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Application of the Riverine Ecosystem Synthesis (RES) and the Functional Process Zone (FPZ) Approach to EPA Environmental Mission Tasks for Rivers

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Application of the Riverine Ecosystem Synthesis (RES) and the Functional Process Zone (FPZ) Approach to EPA Environmental Mission Tasks for Rivers

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Acronyms

DEM	Digital elevation model
EPA	United States Environmental Protection Agency
EPSCoR	Experimental Program to Stimulate Competitive Research
FCL	Food chain length
FPZ	Functional process zones
GIS	Geographical information system
GPS	Global positioning unit
LIDAR	Light detection and ranging
NDH	Network dynamics hypothesis
NERL	National Exposure Research Laboratory
NGO	Non-governmental organizations
NS	Nutrient spiraling
NSF	National Science Foundation
ORD	Office of Research and Development
RCC	River continuum concept
RES	Riverine Ecosystem Synthesis
SpD	Species diversity
STAR	Science to Achieve Results
USGS	United States Geological Survey

Table of Contents

List of Figures

1.0 Introduction and Background

The shift to watershed management of rivers from a more reach-based approach has had far-reaching implications for the way we characterize and classify rivers and then use this information to understand and manage biodiversity, ecological functions, and ecosystem services in riverine landscapes. At the same time, we are faced with inherent challenges of how to best take advantage of past studies (e.g., the many projects on river classification funded by the U.S. Environmental Protection Agency's [EPA's] Science to Achieve Results [STAR] program) while we shift to the higher hierarchical scale necessary to manage at the watershed level. To meet these challenges, we require a model that links the physical structure of a river with its ecosystem functioning and allows us to evaluate past, present, and future river conditions. Such a model would ideally be cost effective, easy to employ, and capable of answering questions at different hierarchical scales in river basins of varying sizes. One model that meets all these criteria, while also accommodating many of the prominent approaches used by and/or developed in collaboration with the EPA, is the *Riverine Ecosystem Synthesis*, or RES (Thorp et al. 2006, 2008).

Contrasting with earlier views of rivers as simple, continuous gradients in physical conditions from headwaters to great rivers (i.e., river continuum concept [RCC]), research and conceptual models in the last decade support the conclusion that rivers are more accurately portrayed as downstream arrays of large *hydrogeomorphic patches* formed by factors such as hydrologic patterns, geomorphic structure of the channel bed and valley, climate, and riparian conditions (e.g., Montgomery 1999; Poole 2002; Thoms and Parson 2002, 2003; Thorp et al. 2006, 2008). These patches are described in the RES, at the critical valley-to-reach scale, as functional process zones (FPZs). FPZs are named based on statistically-derived features of the channel and surrounding valley along with geological and precipitation features, but some widely known examples of channel types in different FPZs are constricted, meandering, braided, anastomosing, and distributary. According to the RES, FPZs are *repeatable* along the longitudinal dimension of rivers and only *partially predictable* in location (Fig. 1), especially at scales above the ecoregional level. Because of physicochemical habitat differences, ecosystem structure and function vary significantly (and predictably) among FPZs.

Use of the RES model in river management is just beginning to expand, especially as it relates to tasks characteristic of EPA's mission. The FPZ approach is being applied at present to the Kansas, Kanawha, and Neuse rivers in the U.S. and has previously been applied to dryland rivers on other continents. However, this approach needs to be applied and evaluated for a fuller spectrum of ecoregions, such as those characterizing the humid through arid regions and/or northern through southern portions of the U.S. Starting with a foundation of ideas from "river typing" work in Australia, we have now been able to accelerate the river typing process and are starting to explore its use in multiple environmental tasks in the EPA mission. While we are now involved in the planning and execution phases for some applications of the RES (e.g., the physical classification of rivers), more research and development is needed to firmly establish links between the physical and ecological portions of the RES. We propose to research, develop, pilot, and implement the products necessary to successfully apply the RES concept and FPZ approach to the mission tasks facing EPA.

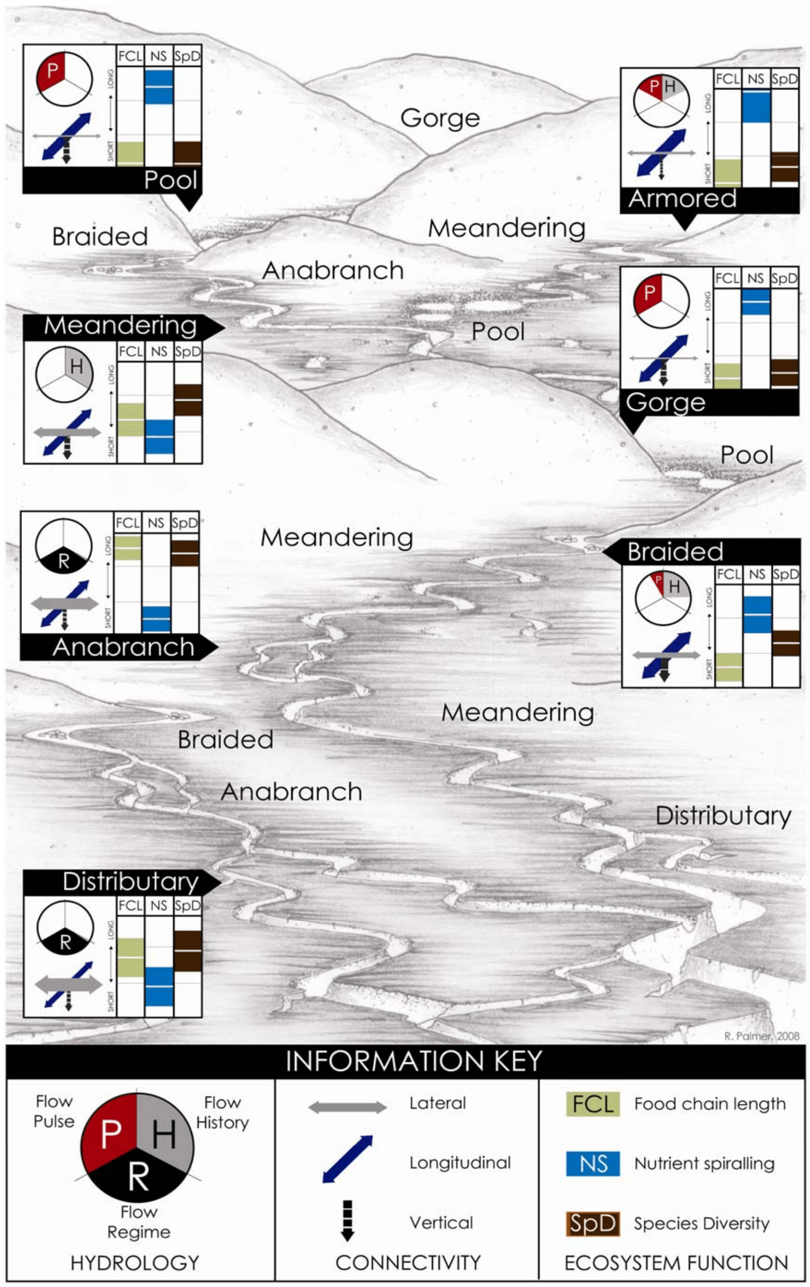

Figure 1. A conceptual riverine landscape depicting various functional process zones (FPZs) and their possible arrangement in the longitudinal dimension. Not all FPZs and their possible spatial arrangements are shown. Information contained in the boxes within the figure depicts the predominant hydrological (i.e., flow pulse, flow history, and flow regime [Thoms and Parsons 2002]) and ecological (i.e., food chain length, nutrient spiraling, and species diversity) conditions predicted for each FPZ. The ecological measures are scaled from long to short (i.e., low to high for species diversity); the light bar indicates the expected median for each ecosystem function and the shading estimates the range of conditions. The size of each connectivity arrow reflects the magnitude of vertical, lateral, and longitudinal connectivity. [Revised from Fig. 1.1 in Thorp et al. (2008).]

This report presents some of the high points of the RES model, describes its uses in meeting tasks in EPA's environmental mission, and integrates it with both current and past classification and management techniques, as a way of improving implementation of mission tasks.**Business Case**

Protection of riverine ecosystems, especially at the watershed level, requires accurate knowledge of how differences in physical structure among sections of a river can alter the river's fundamental ecological structure (e.g., species richness) and function (e.g., nitrogen processing and carbon sequestration). This knowledge can greatly improve the ability to select reference sites, contribute to the robustness of condition assessment, maximize ecological endpoints of restoration, evaluate actual and potential ecosystem services, and establish a fair basis for asset trading. A focus on hydrogeomorphic patches at the valley-to-reach scale (i.e., FPZs) will improve EPA's ability to set study-reach lengths that are both mission-relevant and feasible within a watershed approach to basin management. Furthermore, a statistically rigorous approach to delineating FPZ that relies primarily on geospatial analysis will provide an efficient, national framework for river classification at multiple spatial scales.

This report emphasizes both the "research and development" and "planning and execution" needed to employ the FPZ framework for multiple components of the EPA mission. In particular, it suggests a multi-component program over time to: (i) further develop and refine applications of FPZs for specific EPA mission goals (e.g., reference site selection, condition assessment, ecosystem services evaluation, etc.); (ii) test the efficacy of this approach for rivers in multiple EPA regions by first statistically delineating FPZs from geospatial data and then testing FPZ distributions against ecological variables previously generated by EPA and state aquatic data sets; (iii) recommend specific, future plans for implementing these approaches at the national and regional levels within EPA; and (iv) produce documents delineating the uses and techniques of the FPZ approach for publication both within EPA and external to the Agency, in refereed scientific literature. Plans for employing the FPZ framework in EPA mission tasks are described in Section 5.0, Future Directions, and some of the major applications of the FPZ approach are summarized in Appendix A.

3.0 Problem Statement

Federal and state agencies are increasingly faced with two daunting tasks. First, they must distinguish between and evaluate sections of riverine ecosystems for multiple purposes, such as reference site selection, rehabilitation, and asset trading (i.e., the dual process of river *characterization* and *classification*). Second, they need to have a link between river classification and the ecological functioning and environmental sensitivity of those sites. For both tasks, it is vital that patterns be identified and processes be evaluated at correct hierarchical scales in a quantitative, statistically rigorous fashion.

3.1 Why Identifying the Hydrogeomorphic Character of Rivers is Important

Identifying the hydrogeomorphic nature of a river section is vital for many reasons, as illustrated in the following situations potentially facing government environmental agencies; additional examples are given in Appendix A.

- Suppose a state environmental agency has to decide whether to allow a company to degrade the quality of a 10-km section of a river in return for improving another 10-km section. Is this a fair trade in ecosystem services from a regulatory perspective? How much of an improvement would be required to at least balance the proposed degradation elsewhere? The answers here require knowledge of the current FPZs of each section (and original FPZs, if the river has been extensively altered) and an understanding of how each section is likely to respond to the proposed changes from both hydrogeomorphic and ecological perspectives.

- In response to the need to identify reference sites, this same state agency selects site R-2 as a reference site based on water quality parameters. A later comparison of site R-2 with "impaired" site I-4 indicates, however, that the "impaired site" actually has greater species richness. The reason for this anomaly could be based on the hydrogeomorphic differences between the two sites. For example, if site I-4 was a multi-channeled FPZ and site R-2 was a constricted channel FPZ, their community compositions would likely vary significantly, even if both were pristine.

- After identifying various target areas for river rehabilitation, the agency must prioritize their actions because of limited funds. Following evaluation of the essential socioeconomic and environmental issues for multiple sites where dam removal, set-back levees, or floodplain connections have been proposed, the agency could ask the following questions: What are the original, present-day, and future FPZs (including likely FPZs if rehabilitation efforts are undertaken) for each site? What would be the relative value (e.g., ecosystem services, etc.) returned for every restoration dollar spent at each site? If site A is a potential meandering, single channel FPZ while site B is a potential anastomosing, multiple channel system, would the cost/benefit ratio be the same at each site for a levee set back 100 m, 500 m, or 1 km?

Answers to some of the questions raised in these examples are discussed in a recent manuscript in *BioScience* entitled "Linking ecosystem services, rehabilitation, and river hydrogeomorphology" (Thorp et al. 2010).

3.2 Alternative Approaches to Characterizing and Classifying Rivers

Recently, attempts to develop a "national river classification" system for use by government agencies and non-governmental organizations (NGOs) have begun. An EPA-sponsored workshop in Michigan in February 2009 contributed significantly to this process by identifying the need to classify rivers at multiple scales, including the ecoregion, basin, valley (i.e., the valley-to-reach), and reach levels.

River classification schemes rely on investigators to first measure a set of fundamental and/or derived attributes for a river section and then place that section into a category that best fits the set of attributes found. Fundamental attributes for rivers consist of physical habitat features (i.e., principally geomorphic, hydrologic, and climatic attributes). Derived attributes are biotic features (i.e., species composition, species abundance, etc.), which vary in response to both natural and anthropogenic variables. Classification schemes based on fundamental attributes can be used to answer many other questions (e.g., evaluating ecosystem services), while those based on derived attributes, while useful in their own right, are more limited in their applications to other questions. The process of classification can vary between qualitative (e.g., comparing investigator measurements of a river channel pattern with photographs in a manual) and quantitative and statistically rigorous. Acquiring data for these approaches can vary from expensive, labor-intensive, bottom-up approaches to relatively cost-effective, top-down approaches using geospatial data.

Fundamental attributes can be measured and evaluated at different spatial scales. The most commonly used is the reach scale, where extensive measurements are made using bottom-up approaches like the Rosgen Method (e.g., Rosgen 1994, 1996, 2006); extension of this method to higher spatial scales requires the problematic merger of measurements and results from multiple spatial scales over a large area. In contrast, the FPZ approach is employed at a higher spatial scale (i.e., valley-to-reach scale) and can employ either the more efficient top-down geospatial data (e.g., digital elevation model [DEM], remote aerial imagery) or more labor-intensive bottom-up measurements.

Derived attributes typically consist of either taxonomic (e.g., species) or functional group (e.g., cold-water vs. warm-water) compositions of biota (e.g., fish, macroinvertebrates, etc.). In classification schemes based on these attributes, the investigator starts with a known distribution of species and then correlates the distribution with certain natural (e.g., temperature, water hardness, etc.) or anthropogenic variables (e.g., nitrate levels, land use, etc.) in an attempt to infer causative mechanisms. Using this approach, the investigator can identify gaps in the distribution range of a species (later seeking either new species distribution records or explanations for its absence). Another goal of this approach is to make predictions on distributions outside the known distribution range to other river sections or even different rivers. This approach, while very useful, is difficult without adequate information on the hydrogeomorphic structure of the rivers. GAP models and the National Fish Habitat Initiative are examples of this widely-used approach in the U.S.

Earlier this decade, the STAR program funded a large number of studies seeking to classify rivers; most used derived characters, but a few employed fundamental characteristics of the channel or watershed to predict ecosystem structure or, on rare occasion, ecosystem function.

3.3 Why Hierarchical Scale is Important

Protecting, rehabilitating, and managing riverine ecosystems requires accurate knowledge of the hydrogeomorphic nature of the river section(s) under consideration The hydrogeomorphic nature of a river directly affects ecosystem structure and function by altering spatial and temporal components of the habitat template (Frissell et al. 1986) within the riverine landscape (e.g., wetted channels, slackwaters, and floodplains). For some questions, knowledge of the stream order/size and position downstream (as in the RCC) or the number of upstream tributary connections (as in the network dynamics hypothesis [NDH]; Benda et al. 2004) provides valuable information needed for river management. In other cases, however, investigators need additional or alternative higher spatial scale data; this is particularly true when attempting to manage rivers at the ecosystem level.

Matching the appropriate spatial scale of analysis with the ecological question or environmental task being addressed is vital to obtaining accurate and relevant answers (Fig. 2), as also discussed in a separate manuscript nearing submission (Thorp, Flotemersch, et al., In Prep.). Mismatches of spatiotemporal scale and management goals are all too common around the world (Thorp et al. 2008). For tasks involving many aspects of watershed management, the appropriate ecological level at which to evaluate ecosystem function or ecosystem services is the valley-to-reach scale, or FPZ (see Appendix A-7). Evaluations at higher spatial scales are rarely both mission-relevant and economically feasible for EPA and the states to employ. Analyses at smaller spatial scales, such as the reach level, are particularly useful for providing detailed data on questions involving, for example, point-source pollution and can also provide information on mechanisms operating at higher spatial scales. However, from a purely economic perspective, it is considerably more expensive and problematic to merge detailed data collected at the reach scale to answer broader scale questions than it is to collect sufficiently accurate, but less spatially precise data at the FPZ level.

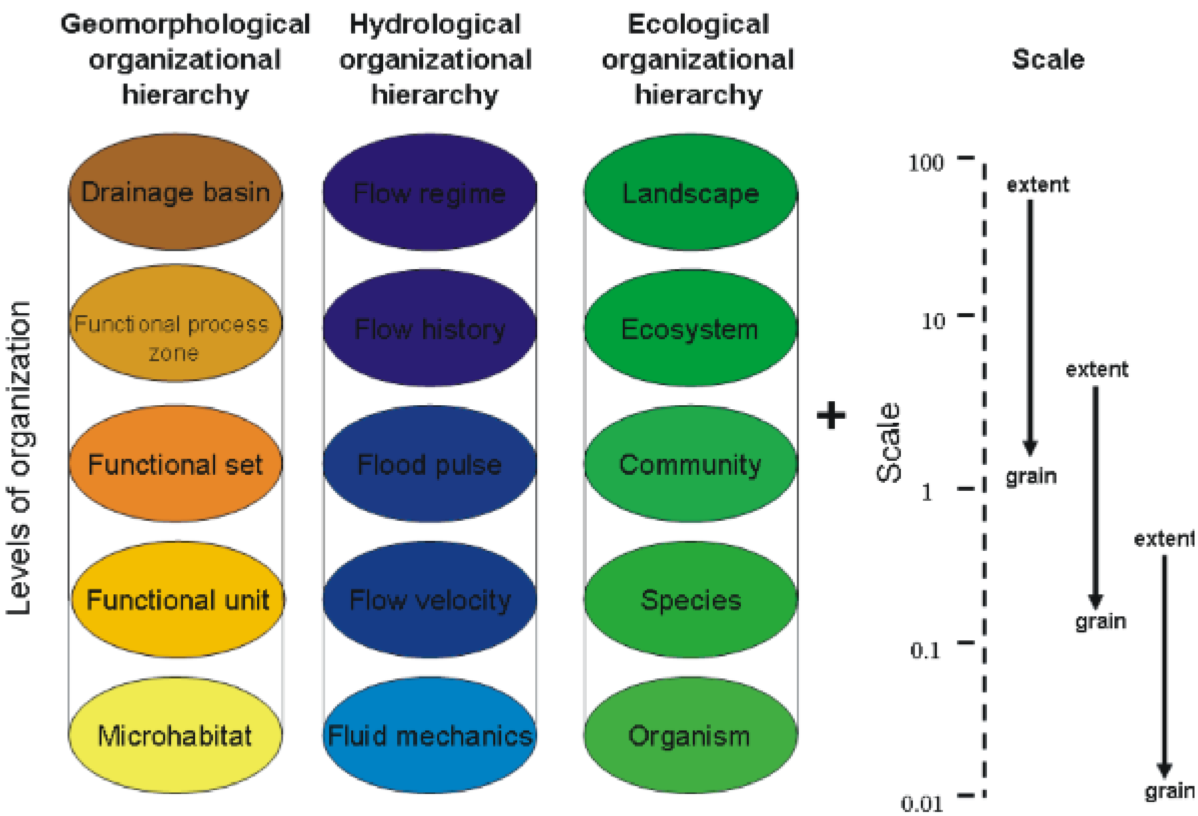

Figure 2. Organizational hierarchies in river science. To use this framework, one must first define the relevant spatiotemporal dimension for the study or question. Scales for each hierarchy are then determined to allow the appropriate levels of organization to be linked. The scale at the right demonstrates that linking levels across the three hierarchies may be vertical depending on the nature of the question. [From Fig. 3.2 in Thorp et al. (2008).]

3.4 Lateral Perspectives, Classification Schemes, and Watershed Management

River ecosystems consist of complex riverine landscapes composed of the riverscape (i.e., main channel and lateral slackwaters, such as bays, side channels, backwaters, etc.), and the floodscape (e.g., isolated oxbows, lakes, wetlands, and usually dry alluvial floodplains; Thorp et al. 2008). Consequently, watershed management of riverine ecosystems necessarily requires ecosystem models and classification schemes that incorporate both the riverscape and floodscape. Reach-level analyses, such as those employing the Rosgen Method, and most derivative models typically focus solely on the riverscape (i.e., the main channel only or occasionally, the main channel and slackwater areas). For example, if a river is classified as "warm-water fisheries," useful information can be gleaned about what species should live there, but no information is provided on how hydrogeomorphically complex the system is or what kind of interactions would be expected to occur between the main channel, slackwaters, and terrestrial watershed. Likewise, both channel-oriented (e.g., RCC and NDH) and floodplains-oriented models, such as the flood pulse concept (Junk et al. 1989; Junk and Wantzen 2004), only include a portion of the riverine landscape. In contrast, the Riverine Ecosystem Synthesis is designed to encompass (with FPZs) the entire longitudinal and lateral dimension of the riverine landscape. In fact, the lateral extent of an FPZ is for all practical purposes, the distance from the hillslope on one side of the river to the hillslope on the opposite side. It is within this area that the channel(s) move and/or interact during floods, and these areas are directly pertinent to EPA's program goals for Healthy Watershed Initiative through the Office of Water. FPZs are present from first-order streams downstream to the mouth of the river, but their delineation using solely top-down approaches is limited by the investigator's ability to distinguish the channel in a canopied covered area and to gain access to high-quality elevation data, which may require LIDAR data (see Appendix B).

3.5 Linking Classification, Ecological Functioning, and Environmental Sensitivity

The primary purposes for constructing classification schemes are to: (i) enable the investigator or government regulator to compare and contrast different river sections; (ii) infer ecological structure and function as well as ecosystem services; and (iii) predict effects of anthropogenic change (i.e., disturbance or rehabilitation) to that river section. To do so, the classification scheme needs to be quantitative, statistically rigorous, and either embedded in a more comprehensive model or linkable *a posteriori* to its ecological components. A distinct and rather unique advantage of the RES is its multi-faceted nature. That is, the RES incorporates a physical model based on FPZs, serves as a hierarchically-scaled investigative framework, and contains explicit ecological components linked to the physical model. The RES currently contains a set of 17 ecological hypotheses that address issues ranging from species distributions to landscape properties; as more is learned about rivers, these hypotheses can be expanded in detail and number. Equally valuable from EPA's standpoint is that the RES is flexible enough both to incorporate information obtained using many other approaches and to provide valuable analytical tools to those other models. For example, the physical variables in many GAP-type models would benefit from additional information on the arrangement of FPZs in relation to species distributions in the river(s) being assessed. Likewise, the distribution of fishes from habitat assessment models could be used to test the predictions of the RES' ecological hypotheses and predict the effects of changing the local FPZ(s).

4.0 Proposed Solutions

4.1 Introduction to Solutions

Our proposed solutions to the issues described in Section 3.0, Problem Statement, involve: (i) use of the RES as the comprehensive model for ecosystem management at the watershed level, including rehabilitation projects; (ii) inclusion of the FPZ approach as one of the hierarchical levels in developing classification schemes for rivers throughout the U.S.; (iii) incorporation of data from other EPA sampling programs to improve predictions of the RES; and (iv) employment of the FPZ approach to improve predictions of larger-scale derivative models. Within the RES, the FPZ approach is hydrogeomorphically-based, of direct ecological relevance (Fig. 1; Thorp et al. 2008), and scaled to be economically feasible and mission relevant. In addition, the FPZ approach has seven other characteristics especially important to EPA:

1. Delineation of FPZs is quantitative and statistically rigorous. [See Appendix B for a brief description of how FPZs are delineated.]
2. The FPZ approach can easily be merged with many previous approaches used by EPA over the last two decades. For example, the approach fits easily with ecoregional classifications; it can provide information helpful for data analysis in monitoring studies that have employed random or stratified random approaches; and it can use data from other studies in its own RES model to link FPZs with ecosystem function.
3. FPZs can be delineated using top-down, geospatial approaches, thereby greatly reducing personnel costs and time delays (see Appendix B). Alternatively, FPZs can also be delineated using previously collected, bottom-up data and some geospatial information on the watershed.
4. Although FPZs are most easily delineated from current conditions, it is possible in some cases to evaluate past and future conditions in relationship to anthropogenic modifications of the channel and watershed, thereby aiding mission tasks, such as rehabilitation actions.
5. Once a river’s FPZs have been delineated, the FPZ composition is relatively permanent and is subject to change only with major changes to the watershed and channel (addition or removal of dams, levees, etc.). Therefore, the FPZ delineation can be used for many future tasks without periodic re-analysis.
6. The FPZ approach can be applied anywhere within the U.S. or world, even if a given river has not been sampled previously and is relatively inaccessible or difficult to sample by traditional ground methods, as long as the needed data layers (principally geospatial data, but some geologic and precipitation data as well as remote sensing imagery of channels) are available.
7. Finally, the FPZ approach is not limited in its application to one or two tasks in the EPA mission, but instead can be employed in a wide variety of ways with past and future data. Some of the potential uses of this approach are summarized in Appendix A.

The concept of linking hierarchically-scaled components of fluvial geomorphology to ecosystem structure and function in longitudinal, lateral, vertical, and temporal dimensions of riverine ecosystems first began to coalesce following a 2003 plenary session talk by J.H. Thorp at a regulated rivers meeting in Australia organized by M.C. Thoms. This led to development of a journal article on the riverine ecosystem synthesis (Thorp et al. 2006). The original model was based on fundamental theory and pristine systems; however, plans to expand the model to modern, regulated rivers and apply it to the environmental missions of governments and NGOs were underway before 2006, culminating in the 2008 Thorp et al. book. The hydrogeomorphic patchiness of rivers has been recognized for decades by fluvial geomorphologists, but the division into repeatable patches (FPZs) at the valley-to-reach scale was refined by Thoms and Parsons (2002, 2003).

Use of the RES model in river management is in its infancy, especially as it relates to tasks characteristic of EPA's mission. There are two reasons for this. First, while the FPZ approach to watershed management has been successfully applied in dryland rivers in Australia (i.e., the Murray-Darling River system) and South Africa (i.e., rivers in Kruger National Park), the approach needs to be applied and evaluated for a fuller spectrum of ecoregions, such as those characterizing the U.S. Details of these applications are described in Thorp et al. 2008, as are the conclusions that many assessments of river condition use data collected at an inappropriately low level or scale (e.g., the reach or site level) to infer catchment-scale condition and manage river ecosystems. This prior work on other continents and our current work on the Kansas, Kanawha, and Neuse rivers in the U.S. will enable us to accelerate analyses of ecoregions in the U.S. using the FPZ approach. Second, the link within the RES between the physical model (the nature and distribution of FPZs) and ecosystem function is primarily conceptual at this point, although there is a strong body of aquatic literature supporting the concept and likely links. Therefore, while we can begin planning and execution of some applications of the RES (e.g., the physical classification of rivers), more research and development is needed to firmly establish links between the physical and ecological portions of the RES.

4.2 Recommended Steps

The following are suggestions (in recommended chronological order) for how to refine and employ the FPZ approach for EPA's use in completing its mission to protect riverine environments:

1. Refine techniques and protocols for rapid delineation of FPZs using computer-based, top-down geospatial approaches for integrating geomorphic, climatic, and hydrologic data and employing statistical clustering and analysis techniques. Develop a user manual for employing these ArcGIS-based techniques. [Note: We are currently refining and applying the approaches for EPA's use, but we have not yet written and tested a user manual.]
2. Test the efficacy of this approach with field data from rivers in one or more EPA regions by: (i) statistically delineating FPZs from geospatial data; and (ii) conducting a pilot study testing the FPZ distribution against ecological variables in aquatic data sets generated previously by EPA. [This task began for the Kanawha River in the summer of 2010, but it needs to be complete there and extended to other types of rivers.]
3. Recommend specific plans for implementing these approaches in future mission tasks at the national and regional levels within EPA; begin these task activities once funds are available.
4. Determine how the RES concept/FPZ approach can be best integrated with other past and present EPA river management approaches, classification schemes, and field data.
5. Produce documents describing, in greater detail, the uses for the RES and FPZ approach and methods for delineating FPZs; publish the information in EPA documents and refereed scientific literature.

4.3 Applications of Solutions

Almost all rivers have multiple FPZs, but the types, diversity, total number, average downstream expanse, and distribution will vary among rivers. As rivers increase in size downstream, the length of an individual FPZ generally increases and the diversity of FPZ types decrease. The ability to predict the types and distribution of FPZs for a river decreases above the ecoregional level because of inherent changes in climate, geology, and topography, all of which impact a river's hydrogeomorphic characteristics. River regulation frequently changes the local FPZs, primarily through alteration in the channel form and numbers, bed characteristics, flow patterns, and interactions with the riparian zone and watershed.

Success in delineating FPZs for any particular river, once the procedures are refined, will depend primarily on access to geospatial data (see also Appendix B). DEM data of at least 10-m pixel size are sufficient in most cases; 10-m DEM data is currently available for most of the U.S. and can be obtained from the U.S. Geological Survey (USGS). While finer-resolution, remotely-sensed data, such as light detection and ranging (LIDAR) data, are more precise (and thus could produce more accurate FPZ delineations, especially for headwater streams), these data have some disadvantages. First, evaluating LIDAR data for large watersheds demands much greater computer processing speeds, huge data storage capacity, and software that can handle these monumental data sets. Second, the spatial scale of the LIDAR data is much more precise than is needed for all but the smallest streams at the valley-to-reach scale of FPZs. However, if both the LIDAR data and computing capabilities are available, then it is a good option. Much of the precipitation data required for FPZ delineation on most rivers of the conterminous U.S. is available at no cost from multiple sources (e.g., National Climate Data Center, or the PRISM Group at Oregon State University). For the channel planform parameters used in the model, access to remote sensing imagery is very useful. Such data can be obtained for some areas and for growing seasons for free from the National Agriculture Imagery Program (NAIP) or be purchased in bulk from sources such as the commercial company DigitalGlobe®; this company provides geo-referenced satellite images, aerial photographs, and maps for sites throughout the U.S. Success in determining the original FPZ of a site (prior to regulation) will depend on the historical/archive data available; however, reasonable estimates can sometimes be made from the valley characteristics depicted in the site's current imagery.

5.0 Future Directions

Once the techniques for rapidly delineating FPZs are refined in the first year of the project and the approach has been field tested using current EPA data sets, it would be possible to move forward simultaneously on tasks listed in Section 4.0 and those described below. The first two "directions" below have relatively defined objectives, while the third and fourth are more diffuse and could involve many avenues of pursuit.

5.1 Government Training Course in FPZ Delineation

As soon as the techniques for FPZ delineation are refined and simplified for rapid, but statistically rigorous use and a user manual has been written, a five-day introductory training course could be developed for federal employees, other scientists, and river managers. This course could: (i) briefly familiarize participants with the principles of river science that are fundamental to understanding the ecological and hydrogeomorphic bases of using FPZs; (ii) present a background introduction to the nature and availability of environmental data necessary to delineate FPZs; (iii) discuss uses of the FPZ approach for accomplishing the environmental mission of EPA, other government agencies, and NGOs; and (iv) provide extensive, hands-on training in delineating FPZs. Parts i-iii would require much of Day 1, while Part iv would occupy the remainder of the week. Interactive, PowerPoint-based lectures could be supplemented by a printed manual (developed by EPA) and computer software on FPZs and their delineation. In addition, optional textbooks could be made available for use, including *The Riverine Ecosystem Synthesis* (Thorp et al. 2008) and a primer on fluvial geomorphology.

5.2 National Rivers Classification Manual

One recommended goal of this report is the development of a national river classification framework that employs the FPZ approach for classifying rivers at multiple spatial scales. As a corollary to this, EPA should consider publishing a *National Rivers Classification Manual*, generically comparable in scope to the ecoregional manuals for terrestrial (Ricketts et al. 1999) and aquatic systems (Abell et al. 2000). Such a manual could include an introductory chapter describing the scientific basis for this framework and its integration with other ecoregional and watershed approaches, followed by individual chapters on major river systems of the U.S. Individual chapters would include information on FPZs of the river ecosystem and any additional environmental information, as desired. Depending on the legal ramifications, it might be possible to extract and reprint maps and other desired information from the rivers manual by Benke and Cushing (2005) with agreement from the editors and publisher; alternatively, EPA could independently produce similar river basin maps and information.

The steps to producing a *National Rivers Classification Manual* include: (i) developing the national framework for classification (as discussed in this report); (ii) selecting target rivers; (iii) statistically delineating FPZs for the main channels and as many tributaries as is cost- and time-effective; and (iv) preparing, publishing, and distributing the manual.

5.3 Documents on Applications of the RES/FPZ Approach to Other Mission Tasks

The FPZ approach within the RES could be employed to help address other EPA mission tasks, such as challenges related to ecosystem services, river rehabilitation, and asset trading. We recommend the development of document(s) addressing the use of the RES/FPZ approach in these specific tasks. As an initial step in the process, a workshop on ecosystem services and river hydrogeomorphology was held at the University of Kansas' Kansas Biological Survey in December 2008 under the sponsorship of the EPA's Office of Research and Development (ORD) National Exposure Research Laboratory (NERL) in Cincinnati and a grant from the State of Kansas' National Science Foundation (NSF) Experimental Program to Stimulate Competitive Research (EPSCoR). The first product from this workshop was a manuscript linking ecosystem services, rehabilitation, and river hydrogeomorphology (Thorp et al. 2010); a follow-up book is currently being considered.

5.4 Integration with Previous and On-going EPA Analyses

In addition to applying the FPZ approach to future mission tasks at the EPA, this approach can be applied to past and on-going studies, with the former involving re-analysis of existing biological data trends. For example, if an assessment study was previously conducted using a random or stratified-random design, the data could be sorted by FPZs separate from or within ecoregions, and then the data re-analyzed to see if predictability improved. An advantage of this would be that the prior sampling design would not be lost, but merely integrated with the FPZ approach. Depending on the flexibility of on-going regional or national studies (e.g., the national survey of non-wadeable streams), the FPZ approach could also be integrated into the sampling design or later statistical analyses of these various projects.

6.0 Conclusions

This report recommends adoption of both an internationally-proven approach to river characterization and classification based on hydrogeomorphically-defined sections of rivers at the valley-to-reach scale (i.e., functional process zones) and a watershed-level management of rivers based on the Riverine Ecosystem Synthesis concept. Functional process zones are at the appropriate hierarchical scale for feasibly assessing catchments, and the FPZ approach is applicable to a wide diversity of mission tasks and can be easily integrated, using the RES, with current approaches to analyze present-day, future, and past environmental data.

Five initial steps for adoption of this approach are recommended: (i) refine the protocols and produce a user manual for delineating FPZs for EPA’s use (partially underway); (ii) test the FPZ approach with environmental data previously collected by EPA for rivers in multiple EPA regions; (iii) analyze the diversity of uses of the FPZ approach for EPA’s mission to protect riverine ecosystems; (iv) determine how the RES/FPZ approach can be best integrated with other past and present EPA river management approaches, classification schemes, and field data; and (v) publish EPA and externally refereed documents on the application of this approach to environmental protection and management of rivers (begun with Thorp et al. 2010).

Appendix A: Summary of Some Potential Applications of the FPZ Approach

Below are summaries of some major applications of this hydrogeomorphic approach to EPA's mission of protecting riverine ecosystems.

A.1 National Framework for River Classification

One of the initial uses of the RES/FPZ approach is its contribution to the development of a national river classification framework. To solve the primary problems described in Section 3.0, we recommend that EPA incorporate the quantitatively and statistically rigorous FPZ approach to classify rivers of the U.S., with an initial focus on delineating FPZs in major and otherwise important rivers. This FPZ approach would be integrated with hierarchical levels larger (e.g., ecoregion) and smaller (e.g., reach level) the valley-to-reach scale at which the FPZs are delineated. The FPZ approach, which emphasizes the hydrogeomorphic patchiness of rivers, will benefit greatly from more economical top-down approaches that rely primarily on geospatial data and can be integrated with more traditional bottom-up approaches at the reach level, such as the Rosgen Method, to delineate smaller spatial areas (e.g. very small headwater streams whose channels are obscured by canopies through most of the year), thereby developing a broad river classification scheme for the entire river network. The FPZ delineation of major U.S. rivers can proceed rapidly in an assembly-line fashion once initial procedures are refined, the approach is tested on a few rivers (e.g., the Kansas and Kanawha Rivers have already been delineated), priorities are set for river selection, and funding sources are identified.

A.2 Monitoring Design and Study Reach Lengths

Monitoring designs are typically: (i) unit-based (e.g., samples per a set distance); (ii) stratified by some natural or anthropogenic feature of the river (e.g., above, between, or below a chain of reservoirs) or land (e.g., ecoregions or political boundaries); and (iii) either stratified-random or statistically random within the river network. Most of these sampling designs would benefit from the simple inclusion of information on the hydrogeomorphic nature of the river being assessed.

Because FPZs are ecologically relevant, statistically delineated, and intermediate in size between reaches and entire watersheds, their use would enable EPA to set study-reach lengths that are mission-relevant, logistically feasible, and economically flexible.

A.3 Reference Site Selection and Condition Assessment

The ideal reference site would be pristine and comparable in size, hydrogeomorphic nature, and community composition to that originally present in streams now considered impaired. Pristine or even near-pristine streams are difficult to locate throughout much of the U.S.; instead, states are often forced to use least-impaired systems for comparison. As discussed in Section 3.1, however, a problem arises when the quasi-reference sites differ in the nature of their FPZ from comparative streams. In those cases, hydrogeomorphic conditions could be so different in the natural state that valid assessment of impairment could be difficult to detect or a challenge to defend in court. The delineation of FPZs offers a scientifically defensible method for the characterization of river sections that facilitates comparison to other sections of river that are equivalent in both structure and function. These "comparable" sections may be within the same river or in other rivers. With the ability to account for an increased amount of the natural variability inherent to a system, EPA's ability to accurately assess the condition of rivers, and sections within rivers, will be greatly enhanced.

A.4 Ecosystem Services

The ecological services provided by a river section in the past, present, and future are linked directly to ecosystem structure and function, both of which are directly influenced by the hydrogeomorphic nature of that section of the river and how it has been impacted by natural and anthropogenic influences. Ecological services are to some extent dependent on both temporal and spatial scales of the ecosystem, as described in Thorp et al. (2008). As a general relationship, the greater the hydrogeomorphic complexity (and thus habitat complexity) of the FPZ, the greater the biodiversity and functional complexity in that FPZ (Thorp et al. 2008). Moreover, "The levels of ecosystem services provided by riverine landscapes are an increasing function of the hydrogeomorphic complexity of the local functional process zone" (Thorp et al. 2010). For example, the hypoxia zone off the coast of Louisiana results from anthropogenic changes in both nitrogen inputs and nitrogen processing. The former is affected by the amount of nutrients entering the river from upstream agricultural lands and non-point source pollution, while the latter is affected by the vast levee system in the Mississippi River (especially the lower Mississippi). In the latter case, the river's natural ability to decrease nutrient spiraling lengths (i.e., the distance a nutrient atom must travel to complete one nutrient cycle from inorganic to organic and back to inorganic form) and increase nitrogen processing are related to the amount of lateral slackwater that is present. By understanding the original, current, and future FPZs for a river, the ecosystem services can be evaluated under different scenarios of river complexity. This also provides the empirical and conceptual bases for guiding processes to improve the environmental quality of the river through activities such as river rehabilitation (Section A.6) and asset trading (Section A.5). Other ecosystems services (provisioning, regulating, supporting, and cultural services; Limburg 2008) are also intimately affected by current FPZ complexity.

At present, and in support of the Ecosystem Research Program, the FPZs of the Neuse River Basin are currently being delineated. This information will also be useful for the characterization of ecosystem services basin-wide. As stated earlier in this document, because FPZs differ substantially in hydrogeomorphic characteristics, FPZs are also likely to vary significantly in community structure, ecosystem function, and response to nutrient loadings, and thus will respond differently to efforts at river rehabilitation. For this project, the FPZs will be delineated for the entire Neuse River Basin using 10-m DEM data supplemented by some vertical LIDAR data. Our focus on the Neuse River provides an opportunity to test the ArcGIS river delineation model on a river that is hydrogeomorphically distinct from both Kansas River of the Great Plains and the Kanawha River of the mountainous East.

A.5 Asset Trading

The use of FPZs to improve asset trading was briefly discussed in Section 3.0. Two of the components necessary for a fair basis of trading are: (i) a regional or national framework for classifying rivers at the appropriate scale (including at least the valley-to-reach scale of FPZs);

and (ii) an understanding of the link between river classes and resulting differences in ecosystem structure and function for the river sections being compared. Thorp et al. (2008) provided a framework for both classifying the relevant scale of rivers and for understanding the likely ecological responses to different actions. However, many of the predicted ecological differences between FPZs presented in Thorp et al. (2008) are hypothetical, because river typing using hydrogeomorphic classification into FPZs is just beginning in the U.S. through a joint venture between EPA-ORD (i.e., NERL-Cincinnati) and the Kansas Biological Survey at the University of Kansas. It should be possible, however, to refine these hypotheses using current EPA ecological data and develop general guidelines for differences in biodiversity patterns and ecosystem services among FPZs to enhance the basis for fair asset trading.

A.6 River Rehabilitation

Many attributes are factored into decisions on river rehabilitation/restoration, some of which were alluded to in Section 3.0. Rehabilitation can have many objectives, including removal of dams, reconnecting the main channel with floodplains, improvement of channel bed structure (inorganic and organic), enhancement of riparian/channel exchange, naturalization of the flow regime, removal of exotic species, and the addition of formerly native species. Decisions on many of these objectives would be improved by knowledge of the past, current, and future FPZs likely in the affected area.

Some types of river rehabilitation are relatively straight-forward and focused on a specific site and rehabilitation object. For example, dams on several rivers in the state of Maine were considered for removal based on various socioeconomic, political, and environmental reasons. In this case the environmental action involved a simple decision - removal or non-removal - with no reasonable, intermediate position. The old Edwards Dam, the most downstream dam on the Kennebec River, was selected for removal. Some obvious ecological responses to the dam's removal were predicted (as discussed by Casper et al. 2006), such as increased activity of migratory fish. Had the FPZ composition of the river been delineated, however, it would have been possible to evaluate the ecological benefits likely to accrue from dam removal (in terms of the past, present, and near-future nature of the FPZs) for this river and others in Maine. Knowledge of the future FPZs is not always clear when the past state is not known. For example, removal of mill dams in the eastern U.S. did not immediately produce meandering streams (as was expected) or the original anastomosing channels characteristic of the region (which was initially unexpected); these both may develop over time (Walter and Merritts 2008).

More complicated decisions in river rehabilitation involve: (i) how far to set back a levee in order to develop favorable cost/benefit ratios; and (ii) where to locate controllable breaches in a levee to connect with wetlands, how many should be present, and how they should be operated (e.g., amount of flow and the frequency, length, and seasonality of connection). These decisions involve a balance of costs (e.g., construction, operation, and purchase of land) and returns from ecosystem services. Clearly, the farther the levee is set back laterally and the more populated the region, the more expensive the process; however, the ecological endpoints will *not* directly track with economic costs (Thorp et al. 2010), but rather will depend on what type of FPZ develops in the restored area (which is influenced strongly by what was there in the beginning). For example, if a channelized section of river was originally characterized by a simple meandering FPZ with nominal lateral movement, then minimal set-back levees would be required as larger lateral areas produced by increased levee set-backs would not produce many additional benefits. In contrast, if the section of river was originally characterized by side channels, parallel channels, and forested islands (a braided or possibly anastomosing FPZ), then, in terms of ecosystem services, more extensive set-backs would be warranted. In addition to the differences among FPZs, cost/benefit ratios for rehabilitation are also influenced in a non-linear fashion by the type of ecosystem services highlighted (Thorp et al. 2010). To maximize ecological endpoints of rehabilitation, the future FPZ for the area in question (which is strongly influenced by the original FPZ present) needs to be known, as well as the time needed to obtain that state.

A.7 Watershed Management

"Management" is a hierarchical process in rivers, just as it is in most human endeavors, and thus is subject to a variety of often vague definitions. When the meaning of this and other critical terms are not specified, communication is confounded and environmental action is impeded. *River management* may involve activities in the main channel, full riverscape (main channel plus lateral slackwaters), or riverscape and floodplains. If the geographic coverage extends laterally into the floodplains and surrounding valley basin or catchment, the process is sometimes called *watershed management*. Except in very limited cases, river management should most effectively encompass processes operating in both aquatic and terrestrial components of the riverine landscape.

The appropriate hierarchical level of management activities depends on the human concerns/targets and their spatial extent. At the highest spatial scale, river management involves the entire drainage basin or watershed (i.e., from the highest-elevation first-order stream to the lowest-elevation river section where the river enters a larger river, ocean, lake, or dry basin). In contrast, river management may operate at a much lower scale, such as a small reach. The management level is affected by river network size, political boundaries, and availability of management funds.

EPA research should be conducted at multiple hydrogeomorphic levels and spatiotemporal scales in order to address various tasks in the agency's environmental mission. The hierarchical level and spatial scale of the research will vary among and within tasks; generally speaking, the larger the spatial scale of the stressor (e.g., non-point source pollution commonly operates at a greater scale than point-source pollution) or effect to be achieved, the higher the appropriate focal level in the hierarchy. Moreover, the hierarchical level and spatial scale appropriate for a study tend to increase with river size and are affected by the number of FPZs per linear length of the river. For example, a focus at the valley-to-reach level is more appropriate when FPZs change frequently along the length of the river than when they are relatively constant in type over long distances.

To manage at any given level and scale, the controls exerted at the next higher level and mechanisms operating at the next lower level are especially relevant to consider. For example, if you wished to manage the hydrogeomorphic structure, the ecology, or the inputs to an entire river, or at least a very large section within a state, the appropriate level for understanding mechanisms would be the valley-to-reach level. In contrast, if you are concerned with more spatially-limited stressors, you might focus instead at the reach level within an FPZ (realizing that comparisons among reaches in different FPZs will require knowledge of the differential impacts of the various FPZs). Management at any hierarchical level is better guaranteed success when the scale of field assessment activities carefully account for the hierarchical level of the management target or research question. Thorp et al. (2008) provide a framework for different aspects and scales of river management.

Appendix B: Summary of FPZ Delineation Techniques

Functional process zones can be identified with either top-down techniques (e.g. geospatial–based analyses) or bottom-up field methods (e.g., traditional on-site methods in fluvial geomorphology). Because the former is sufficiently accurate and much less costly, labor intensive, and time consuming, it is usually the recommended approach. General techniques for delineating FPZs are described in Thorp et al. (2008).

The following 14 independent and dependent variables are used to derive FPZs: geological conditions, mean annual rainfall, elevation, valley width, valley floor width, valley side slope, down-valley slope, ratio of valley to valley floor width, wavelength of the channel belt, sinuosity of the channel belt, width of the river channel belt, sinuosity of the river channel, number of channels, and channel planform (Thorp et al. 2008). Other variables can be added, but the data in this list has proven sufficient for FPZ delineation using an ArcGIS model. Using one of several multivariate clustering techniques, a dendrogram of sites is produced with an appropriate threshold level. Groups of sites can be ordinated with semi-strong, hybrid multi-dimensional scaling and then tested to see whether they occurred by chance. To determine which physical variables were most important in separating clusters, a principal axis correlation can be conducted, followed by a Monte Carlo permutation test; only variables with an R^2 greater than the 75th percentile are recommended as being significant. Once the significant clusters are identified and named using standard terminology for river channel types (e.g., braided FPZ) as modified for other important contributors (e.g., upland or lowland), these clusters can then be added to maps at specific coordinates to depict the spatial arrangement of FPZs along the river.

While FPZs can theoretically be delineated from the smallest headwater stream to the largest great river, there can be practical limitations in headwater regions. The primary issue is the ability of the investigator to determine the channel planform (number and type of channels) by remote sensing, which can be limited by the presence of riparian cover (ecoregional and seasonal) and the precision (i.e., pixel size) of available data. Consequently, FPZs can be determined more easily for smaller streams in prairies than in forested areas, because the riparian canopy of the forested areas tends to cause errors in the elevation data. Extensive coniferous canopies cause more trouble than deciduous canopies, of course, because the former is closed throughout the year. However, in most cases FPZs can be determined for at least third-order streams in most ecoregions using LIDAR, 10-m DEM, or 30-m DEM data and down to first order streams in many prairie watersheds. Where canopies obscure the channel form, on-site reach data (derived by traditional bottom-up approaches) can be used profitably to delineate the FPZ. The advantage of the more precise data decreases proportionately with stream size, while the large computer processing demands stay the same. Hence, LIDAR is useful in very small streams, while 30-m DEM data may be sufficient for most other stream sizes.

Analyzing FPZs requires a moderately-fast, memory-rich computer (especially if using LIDAR data) and the appropriate software to download the necessary data and extract the needed variables. The geospatial data are combined with the other variables in the model to produce the needed clusters for FPZ delineation. Some knowledge of fluvial geomorphology is needed, but this is minimal compared to the ability to process the DEM or LIDAR data and analyze the data statistically. Efforts are currently underway to allow data processing and analysis to be conducted with minimal time and effort by the user through semi-automation of the process.

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