### Title
DESIGNING RIVERS WITH MULTIPLE SCALES OF CHANNEL AND FLOODPLAIN VARIATION TO YIELD DIVERSE PROCESSES AND ECOSYSTEM SERVICES




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# DESIGNING RIVERS WITH MULTIPLE SCALES OF CHANNEL AND FLOODPLAIN VARIATION TO YIELD DIVERSE PROCESSES AND ECOSYSTEM SERVICES

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A new theory for alluvial river-corridor design using geometric modeling of local to reach scale channel and floodplain features was recently developed. Software implementing this theory for river design has now been programmed into a platform to quickly produce accurate, precise, and objective digital elevation models that capture diverse topographic controls on fluvial processes. Template files for different types of rivers have been developed to further speed design, and results can be exported to CAD and GIS for further application.

## 1 INTRODUCTION

Designing alluvial river channels that behave naturally is a central challenge facing river scientists and engineers in the 21st century. Though organized and responsive to driving forces, rivers exhibit complex patterns and processes. Despite 60 years of research it remains highly uncertain as to which ones are most important to design explicitly versus which ones should be allowed to emerge on their own after construction. Decades of empirical study of longitudinal and lateral transects of alluvial rivers have yielded an explanation for the central tendency of channel geometric variables averaged over a length of 100–1000 channel widths (i.e. the reach scale) to grow or decline with discharge on the basis of mutual adjustment in order to pass the typical water and sediment delivered by the catchment. Such variables include slope, bankfull width, bankfull depth, sinuosity, entrenchment, and median particle size. However, for any reach there can be large uncertainties in the average values of geometric variables compared to regional regression expectations. Further, many rivers exhibit large longitudinal variations in shape within a reach. For example, the bankfull channel in a gravel-cobble reach of the lower Yuba River in California exhibits variations in standardized (i.e. value minus mean divided by standard deviation) wetted top width ($W_s$) and detrended, standardized mean cross-sectional (XS) bed elevation ($Z_{d,s}$) that are up to four times the reach-average values (Figure 1; data from ground, boat, and aerial surveys). Notably, the correlation between $W_s$ and $Z_{d,s}$ is 0.78 and both show quasi-periodic undulations. This is explainable by the tendency for riffle-forming gravel bars to be high and wide, while intervening pools are narrow and deep. Data such as this suggest that the design of alluvial channels cannot rely on reach-scale central tendency, but must go further to account for systematically organized patterns of fluvial landforms at the scale of 0.1–10 channel widths. Looking beyond the channel to floodplains and terraces, there is less science available to guide their design, including natural patterns of variability, but it remains important to consider in design.

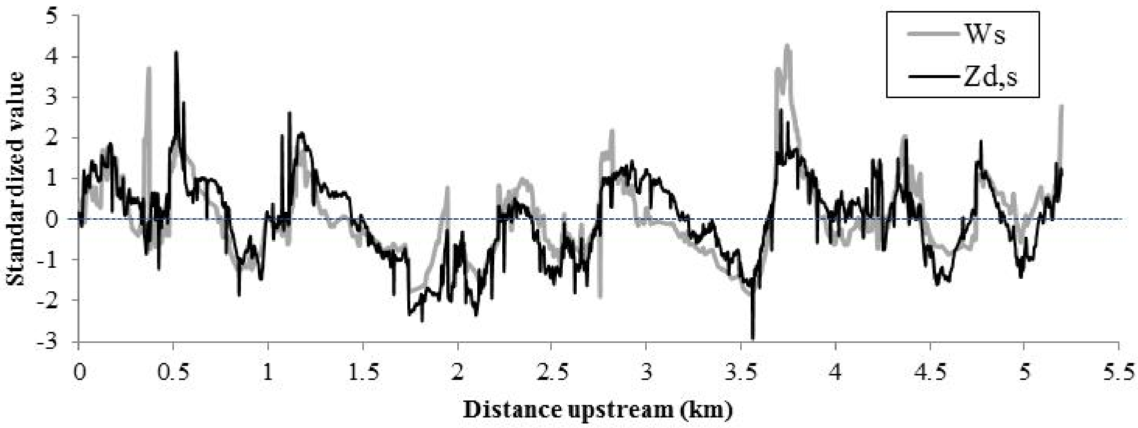


Figure 1. Example longitudinal profiles of width and bed elevation showing organized sub-reach variability.

The common practice for design of subreach fluvial landforms (for which there are fewer geomorphic ideas and quantitative tools available compared to the reach scale) is to use lessons from senior mentors and expert-based practical experience gained by trial and error. Practical experience is available not only for the design of landforms like riffles, runs, glides, and pools, but also for artificial structures like boulder clusters, logjams, and bed steps. Computer aided design (CAD) software enables landscape architects and civil engineers to manually draw contours and breaklines to represent local landform features on topographic maps often guided by regional specifications for a few parameters, such as bank slopes and riffle-pool relief. Using a manual design approach is time consuming and costly, and it offers no capability to eventually adopt precise, accurate, and objective scientific developments at the subreach scale into design. Therefore, the goal of this project was to develop concepts, methods, and software to fundamentally transform subreach design of channels and floodplains on the basis of geometric modeling. What makes the new approach unique is that at a practical level, all one has to do to design an accurate river DEM with multiple scales of coherent variability is make choices through dialogue boxes and then the computer will render the DEM exactly to specification—no subjective, manual drawing.

## 2 SYNTHETIC RIVER VALLEY THEORY

Brown *et al.* [1] presented a new seven-step method of channel-floodplain design involving geometric modeling in which multiple scales of continuous equations are specified in each plane (XY, XZ, and YZ) and combined in a digital elevation model (DEM). First, you conceptualize the river corridor in terms of its essential elements and scales on the basis of ecogeomorphic goals. Second, you specify the model domain, including coordinate systems, units, boundaries, and resolution. Third, you determine the geometric elements for each plane at all scales of interest that are going to be needed, including but not limited to, channel centerline longitudinal profile, channel bed elevation longitudinal profile along the centerline, channel width longitudinal profile, XS channel shape (which can be uniform or vary downstream according to a function), longitudinal profile of the outer floodplain boundary on each side of the valley, and the same for optional terrace boundaries beyond the floodplain on each side. The floodplain on each side of the river is treated independently for greater freedom in design. Fourth, you determine reach-average values of geometric elements using standard geomorphic methods. Key values include reach-average bed slope, channel width, floodplain width, median grain size, and either hydraulic radius or bankfull depth. Some variables may be computed from theory and other variables to ensure adherence with process concepts, such as computing mean bankfull depth from Shields equation. Fifth, you select equations for the longitudinal variations of each geometric element. Although Brown *et al.* [1] focused on sinusoids, by now the available functions have expanded to include lines, curves, sinusoidal and cnoidal oscillations, Perlin noise profiles, and manually generated polylines and splines (e.g. imported river reach's centerline profile). The decision of which equation to use rests on a firm geomorphic understanding of the local reach, its river, and the region. You can use multiple functions for any one geometric element to obtain complex patterns, especially if the parameters are set to obtain different spatial scaling for each function. For example, one might use a cnoidal function for floodplain sinuosity in a confined valley to represent the river impinging on a bedrock wall and then nest within that a higher frequency sinusoidal function for inset channel sinuosity. Sixth, you construct the geometric model. Brown *et al.* [1] described how to program an implementation of the theory and provided a Microsoft Excel version for simplified cases. The next section will illustrate new software that does this for you. Finally, you parameterize the equations to obtain the locally sized and positioned attributes of the synthetic river. Although parameters for each equation may be specified independently, self-maintenance processes in rivers often produce coherent patterns among multiple geometric elements, including mutual longitudinal variations identified through spectral or wavelet analysis of spatial series or the covariance function between them. Thus, the key decision for parameterization is to decide which two or more variables will be linked to vary coherently. For that to happen the variables have to be described by the same equation, and then parameters governing frequency, amplitude, and phase are specified to yield oscillations that produce the desired landform structure. Beyond creating landforms, the deeper goal is to obtain topographically steered, stage-dependent hydraulics that drive channel maintenance when operated on by a natural flow regime. How geometric elements oscillate down a river with respect to each other is termed the geomorphic covariance structure (GCS). For example, Figure 2 shows a case of width and bed elevation oscillating in sync at a subreach scale, which is a positive GCS. This is the hallmark of a self-maintaining riffle-pool sequence, so one can specify a positive GCS between the bed and width profiles through parameterization of the geometric functions. For full details on the theory sketched in this section, see Brown *et al.* [1].

## 3 WORLD MACHINE RIVER SOFTWARE

During 2015, the theory described in the previous section was implemented within a software platform to allow practitioners to easily create river corridors with complex yet coherent channel and floodplain landforms at local to reach scales. Although CAD and GIS are well-established platforms for topographic design and analysis, and it is feasible to implement this theory into them in the future, the World Machine software platform was selected as the best for initial development on the basis of several factors. Note that the authors receive no remuneration or gifts, but chose World Machine purely on its technical merits. World Machine (http://www.world-machine.com) is a native geometric modeling platform for DEMs that allows for precise specification of parameters to design diverse landscapes through dialogue boxes and flowcharting. This software renders landscapes quickly on a Windows PC and has a highly efficient interactive view of designs that allows users to 3D orbit, zoom, and fly through terrains for thorough and fast visual assessment of results. It also includes many tools for creating, manipulating, and visualizing terrains, most notably an efficient landscape evolution model for geologically eroding terrain by thermal weathering, soil diffusion, fluvial advection, wave-based coastal erosion, and any combination thereof. As a result, a synthetic river may be designed as an individual object or blended into a larger artificial or real landscape at subcatchment to regional scales (Figure 2).

Designing a river in World Machine using the new developmental software (version 3R6) is fast and easy to perform, especially given a template. Before even starting with producing a design in the software, one should already have completed as much of the procedure described in the previous section as possible and documented the design decisions. World Machine does not tell a user what the attributes of a specific design should be—that has to come from educational background, prior experience, and data analysis. Sometimes one may want to use exploratory freedom in World Machine to try different parameters and equations in the software just to see what happens, and this is where the efficiency and visualization capabilities of the platform are so beneficial. This is also the cornerstone of the utility of the software for other industries, such as animation, video game development, and graphic design. However, the more that the ideas of a real river design are worked out in advance, including reach-scale geomorphic variable values and analysis of subreach-scale oscillations and GCSs, the more a design can be produced that matches project goals.

Starting from scratch in the software, the design process in World Machine involves four steps. Most of the effort consists of adding boxes (called “devices” in the software) to a rendering flow chart, with each device specifying the features of an individual aspect of the terrain. The first step involves entering project settings, such as the size, position, and resolution of the terrain. Then one places the “river reach” device and enters its dialogue box to provide the reach-scale attributes of the river corridor. This is also where one specifies XS shape. Next, a “river scaling” device is added that specifies whether features are scaled relative to total reach length, bankfull width, or one kilometer. For example, if riffle-to-riffle spacing is desired to be every five channel widths, then one would want to scale subreach oscillations by bankfull width. Finally, the longitudinal profiles of each geometric element are specified with any one of the available profile functions or with an imported polyline, such as a DXF file from CAD. These are the required steps that set up a design in the flowchart before a river terrain is rendered and reviewed. Many additional tools aid the process beyond what can be described herein, such as on-the-fly rendering of views of each profile while entering values, sliders for quick sensitivity analysis of each variable and parameter, and the ability to render individual and subsets of a complete terrain. Also, World Machine has preset and customizable color schemes for visualization and the ability to add surface material types. Although the development effort thus far has focused on designing single-threaded rivers and embedding them into regional terrains, World Machine can be used to design multi-threaded rivers, oxbow lakes, and diverse other terrain elements. This is achieved by creating each landform with its own flowchart using proper positioning and heading, and then combining all features into a single DEM.

Seven examples of rivers designed in World Machine are shown in Figure 2. Four examples (A-D) illustrate single-threaded channels embedded into simple, symmetrical floodplains, but with significantly different channel attributes and entrenchment. Each of these were made in just a few minutes effort and were designed starting with a concept from the Rosgen river classification system, though that is not required. Two examples (E, F) are shown in which the river is embedded into a regional landscape produced with the landscape evolution model to illustrate the ability to combine a channel design into the larger landscape, which is necessary in real world applications. Finally, an example (G) with asymmetric floodplains and terraces is shown to illustrate that capability, though the available science for floodplain design is well behind that for channel design. Overall, World Machine has proven to be an effective platform to implement synthetic river valley theory to enable river designers to create a diverse palette of river types to suit their needs.

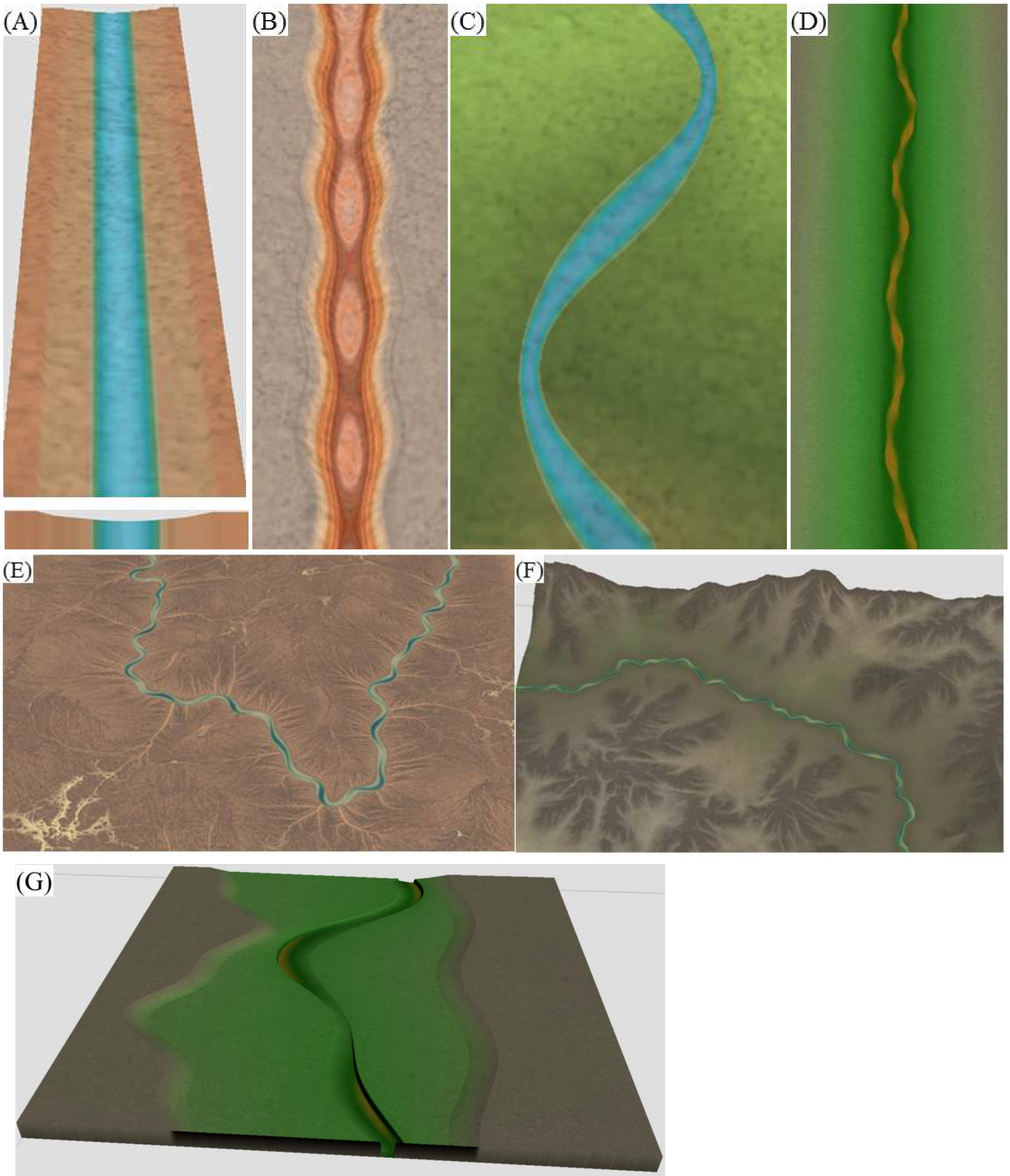


Figure 2. Example synthetic rivers. (A) straight Rosgen F4 river corridor showing both 3D oblique and XS views of the floodway, (B) oscillating bedrock slot canyon with negative GCS, (C) sinuous Rosgen B4 channel and floodplain with U-shaped XS, (D) straight channel incised into cohesive sediment with Perlin centerline alignment and thalweg curvature as well as sinusoidal W and Z profiles; (E) complex sinuous river with multiple scales of subreach variation embedded into a dendritic terrain with a moderate relief and a narrow valley impinged by actively eroding small tributaries; (F) complex river with Perlin centerline alignment embedded into a wide glacial-type valley in the mountains; (G) illustration of corridor with asymmetric floodplains and terraces as well as a channel with an asymmetric XS-section that oscillates back and forth across the channel along the centerline, while the bed elevation and channel width are also oscillating according to a negative GCS.

**REFERENCES**

[1] Brown R.A., Pasternack G.B and Wallendar, W.W., "Synthetic river valleys: creating prescribed topography for form-process inquiry and river rehabilitation design", *Geomorphology*, Vol. 214, (2014), pp 40–55.