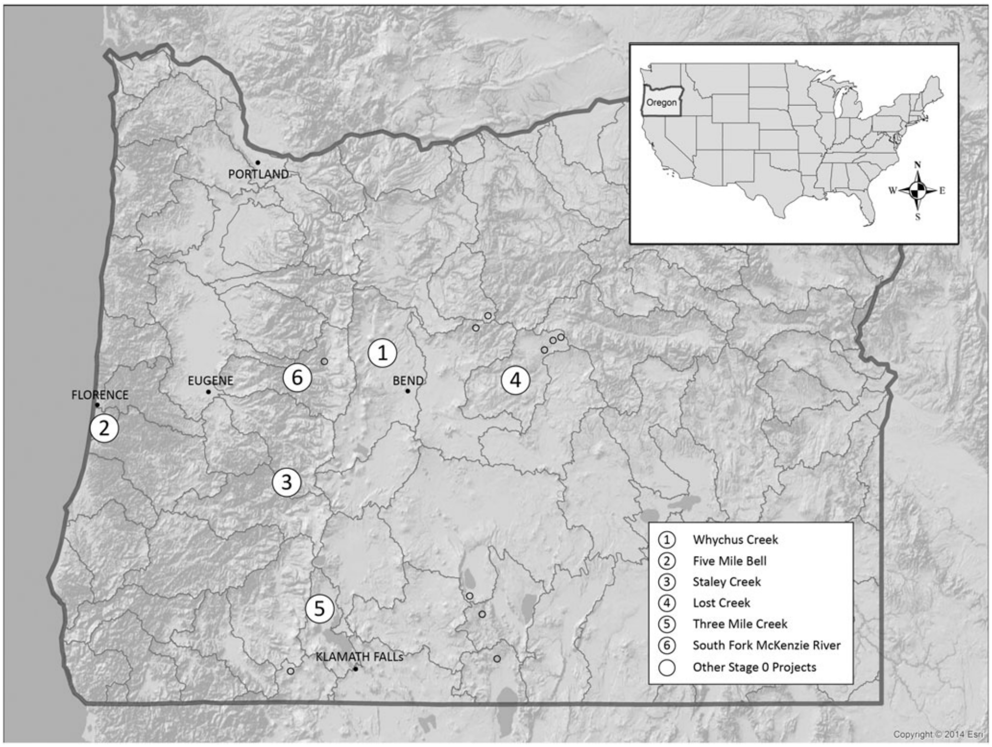


FIGURE 5 Location map of Stage 0 projects completed within Oregon State, USA

TABLE 2 Summary of climate, watershed-scale, and valley-scale attributes of six Stage 0 restoration projects successfully completed in the Pacific Northwest, USA

Project stream	Ecoregion[a]	Hydrology	Mean annual rainfall (mm)	Drainage area (km^2)	Base flow (cms)	Valley type	Valley slope (%)	Valley width (m)
Five Mile Bell Creek	Oregon Coast Range Coastal Lowlands	Rain dominated	1,500–2,000	20.6	0.5	Lacustrine	0.02	200
Lost Creek	John Day/Clarno Uplands	Snowmelt, rain on snow	500–750	21.1	>0.2	Lacustrine	1	50
South Fork McKenzie River	Western Cascades Lowlands and Valleys	Reservoir controlled	2,000–2,500	559.4	9.3	Alluvial fan	0.75	500
Staley Creek	Western Cascades Lowlands and Valleys	Rain with rain on snow	1,500–2,000	105.2	0.8	Unconfined	2	240
Three Mile Creek	High Southern Cascades Montane Forest	Spring with rain	1,000–1,500	25.1	>0.2	Unconfined	7	60
Whychus Creek	Ponderosa Pine/Bitterbrush Woodland	Glacial with rain on snow	500–750	652.7	0.7	Unconfined	0.9	120

[a] For a description of ecoregions, see Omernik (1995) and the identification of ecoregions in Oregon, see Thorson et al. (2003).

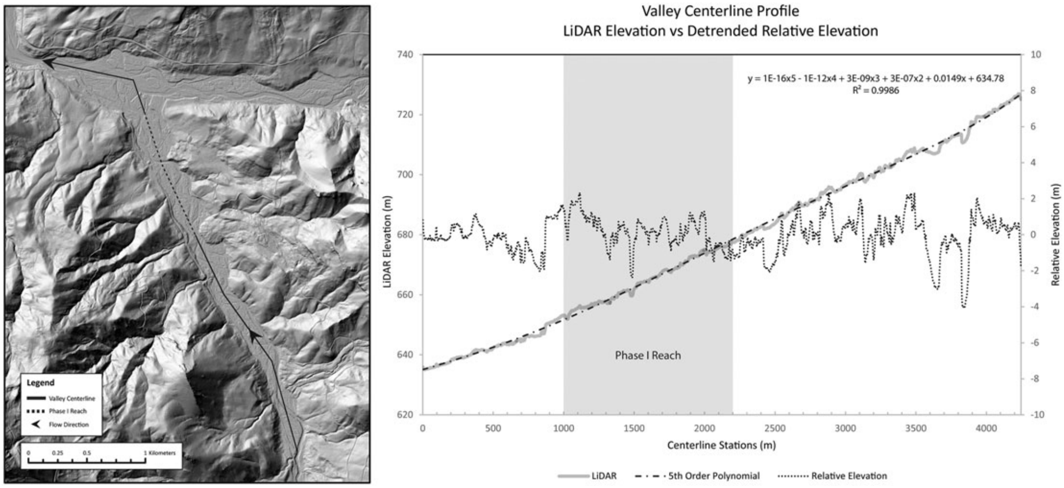


FIGURE 6 (a) LiDAR DEM of Staley Creek and MFWR with valley centreline (black dashed line) and Phase 1 project extent (black line) shown; (b) centreline profile plot showing project reach and Geomorphic Grade Line (trendline and equation). DEM: digital elevation model; MFWR: Middle Fork Willamette River

dataset. Figure 7b provides the final grading plan developed for Staley Creek to restore it to a Stage 0 system.

The photos in Figure 8 illustrate the final result of the restoration and immediate conversion of Staley Creek from a simplified and efficient transport channel in the preproject condition to a highly dynamic, low energy depositional environment postconstruction (Stage 0). It can be seen that Staley Creek has converted from a channelized single flow path to a well-distributed complex of channels and wetlands that can promote instream biological processes and delivery of ecosystem benefits as seen in Table 1.

4 | DISCUSSION

The greatest potential of the Stage 0 restoration goal is a restored river system with complexity and connectivity that promotes metastability, thus creating a more resilient and self-sustaining river system that can self-adjust to changes or disturbances. Resilience is achieved by removing the constraints imposed by a channel and allowing the river/valley to adjust to a great range of disturbances such as fires, floods, or changes in climate. A Stage 0 approach restores the fluvial processes of a depositional valley at the reach scale. Therefore, the complete range of possible lower tier processes (such as habitat development) is available and viable. As a result, events such as large floods are no longer something to design a project to withstand but instead incorporated as a mechanism for restoring needed sediment and organic inputs and accelerating habitat development. An unexpected potential benefit is that if the entire valley floor can be restored to the premanipulation condition, this may be of significant cultural value to local partners, tribes, and other entities. In addition, the method presented is also relatively inexpensive to design and implement as compared with a more classic approach. It requires initial earth moving and wood placement but beyond that it allows natural geomorphic processes to do most of the work, and most importantly, it allows those processes to evolve over time on a resilient landscape.

There are a number of key considerations when designing a Stage 0 restoration project. Most importantly, it is critical that this technique

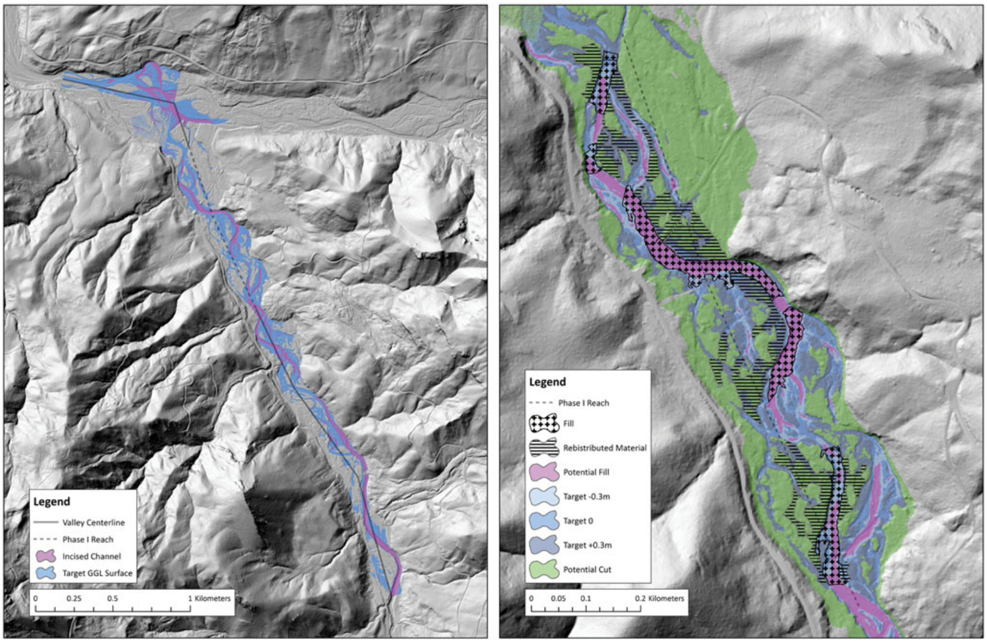


FIGURE 7 (a) Relative elevation model (REM) showing Staley Creek valley surfaces matching the GGL target elevations displayed in blue, those surfaces below the GGL displayed in pink, and those surfaces above the GGL not coloured. This map shows the anastomosing Stage 0 system that once occupied this valley (predisturbance) and reference condition for restoration. (b) Zoom to Staley Creek Phase 1 project area with green added to show areas above the GGL. Final design map (grading plan) for construction of Staley Creek Phase 1 with dotted areas showing fill areas and hatched showing cut areas. GGL: Geomorphic Grade Line [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 8 Views of Staley Creek Stage 0 restoration: (a) prerestoration aerial photograph including incised channel and dry terrace, (b) postrestoration aerial photograph showing full connection and added wood, (c) prerestoration downstream view, and (d) postrestoration downstream view (taken at same location and at approximately the same flow as pre-restoration photo) [Colour figure can be viewed at wileyonlinelibrary.com]

be applied within alluvial valleys that can accommodate the recovery of depositional processes (see Table 2). The need to protect infrastructure from interactions with river systems would likely preclude this approach from most urban settings although pockets of available land and scaling a new valley width/length would both be valuable ecosystem interventions. It also follows that the underlying or root causes that led to the initial degradation must be addressed. Restoring the fluvial processes to a river valley without first alleviating the cause of the initial degradation would not be prudent. If the root causes of degradation persist, such as a permanently lowered valley base level control, it is fully expected that they would degrade recently restored project areas again. However, it is not an all or nothing scenario, and it is suggested that a modified Stage 0 design be considered and weighed against other design alternatives to find a solution that can provide the most ecological uplift in light of potential continued degradation. Although Stage 0 may not always be attainable given limitations imposed by infrastructure, restoration projects advancing from SEM Stages 3–4 to Stages 6–8 will also enhance fluvial processes and biological response (see Figure 1b).

Monitoring methods that are applied to determine the effectiveness of traditional restoration projects, such as counting large wood per mile or measuring the increased length of secondary habitat, do not capture the complexity of Stage 0 projects. Thus, a Stage 0 restoration requires new monitoring methods that can be applied to examine sediment storage, channel migration and avulsion, diversity and frequency of geomorphic features, abundance and retention of large wood and organic matter, water table height, wetted area, substrate size class diversity and patchiness, diversity of water velocities, area of cold water refugia, and other biological processes (Meyer, 2018) at small spatial scales. Initial monitoring results are showing that when compared with an untreated reach, a restored Stage 0 system has (a) a significant increase in large wood abundance, (b) more wetted area with multithread channels that are significantly slower, (c) a larger abundance of gravels and fines, with less cobbles and boulders, and (d) a significant increase in pool and glide habitat, with less riffle habitat (Meyer, 2018). Overall, the Stage 0 projects implemented (Table 2) thus far have all expressed the diversity and dynamism presented by Cluer and Thorne (2013) and summarized in Table 1. However, due to the complexity in examining the effectiveness of these projects, new methods or strategies for monitoring Stage 0 projects remain an area in need of further research and testing to better track physical evolution as well as ecological uplift after project completion, and through time.

Implementation of a Stage 0 restoration project occurs in three key phases and relies on fluvial processes and the ability of the river to adjust through time. Phase I involves the heavy equipment work, which includes grading of valley surfaces according to the final REM and grading plan, and large wood placement. Phase II includes allowing the constructed system to respond freely to subsequent storm events over a few years. As a result, the project area will naturally respond to the Phase I disturbance, sort sediments, and develop new flow paths, pools, and other habitat attributes. Phase III comes as riparian dependent vegetation is established and biological elements (vegetation, macroinvertebrates, and beavers) begin influencing flow-field patterns, sediment routing, and channel development. It follows that when considering employing the Stage 0 approach for a rehabilitation project, it is important to consider habitat types and the rate of habitat development. Because features such as deep pools are not manually constructed, it is important to allow time for the channel networks to develop targeted features. Unlike traditional construction projects that are “done” when the heavy equipment demobilizes, Stage 0 projects are only beginning. After the initial disturbance created by Phase I construction, the stream systems continues to evolve and change through time. Expectations must be adjusted accordingly.

5 | SUMMARY

The work presented here is a novel process-based approach to restoring alluvial valleys to their process domain-appropriate predisturbance depositional Stage 0 (anastomosing or anabranching) system. The GGL design approach presented (Figure 4) is a valley-wide, approach founded on an understanding of both reach scale and watershed scale processes. It requires that designers consider the depositional response reach tendencies of unconfined valleys (Figure 2). The design methodology is novel in that it finds and exposes historic valley surfaces as determined directly from persistent relic valley and channel features and valley morphology. The methods presented here are relatively simple, requiring quality topographic data and moderate ArcGIS skill to define the historic valley slope (GGL) to create a REM for the project valley that references historic valley elevations. By presenting Stage 0 restoration methods, and applications across a range of physical settings, the authors hope to inspire other practitioners to embrace the restoration of dynamism and diversity through restoring the processes that create multifaceted river systems that provide long-term resiliency, meta-stability, and more complex and diverse habitat and optimal ecosystem benefits.

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