The River Process Corridor: A Modular River Assessment Method Based on Process Units and Widely Available Data in the Northeast US.

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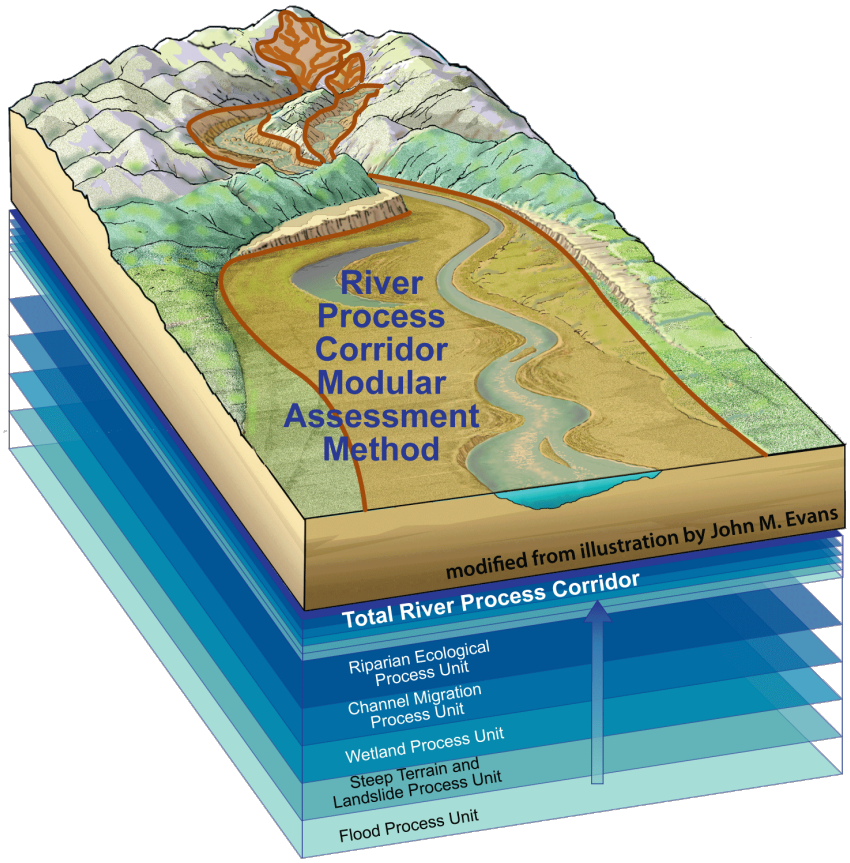

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Abstract

We define the river process corridor (RPC) as the area adjacent to a river that is likely to affect and be affected by river and floodplain processes. Here we present a novel approach for delineating the RPC that utilizes widely available geospatial data, can be applied uniformly across broad and multi-scalar spatial extents, requires relatively low levels of expertise and cost, and allows for modular additions and adaptations using additional data that is available in particular areas. Land managers are increasingly using a variety of delineated river and floodplain areas for applied purposes such as hazard avoidance, ecological conservation, and water quality protection. Currently, the most-used delineation methods rely on historic maps, field surveys, and/or calibrated empirical models. These approaches are examples of what is possible, but they may be time-intensive, may rely on jurisdiction or organization-specific data or data information systems, or may require specific local-user input or hand-drawing. Our approach, the River Process Corridor Modular Assessment Method, offers a rapid, uniform and objective river and floodplain process area delineation method that uses transparent, easily accessible data, and may be used across large areas. it is derived from the sum of five functional process units that together capture the RPC: (i) the Flood Processes Unit, derived from hydraulic modeling to determine areas subject to overbank deposition and erosion, in-channel deposition and erosion, bank erosion, and channel avulsions; (ii) the Landslide and Steep Terrain Processes Unit, based on terrain slope to show locations subject to sediment delivery, bank failures, and other mass wasting proximal to the flood-prone area; (iii) Wetland Processes Unit, based on the U.S. National Wetlands Inventory to show areas where wetland processes occur; (iv) Channel Migration Processes Unit, based on channel location and migration rates to show areas susceptible to lateral channel movement; and (v) Riparian Ecologic Processes Unit. This paper details the assessment approach for each of these units, and provides a summary outline and table for users. To illustrate and evaluate its potential, we apply the approach in three river reaches in mountainous and low-relief watersheds in the northeastern U.S. and compare results with recent geomorphic change, observed in the field and in historic imagery. The River Process Corridor Modular Assessment Method performs very well, capturing 92% of observed landslide areas, 87% of observed floodplain deposition areas, and 100% of channel migration areas. We also provide an example of how additional data available from the State of Vermont could be added in a modular approach. These results indicate the RPC method is successful at providing both an accurate assessment of potential active hazard areas and sensitive environmental areas, and that it also includes a margin of safety that many managers desire. Its modular nature allows for flexible weighting of different metrics to suit specific applications, and piecewise updating as new data or approaches become available. We conclude that maps of the RPC can be useful as an advisory layer to natural resource managers, property owners, planners and regulators to identify areas that may be valuable for ecological conservation or at risk of future damage during floods, or where they might consider allowing natural river processes occur, in order to enhance ecological processes and help attenuate future flood damage elsewhere.

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1. Introduction

Rivers and the swath of land next to rivers are critically important for aquatic and riparian ecosystems and ecological processes, water resources, human infrastructure, and natural hazards. Several hydrologic and geomorphic processes—including flooding, erosion, deposition, river migration, bank failures, and landslides—create dynamic areas where water, sediment, nutrients, carbon, and pollutants are transported, sometimes gradually and sometimes catastrophically (Bierman et al., 2014). We call this area the river process corridor (RPC), and we define it as the area adjacent to a river that is likely to affect and be affected by river and floodplain processes. It encompasses more than just the river channel up to the ordinary high water mark. It can include floodplains, some wetlands, areas into which river channels may shift locations, areas that ecologic processes influence (and are influenced by) river and floodplain processes, and steep hillslopes that lead directly into rivers and are susceptible to both beneficial and hazardous erosion by river processes.

Dynamic processes within river process corridors create prized ecological areas. They have high biodiversity, spatiotemporal patch dynamics, a variety of riparian habitats, and an ecotone from aquatic to terrestrial communities (Naiman et al., 1993; Pickett and White, 1985). The RPC is a region of heightened ecological connectivity, due to the migration and dispersal of aquatic and riparian species (McCormick et al., 1998; Strayer, 2008). Physical processes also enhance connectivity, with hydrologic and geomorphic processes transporting materials upstream, downstream, and laterally between channels, floodplains, and hillslopes (Allen, 2008; Bracken and Croke, 2007; Croke et al., 2013; Gartner, 2015; Pringle, 2001; Stanford and Ward, 1993; Wohl and Beckman, 2014). Due to both ecological and physical connectivity, the processes that occur in one part of the river process corridor can affect conditions in another part of the RPC, sometimes beneficially, sometimes negatively. As an example, fish habitat could be negatively impacted by sedimentation from road construction that is beyond the edge of a river channel but within the river process corridor. Alternatively, the natural process of geomorphic avulsion may destroy redds in one year but create a new side channel that is excellent rearing habitat the next year. In addition to their important ecological value, connectivity, and dynamism, river process corridors are prone to changes that human beings experience as natural hazards, in which floods, landslides, bank erosion, and sedimentation can damage roads, homes, farms and other infrastructure (Dethier et al., 2016; Gartner et al., 2015; Magilligan et al., 2015). This is a major issue for land owners and users, planners, land and river managers, road crews, emergency response personnel, and state and local policymakers and treasurers. Indeed, the hydrologic and geomorphic effects of floods are consistently among the costliest and most lethal natural hazards (Ward et al., 2017). In the inland Northeast US, as around much of the world, the greatest damage from floods often comes not because of inundation but rather the force applied by fast-moving volumes water, sediment, and debris (Kline and Cahoon, 2010; Vogel et al., 2016). Floods and flood-induced biophysical transformation occurred in historic cultural and climatic conditions, but more intensive human habitations and structures in the past few centuries and decades made these processes more hazardous to people. With climate change in the future, increasing precipitation and storminess are likely to increase the frequency and magnitude of these hazards (Huang et al., 2017; Parry et al., 2007; Stocker et al., 2013; Yellen et al., 2016).

Many human structures—including transportation networks, dams, urban and industrial centers, farms, and homes—are situated in this active river process area in order to take advantage of fertile soils,

natural, relatively flat pathways through rugged terrain, and access to water and hydraulic power. Thus human beings benefit from, but also can become threatened by, processes within these areas. Importantly, because of the connectivity within the river process areas, our structures and activities in one area also have the potential to contribute to, or mitigate, these processes and their damaging effects.

Because of the ecological benefits, the potential for flood-related damage to human beings and our infrastructure, the multiple kinds of connectivity and interaction, and the likelihood of more frequent river floods with climate change, many people have realized they need to know the areas where river-related processes are most active. Recognizing and locating the boundary of the river process corridor is useful for natural resource managers, property owners, planners, regulators, and businesses for five broad reasons.

Why we may want to recognize and delineate the location of the river process corridor:

- It can alert them to areas that may be valuable for ecological purposes (including ecosystems that may benefit from the impacts of flooding).
- It can suggest where they might anticipate future flood hazards, not just from inundation but also the shifting location of river channels, that may threaten human beings and human investments.
- In either of these cases, it highlights places where they may direct further analysis or protection based on concern for risks to specific species or infrastructure.
- It can suggest areas where there may be room away from the built environment to allow natural river processes to occur, enabling river and floodplain processes to continue while lowering the risk and cost of hazards to human investments.
- It can point to areas of concern for further attention, analysis and protection that can help communities adapt to climate change.

2. Where do River Processes Occur?

It is challenging to determine the boundary of the river process area, especially to develop a consistent and rapid approach over large geographic regions. In drawing the boundary of the river process corridor we aim to predict where river-related processes will occur, and predictions are inherently difficult. As stated above, river process corridors are active and dynamic locations. They have fluctuating water levels and channel edges that can move. Many key river processes are not active every day – for example, flooding, channel migration, and near-channel landslides – so they cannot be readily or regularly observed. Direct observations of river processes are also difficult because they may be subtle, such as the sporadic and intermittent buildup of sediment and nutrients on floodplains. In addition, the probability (or the likelihood over time) that any process will occur changes with distance from the river channel. For example, river migration may be very likely to occur a few meters from an existing channel in the next decade, yet there is an unlikely but non-zero chance that a river may migrate hundreds or thousands of meters over century or millennial time-scales (Buraas et al., 2014; Hickin and Nanson, 1984; Schwenk et al., 2017). And, to further complicate matters, the next prediction of that same

process depends heavily on where exactly the previous prediction placed the active river channel. Thus, in addition to being uncertain, river process corridor delineations depend inherently on the time and length scales of interest.

While delineating the RPC may be very helpful for multiple reasons, there is no one way to do it. A number of methods have been developed both in the scholarly literature and in applied management, policy and practice. Methods vary depending on the goals of different organizations, and the resources they have available to them. Our primary goal was a river process corridor delineation that would be useful for the USF&W's mission to manage national wildlife refuges, protect endangered species, manage migratory birds, and restore nationally significant fisheries. To make the method as useful as possible to scientifically informed management, we wanted the method also to inform users about the distinct river and floodplain processes that affect habitat and ecological processes. We thus organize the method into five distinct unit, with each unit mapping the spatial extent of one major physical process. Thus, the "process" part of our River Process Corridor delineation method.

Additionally, we hope that our method will be useful for other agencies and organizations as well as the USF&W. Because each jurisdiction and organization has different goals and resources, we made our system modular, with each step allowing users to add their own distinct data, or even to add or subtract steps.

We targeted creating a river process corridor for the North Atlantic region, which spans from Virginia to Maine. To make one system work across this region's diverse states, towns and non-profit organizations, we chose to use data that was publicly available and largely consistent across this wide geographical area; and to build delineation methods that could be done rapidly by people with training but without deep scientific or engineering expertise. We favored simple over complex mapping rules, and physically-based rules over empirical rules wherever possible. The protocols avoid hand digitizing, to allow reproducibility and mapping over large areas. The result is an approach that we expect to be transferrable to other regions outside the Northeast as well.

In short, we sought to develop a river process corridor delineation strategy that is:

- Process-based, meaning that specific river-related processes are tied to specific steps and mapping rules
- Uniform across the Northeast United States
- Rapid; based on readily available data
- Clear and accurate at both large and small geographic scales, across the Northeast United States
- Objective, meaning it is based on transparent and publicly available mapping rules
- Non-expert, meaning that it does not necessarily rely on hand-digitizing river features, interpretation of field evidence, or local knowledge of specific conditions
- Flexible, so that it can, if desired, incorporate interpretation of field evidence, local knowledge, improved data sets, and changing conditions

The report proceeds as follows. It first reviews existing methodologies for delineating river process corridors and related river protection measures, as well as how the development of the RPC began. The next sections describe our approach to mapping the RPC, from considering the complexity of delineating river processes, to choosing the river-related processes, to deciding appropriate data and their applications, to summarizing the GIS steps to generate the maps. After explaining the development of the method, we provide a summary table and guide for users. We then turn to testing the RPC in three

sites, evaluating its ability to capture empirically measured processes. We provide an example of how the method could be adapted in modular fashion by a jurisdiction with particular goals and additional data. Our final discussion considers the role of climate change, the applicability of the RPC, and offers a summary of findings and conclusions.

3. Why a *River Process Corridor*? Distinguishing the RPC from Other Approaches to Delineating River and Floodplain Corridors and Areas

Currently, a number of federal agencies, states, academic institutions, and others use a range of terms and methods to delineate areas, zones or corridors in and around rivers and floodplains. All aim in some way to understand and demarcate the specific geographic extent of important river –or floodplain– related habitat, and/or river-related hazards that arise from the erosive force of floodwaters. They use many terms to describe this dynamic and important swath of water and land, and the array of terms reflects an even greater set of definitions and purposes. This can be confusing. The differences in terms, methods and resulting maps arise because each method serves a distinct purpose, each jurisdiction's territory has a unique set of hydrological and geological conditions and patterns, and each entity has a distinct set of scientific, regulatory and financial resources. To illustrate conceptually what each delineation method looks like, **Figure 1** shows a schematic drawing of generic floodplain. On top of the same block-diagram drawing, each of the methods described below is represented as a translucent colored field, showing the bounds that might be drawn using the method as described on this map.

In this section, we explain the definitions and purposes associated with our own definition and method. In order to help the reader and user understand what distinguishes our method, we then outline the definition, purposes and approach of several other commonly used terms and methods. Our proposed River Process Corridor Modular Assessment Method is described in more detail in the following sections.

We define the *River Process Corridor* (RPC) as the full area around a river that is affected by river and floodplain processes – processes including river water flow, flooding, erosion, deposition, river migration, bank failures, and landslides. Our definition and delineation of this area reflect our aim to help managers, property owners and others recognize the full area of concern for protection of valuable resources, both natural as well as human lives and property, that may be affected by river and floodplain processes. Our RPC is intended to predict future locations of river-related processes, including under conditions of climate change.

We call our delineation strategy the *River Process Corridor (RPC) Modular Assessment Method*. The first step of this novel approach is to articulate a list of river processes that should be considered in the river corridor delineation. The second step is to group these processes into "Process Units," because many of these processes are driven by a common force. The area prone to flooding, for example, coincides with the area susceptible to overbank sedimentation. The next step is to develop a mapping rule for each of these Process Units, which creates polygons in a Geographic Information System (GIS) that define the extent of a single process or a group of processes. We favor simple over complex mapping rules, and physically-based rules over empirical rules wherever possible. The protocols avoid hand digitizing, to

allow reproducibility and mapping over large areas. The next step is to overlay these polygons for each process to create a single corridor that is the River Process Corridor. A final step is to refine and modify the extent of the corridor. The modifications can occur in three distinct ways, including (a) an improved mapping rule can be developed for a specific river process, (b) an additional river process—and associated mapping rule—can be added to the analysis, if desired by the users of the RPC, and (c) site-specific knowledge and field evidence can be incorporated for smaller scale analyses, if desired.

In contrast, the Special Flood Hazard Area (SPHA) from the Federal Emergency Management Agency (FEMA), sometimes called the "flood zone" or the "FEMA flood zone," which is used for Flood Insurance Rate Maps, aims to identify the area that will become covered in water in a large flood (a large flood that is in the top 1% or 0.2% of all floods in that area, in terms of water volume; refer to a conceptual example in **Figure 1a**). In contrast to the RPC, the FEMA flood zone includes only the areas that are likely to become inundated in a flood, and not those outside the likely inundation zone that face river flood hazards generated by physical processes such as erosion of river banks, the movement and migration of river channels, including avulsing (jumping to a different channel location), bank failures or landslides, or widening as a result of landscape/ land use change, climate change, or ongoing natural processes.

The Ordinary High Water Mark (OHWM) from the U.S. Army Corps of Engineers is a term used in the application of the Clean Water Act (Lichvar and McColley, 2008). In order to designate the areas over which the Clean Water Act has jurisdiction, areas that are "water" (laws apply) and "not water" (laws do not apply) must be distinguished. The OHWM is thus defined as the interface between the banks of a water body and the water body itself. Because the OHWM is designed to designate areas that are mostly water most of the time, it does not encompass many temporally infrequent river processes such as flooding, bank erosion, and floodplain processes. In contrast to the RPC, the OHWM includes only the channel area from bank to bank, under average to modest flows[1].

Many jurisdictions, including Massachusetts, have a river "buffer." Buffers are usually zones of a specific width on either side of a river channel. The Massachusetts River Protection Act, for example, applies an algorithm protecting an area including a 200-foot buffer from each side of the river channel, except in specific urban areas where the protected area is a 25-foot or 50-foot buffer from each side of the channel. These buffers are legislated boundaries, designated as the area protected by the Massachusetts River Protection Act from certain activities. In Massachusetts, as in many other places, buffers are intended to designate the "riparian area" – from the Latin ripa, meaning "banks" – a term for the most active ecological area on either riverbank. These buffer delineations are simple and straightforward to apply because they are the same distance from the channel everywhere (see conceptual example in **Figure 1b**). In contrast to the RPC, buffers do not account for processes like wide flooding that may extend far beyond a set buffer width in some places but not in others, nor do they take into account channel migration or wider landscape features such as elevation and slope. In narrow

[1] "Modest flows" is vague, because most often the OHWM is a physically identifiable change in slope on the channel bank, which may correspond to flows that occur, on average, every 1-2 years. These "modest flows" may be similar to the "bankfull flow" or "bankfull discharge" which will typically fill the channel from bank to bank. This channel width, then, is referred to as the "bankfull width", which is a useful and widely-used metric for comparing stream sizes between locations, and comparing the width of a stream to the width of a crossing structure.

valleys Massachusetts buffers may be wider than the RPC; in flatter areas buffers may be much narrower and more meandering, as they follow the contours of the current channel.

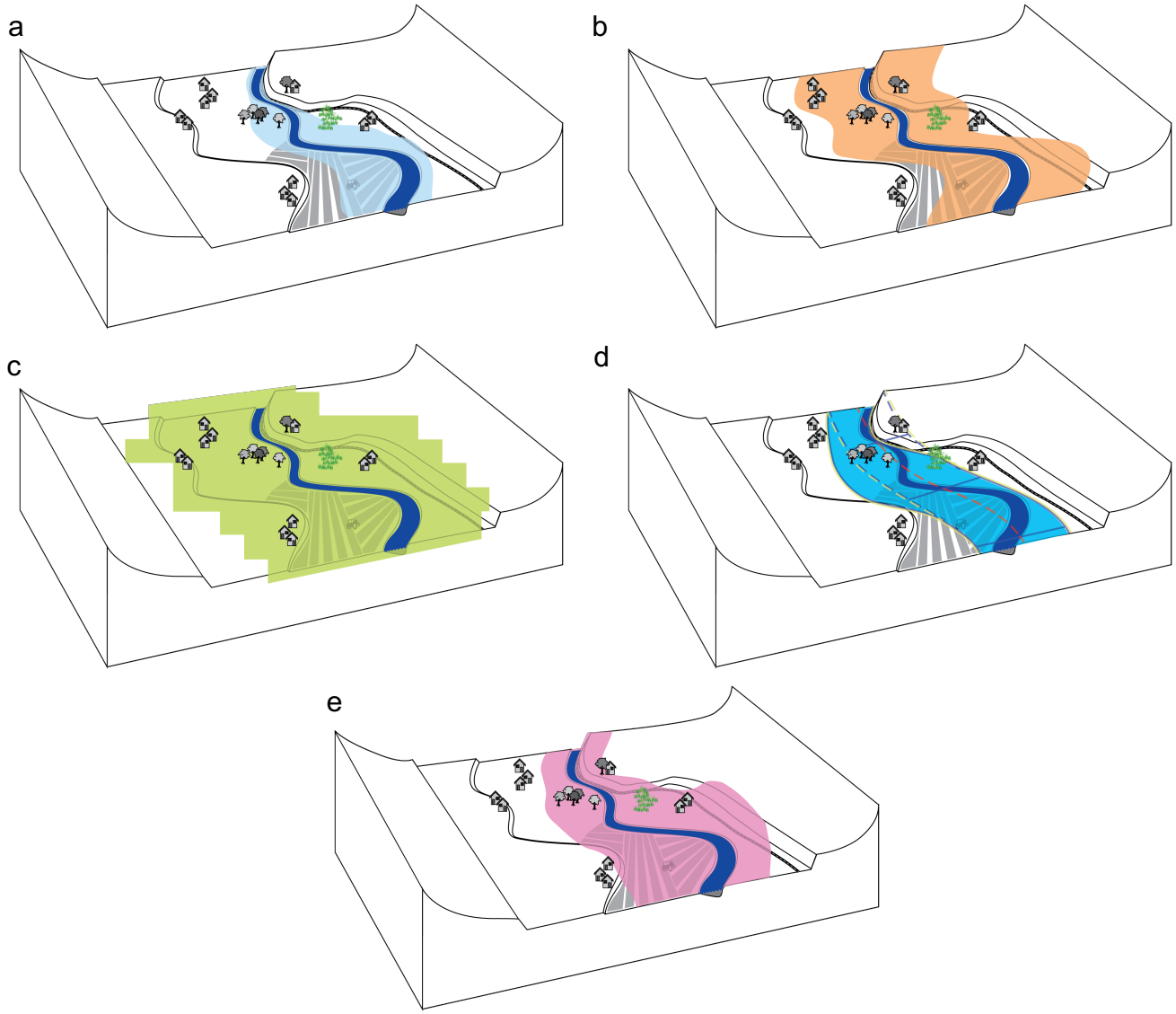


Figure 1. Schematic representation of how different delineation methods with distinct goals and applications theoretically might appear on a generic floodplain. **(a)** Federal Emergency Management Agency (FEMA) 1% Annual Exceedance Probability (AEP) Special Flood Hazard Area. Note that this light blue inundation area barely extends beyond the banks of the deeply incised channel toward the top of the diagram. **(b)** Massachusetts River Protection area consisting of a (maximum) 200-foot orange buffer. **(c)** The Active River Area (ARA) in green covers the entire valley floor, and is pixelated due to the coarse data used to generate these large-scale regional maps, **(d)** The Vermont River Corridor (cyan) is derived from mapping a meander belt centerline (red), and mapping a swath two-four times the channel width on either side of it. In addition, the dashed lines show where a road or highway with bank armoring along the river below the house was excluded from the corridor, and an equal area was added on the opposite side of the valley to accommodate the equilibrium planform and dissipate the river's force downstream. Finally a buffer of safety 50-feet wide is added (yellow), and **(e)** the total River Process Corridor (RPC; pink) is the sum of the five process units.

More encompassing definitions closer to the RPC are offered by "channel migration area" (Rapp and Abbe, 2003a) and "active river area" (Smith et al., 2008). Washington State utilizes an assessment method based on the historic location of river channels to predict their future location. The resulting maps, entitled Channel Migration Zone Maps, are used to help direct grant money to river restoration projects within the areas adjacent to rivers where river processes occur. This method is referred to as the Meander Migration Model, or Morphodynamic evolution model. The model employs detailed analysis of historic maps, image time-series, soils, and field characteristics (Larsen, 2007; Pasquale et al., 2011; Rapp and Abbe, 2003b) to determine where river-related processes have occurred and might occur in the future. With this technique, different river corridor processes can be considered individually using these different lines of evidence. Multiple sources of field evidence are then synthesized into a single map. In many respects, this approach is similar to our River Process Corridor Modular Assessment Method (see following sections): multiple sources of information are overlain and synthesized to form a single, detailed, inclusive mapped area. A key difference is that Washington's Channel Migration Area requires large amounts of time, labor, and place-specific data, and because of this, while it has been applied successfully to specific reaches and sometimes rivers 10's of km long, it is rarely scaled up to larger regions. The RPC uses widely available data that can be accessed and processed quickly with a desktop computer, allowing rapid and uniform mapping of large areas without expert input.

The Active River Area (ARA) is a mapping approach developed by the Nature Conservancy for land and habitat conservation proximal to rivers. The ARA mapping tool intends to capture the most encompassing possible area that might be used by species that depend on connected river-adjacent ecosystems. The ARA tool builds from the insight that the active area around a river, or the places where most river processes occur, is a function of both the distance from and elevation above the river channel (Smith et al., 2008). For the ARA, input parameters for distance-elevation algorithms are determined at selected locations (training sites) where the width of the active area has been evaluated by experts. Next, the algorithm is applied on a 30-m grid using Geographic Information Systems (GIS) across broad regions with physiography similar to applicable training sites. With this strategy, the Active River Area approach has been applied to the entire eastern seaboard of the U.S. (see example, **Figure 1c**). The Active River Area method is particularly skilled at capturing the entire valley bottom for river systems over large geographic areas with computational efficiency and ease. In contrast to the RPC, the Active River Area, because it is based on 30-m gridded source data and a straightforward distance-elevation algorithm, tends to result in a broader, coarser mapped area of active river processes. In theory more detailed source data could be substituted, but the all-encompassing maps serve the Nature Conservancy goals well, as they err on the side of being more inclusive of potential conservation areas than less.

The term "river corridor" tends to explicitly recognize and include a range of river and floodplain processes, but is frequently used for a narrower area than the RPC, and it is often a regulatory zone. The Oxford English Dictionary defines a river corridor as "A narrow stretch of land comprising a river and the areas adjacent to it, especially one important as a route for movements and communications; a (narrow) river valley. Origin 1920s." The term river corridor may describe a full natural river meander corridor – i.e. the meander belt in which a river has or can be expected to meander over time. More commonly in recent practice, river corridor has been used to designate a management area in which a river is allowed to move and meander over time. The State of Vermont, for example, uses the term river corridor to designate the minimum area that allows a full suite of river and floodplain processes that can maintain

geomorphic equilibrium, i.e. no net erosion or deposition. Geomorphic erosion and deposition can be major hazards to infrastructure, farms, and other human investments, so maintaining geomorphic equilibrium promises fewer of these hazards. The state aims to maintain river and stream geomorphic equilibrium as much as possible by protecting river corridors from most kinds of development (Kline and Cahoon, 2010 and Vermont Rivers Program). While the Vermont river corridor is based on a modelled river meander belt, other existing features may be appended through expert analysis, such as oxbows, chute cut-offs, avulsion channels, and land-slide areas. Vermont's river corridor may also be shifted around immutable human investments such as highways and railroads (i.e. those where current river position and alignment will be maintained over time) which may be protected in the future by some kind of bank armoring (see example in **Figure 1d**, where the river bank next to the road would likely be armored). A degree of vulnerability remains, but confidence is higher that this armoring would be relatively stable thanks to the geomorphic equilibrium maintained in the adjacent corridor (Mike Kline, *personal communication*). In contrast to the RPC, then, the Vermont river corridor, because it is often used as a regulatory zone, generally encompasses a narrower area, at times deliberately excluding some areas that might be susceptible to natural river and floodplain processes, in order to minimize the regulated area and demarcate only the minimum area necessary to maintain geomorphic equilibrium.

Finally, other terms are roughly synonymous with the term river process corridor in that they also allude to a river's dynamic nature. Like the RPC, "freedom space for rivers," (Biron et al., 2014; Buffin-Belanger et al., 2015), "fluvial territory" (Ollero, 2010), the "erodible corridor" (Piegay et al., 2005) and the Colorado Flood Hazard Zone (funded by SB 15-245 in 2015; worked with ASFPM, 2016; for factsheets and interactive maps see CHAMP, 2013; regulatory memo drafted by Olsson Associates, 2016) are methods for delineating a river process corridor. They propose that by defining a territory that contains much of the river dynamics within a limited zone, they might allow relatively safe human development outside this area. These delineation methods hope to produce maps that may be eventually adopted as regulatory or management zones, and, in like the Vermont river corridor and in contrast to the RPC, they may exclude some areas that would be naturally susceptible to river and floodplain processes. Instead, they assume that armoring will protect these areas if the river has sufficient space to accommodate its processes in adjacent areas. The zone's goal is not to be all-encompassing but rather just wide enough to maintain desired processes.

The River Process Corridor Modular Assessment Method grew out of the UMass RiverSmart Communities project, an interdisciplinary research-and-outreach program begun in 2012 that uses the science of fluvial geomorphology; an understanding of human communities, policies, and management; and active outreach and engagement with stakeholders, to better manage New England's rivers in ways that promote ecological health and community safety and resilience. In 2016, RiverSmart Communities published a policy report with five recommendations. The top recommendation was to develop fluvial hazard assessments (Vogel et al. 2016). Concurrently, the RiverSmart Communities project assembled a Fluvial Geomorphology Task Force (FGM Task Force), comprised of a UMass steering committee and about 30 river specialists representing academia, consulting, regulatory and conservation agencies, and government at local, state and federal levels from Massachusetts and neighboring states. The FGM Task Force synthesized the many ways river process areas are defined, delineated and used; evaluated delineation strategies, and created a roadmap for what an optimal strategy should contain (Warner et al., 2018). In dialogue with the FGM Task Force, this study was sponsored by the US Fish and Wildlife Service (USFWS) and North Atlantic Landscape Conservation Cooperative (NALCC) to investigate a

delineation method that could be performed consistently across the entire NALCC region across the Northeastern U.S. The NALCC region spans 13 states—along the Atlantic coast from Virginia to Maine plus West Virginia and Vermont. Although the River Process Corridor Modular Assessment Method is developed with the NALCC region in mind, it is our intention that this method could be applied across the U.S. and beyond. Like the Washington Channel Migration Area and The Nature Conservancy's Active River Area, the RPC encompasses nearly all areas naturally affected by river and floodplain processes (a schematic representation is shown in **Figure 1e**). An RPC may include cities and towns, highways, farms, and buildings. Accordingly, it is important to emphasize that the purpose of an RPC map is to inform, not to regulate. Development of the RPC proceeded according to the following scientific goals, many of which were articulated with the RiverSmart FGM Task Force.

DEFINITION & DELINEATION GOALS:

The RPC method and maps:

1. Are scientifically based, with delineated geographic areas defined by the areas in which river and floodplain processes occur;
2. Encompass nearly all river and floodplain processes and thus can be predict the vast majority of past and future erosion, deposition, channel migration, near-channel landslides and other river-related geomorphic processes;
3. Include the river process areas that are most likely to be hazardous under future climate change.

4. Developing the River Process Corridor (RPC): Choosing River and Floodplain Processes

Our first step in developing the RPC is to articulate all of the critical river-related processes. The locations of the processes functionally define the location of the river corridor. The processes we consider are: flooding, river migration, wetland processes, riparian ecological processes, overbank deposition, point bar deposition, bank erosion, avulsion, in-channel deposition, near-channel landslides, and steep terrain processes. These processes were identified as important for inclusion by the RiverSmart FGM Task Force. Different users may vary in what they consider important. The RPC methodology allows for future additional processes to be added for different users of this corridor or to be added as our scientific understanding of the Earth progresses. Such changes are covered in the step to Refine the RPC.

Figure 2 illustrates these processes in a theoretical landscape with two cross-sectional views of two areas in a river valley. Many of the river processes in **Figure 2** are responsible for the transport of water and sediment. These processes also remove, transport, and store pollutants, nutrients, carbon, and other materials which are mobilized with water and sediment movement. The locations of these processes are also likely to be impacted by the removal, transport, and accumulation of pollutants, nutrients, and carbon, because these materials are also mobilized with water and sediment movement (Landis et al., 2012).

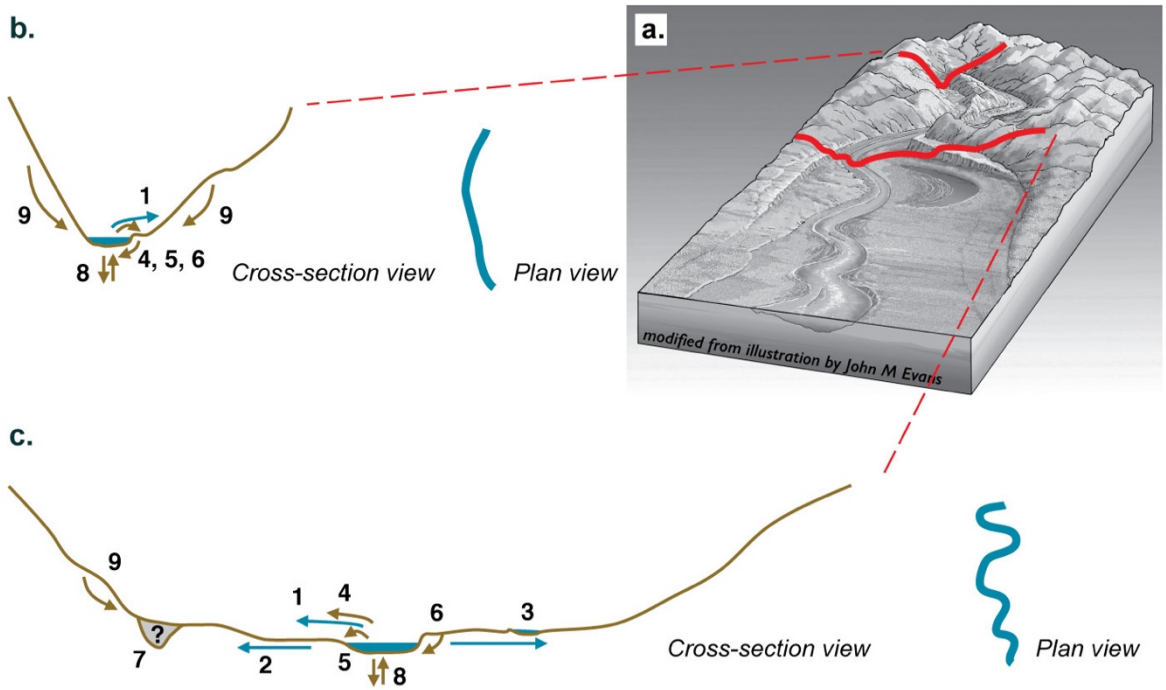


Figure 2. Theoretical landscape **(a)** showing cross-sectional views of river and floodplain processes in **(b)** a narrow, constrained bedrock valley with little alluvium and **(c)** a broad, self-formed valley dominated by alluvium. A plan view of the river at this location is also shown. River processes are identified by number in both c and d, and correspond to the following: (1) Flooding, (2) River migration, (3) Wetland processes including flood water retention and ecosystem services, (4) Overbank deposition, (5) Point bar deposition, (6) Bank erosion, (7) Avulsions, (8) In-channel erosion (incision) and deposition (aggradation), and (9) Landslides, bank failures and debris flows.

We briefly define each of our river processes, which correspond to the numbers in **Figure 2**, as:

- **Flooding** is the process where high waters overtop the channel banks and flow out onto floodplains and other near-channel areas, often with enough force to mobilize sediment and other materials.
- **River migration** occurs as the combination of bank erosion and point bar deposition over time, such that the river channel moves laterally.
- **Wetland processes** occur where frequently saturated soils accelerate biologic processes including the decay of organic matter, the release of sulfur, nitrogen and carbon into the atmosphere, and the removal of nutrients, organic matter, and pollutants from moving water (Novitski et al., 1996). In addition to the ecological benefits, wetlands are low-lying areas that slow down floodwaters and can hold a significant volume of water, mitigating damage downstream (Watson et al., 2016).
- **Overbank deposition** is the process whereby sediment in flood waters settles out of the water column and onto the tops of river banks, floodplains, and other surfaces that are inundated.
- **Point bar deposition** and **in-channel deposition** are processes of sediment settling out of the water column onto point bars (at the inside edge of a curve, bend, or meander, in the river) and channel bottoms, often occurring during, but not limited to high-water events.

- **Bank erosion** occurs both by water-driven sediment removal from channel edges and by gravity-driven slumps that can extend above the water elevation, especially during high water events that undercut banks. Bank erosion typically occurs on the outside edge of a river bend.
- **Avulsion** is the process where an old channel is rapidly abandoned and a new channel is created, often cutting off a river bend. In addition to cutoff avulsions, alluvial fan avulsions can occur when rivers create new, steeper paths down alluvial fans, which are cone-shaped deposits of sediment that can build up where river channels (or valley floors) have a marked decrease in slope.
- **In-channel erosion** occurs when moving water mobilizes sediment, mostly during high water events when transport thresholds are exceeded and the water has enough energy to carry the sediment away.
- **Near-channel landslides** are similar to bank erosion and slumps but larger and can extend several meters above the elevation of flood waters on steep land adjacent to channels and floodplains.
- **Steep terrain processes** such as surface runoff, creep, mass wasting and litter fall can occur adjacent to river channels. These processes create accelerated delivery of sediment, wood, and other materials to rivers even in the absence of landslides.
- Finally, **riparian ecological processes** occur within and adjacent to the channel, floodplains, and nearby wetlands, forming a unique transitional ecotone between wetland and upland areas. Riparian vegetation adjacent to channels delivers carbon, provides shade, protects banks from erosion, traps sediment, consumes and stores nutrients and pollutants, and creates complex habitat at channel margins (Hupp and Osterkamp, 1996; Naiman and Decamps, 1997; Wohl, 2017). Similar to the wetland processes, we feel that the ecological services, flood-wave mitigation, and bank-stabilization that these riparian areas provide to river systems are of critical importance, and should be explicitly included in the RPC. There are other terms for these ecological processes, such as aquatic and floodplain ecological processes, and this unit is intended to capture these as long as they are within or adjacent to the channel, floodplain, and nearby wetlands.

Note that we do not specifically consider anthropogenic processes, nor how these physical and ecological processes may be altered and reshaped by the presence of human-built structures and land use change.

5. Developing the RPC: Definition of Process Units

Because many of these river processes occur in overlapping areas, are driven by similar mechanisms, and operate in similar ways within the fluvial environment, many of these processes can be grouped together. In this step, we organized the river processes into five units that can be mapped together: a) flood process unit, b) landslide and steep terrain process unit, c) wetland process unit, d) channel migration process unit, and e) riparian ecological process unit. Photos depicting examples of these groups of process units are shown in **Figure 3**. Since each process unit is dominated by one or more river process (usually the one for which it is named), this process is highlighted in **Table 1**, where overlapping processes that also occur in this region are also listed.

a

b

c

d

e

Figure 3. **(a)** Flooding of the Saco River in Maine, October 30, 2017, illustrating the inundation associated with the Flood Process Unit. Photo by Andrew Drummond. **(b)** Land sliding and trees collapsing into the Cold River in Massachusetts, illustrating bank failures associated with the Steep Terrain and Landslide Process Unit. Photo by John Gartner. **(c)** A wetland full of floodwater after Hurricane Irene near Orford, NH. Wetland areas connected to river systems are captured by the Wetland Process Unit. Photo by John Gartner. **(d)** The Channel Migration Process Unit represents the meander migration rates and formation of off-channel wet areas such as oxbows over time, illustrated here by Google Earth imagery along the Connecticut River in New Hampshire, near Northumberland, NH (2009). **(e)** Other important aquatic and riparian areas not included in the other units are captured in the Riparian Ecological Process Unit, which can be configured for specific conservation goals. An area off the main channel of Grant Brook near Lyme, NH shown here, photo by John Gartner.

a) Flood Process Unit. This unit intends to capture the many processes that occur only where flood waters reach. These processes include flooding, overbank deposition, point bar deposition, in-channel erosion, and in-channel deposition. The Flood Process Unit also generally overlaps with the area of modern alluvium, which is loose granular sediment deposited by rivers in channels, point bars, and floodplains over the Holocene (approximately the last 12,000 years). Alluvium is unconsolidated, and therefore significantly more erodible than bedrock. Therefore, the Flood Process Unit also characterizes most, but not all, of the areas likely to experience bank erosion, channel migration, and channel cutoff avulsions. (**Figure 3a**. These correspond exclusively to 1, 4, 5 and 8 from **Figure 2**, and also overlap with 2, 3, 6, and 7).

b) Steep Terrain and Landslide Process Unit. This unit intends to capture steep terrain and near-channel landslides that can extend beyond floodwaters and up onto hillslopes and steep areas near streams. These steep terrain processes include overland runoff, creep, mass wasting and litter fall on steeply sloping terrain adjacent to channels and flood-prone areas. (**Figure 3b**. These correspond exclusively to 9 from **Figure 2**, and also overlap with 3 and 6).

c) Wetland Process Unit. This unit intends to capture near-channel wetland processes that may exist within the extent of the Flood Process Unit, but may also extend above and beyond floodwaters. Specifically including these critical wetland habitat areas within the RPC is important both for floodwater dissipation, as well as the intrinsic value and ecosystem services they provide. (**Figure 3c**. These correspond exclusively to 3 from **Figure 2**).

d) Channel Migration Process Unit. This unit intends to capture channel migration, bank failures, and cutoff avulsions, which occur predominantly in the floodplain but may also extend laterally into terraces and other granular and/or unconsolidated deposits. Most channel migration occurs within the bounds of the flooded area due to the low topography and erodible alluvium. However, erodible material, often Holocene or Quaternary glacio-fluvial deposits, may exist adjacent to the floodplain. Thus the Flood Process Unit is not sufficient to include all areas prone to these migration processes, and a Channel Migration Process Unit is warranted. This unit may miss some areas prone to avulsions on alluvial fans. We recognize the importance of alluvial fan avulsions, especially in areas with excess sediment supply, but they are rare on rivers in the North Atlantic region. Alluvial fans are more common in large mountain systems along low order streams in the western US. The refinements described in Step 5 allow for an alluvial fan process unit at specific locations if desired. In addition, this process unit does not specifically address the vertical dimension (e.g. channel incision) or stages of channel evolution, though future refinements could address this also. (**Figure 3d**. These correspond exclusively to 7 from **Figure 2**, and also overlap with 2 and 6).

e) Riparian Ecological Process Unit. This area intends to capture the ecological processes in the riparian zone. The area of these ecological processes is not entirely captured by the process units described above, especially along rivers with flood control and in steep, narrow valleys. In locations where flood control has limited the extent of modern floodwaters, vestigial riparian vegetation communities may exist and provide critical riparian habitat. In steep and narrow valleys, riparian vegetation may extend above and beyond the flood width but still deliver organic matter to channels efficiently and create habitat. Much of the riparian vegetation in the RPC exists within the four other process units, but because riparian vegetation plays such an important role in the RPC and can extend beyond the edge of the other process units, we include it as a separate process unit. (**Figure 3e**. These correspond exclusively to 3 and 9 from **Figure 2**, and also overlap with 3 and 6).

Table 1. River processes included in process units as part of Developing the River Process Corridor: Definition of Process Units

	Process[1]	Flooding	River channel migration	Wetland processes	Riparian ecological processes	Overbank deposition	Point bar deposition	Bank erosion	Avulsion	In-channel deposition	Near-channel landslides	Steep terrain processes
	Process Units[2]	**1**	**2**	**3a**	**3b**	**4**	**5**	**6**	**7**	**8**	**9a**	**9b**
a)	Flood	●	•	•	•	●	●	•	•	●		
b)	Steep/ Landslide				•			•			●	●
c)	Wetland			●								
d)	Channel Migration		●					●	●			
e)	Riparian Ecological			•	●			•				●

Notes:

[1] – numbers correspond to river processes defined in the text above and shown in Figure 1.

[2] –The dominant process(es) within a given process unit are marked with a larger marker "•", and additional processes that occur within a process unit but can also occur elsewhere are marked with a smaller marker "•".

6. Developing the RPC: Establish Mapping Rules

In this step, we developed rules for mapping the five process units. We intentionally designed the procedure to be modular, such that each of the designated process units is independently mapped and summed together with the others. This is for three reasons:

- To help users see and recognize the different river and floodplain processes that provide for value (e.g. ecological migration, riparian habitat, and rejuvenating flood processes) and/or risk (e.g. geomorphic hazard);

- To allow organizations with additional assessments or more detailed data to input their data into the RPC to develop more nuanced or hybridized assessments and maps;
- To allow flexible, piecewise updating as new data become available.

Because of the second and third bullets, the procedure is also iterative: if an improved data set or mapping procedure is developed for a process unit or an individual process, then it can be swapped for the existing rule, remapped, and the resulting area can be summed with the other process unit areas.

The challenge in this step is to choose rules that faithfully represent the five process units and accurately map all of the processes we identified. Moreover, we need data that is widely available, such that river RPCs can be delineated across a large geographic region. In some cases, this means that we are not using the highest-resolution data available (for example, a detailed, reach-scale investigation of the extent of a riparian species of concern, or high-resolution LiDAR elevation data). If refinement is desired for a limited-geographic-scope study, these data could be substituted in.

In general, we favored simple over complex rules, and physically-based rules over empirical rules wherever possible. The protocols do not require hand digitizing, to allow reproducibility and mapping over large areas. In this section, we also describe the potential for future work, model refinements, or other data sources.

Figure 6 illustrates each of the mapping rules described below for the five process units on a schematic drawing of generic floodplain. On top of the same block-diagram drawing, each of the layers, or mapped process units, described below is represented as a translucent colored field, showing the bounds that might be drawn on this map.

a) Flood Process Unit mapping rule: The Flood Process Unit mapping rule is to identify areas subject to inundation. We sought a data set with a physically based representation of areas that are likely to flood over century time scales, which aligns with human time scales on the order of 1 to 100 years (**Figure 6a**). For our purposes, the Federal Emergency Management Agency (FEMA) provides the most widely available geospatial data of flood-inundation areas from hydrologic and hydraulic modeling (**Figure 4**). The 1% Annual Exceedance Probability (AEP)[2] flood extent shows the elevation and width of a flood that has a 1% probability of occurring in any given year at a given location. We've chosen the 1% AEP flood for the Flood Process Unit because it fits with human time scales, and also takes advantage of a common vernacular used for planning purposes among river scientists, engineers, and land managers. There is always uncertainty in delineating areas prone to inundation. Uncertainty arises from sporadic river gaging records, assumptions in hydrologic and hydraulic models, and the resolution of topographic data (Bales and Wagner, 2009). In addition, the magnitude of the 1% AEP flood may increase with land use change, such as increased impervious area from roofs and roads. Land use changes, however, have less of an effect on large magnitude floods like the 1% AEP flood than on moderate floods, like 1.1- to 15-year recurrence interval flood (Pitlick, 1997; Rose and Peters, 2001). Therefore, mapping the 1% AEP will likely include the areas of increasing flood probability due to land use change. Climate change may also adjust the frequency and magnitude of rare flood events, and this is an active area of research that, in

[2] The 1% AEP flood is sometimes misunderstood by non-specialists. It is often called the 100-year recurrence interval flood, but having a 1% AEP flood in one year does not indicate that it will be 100 years until the next 1% AEP flood at that location. Considering broader areas instead of a single location, there is a high likelihood that a "100-year flood" will occur somewhere in the Northeast region every year.

short, shows that hydrologic conditions are changing over time and risk of floods is increasing (Milly et al., 2008; Milly et al., 2002; Rawlins et al., 2012; Yellen et al., 2016). The potential effects of climate change on the RPC are addressed later section, headed “Effects of Climate Change”.

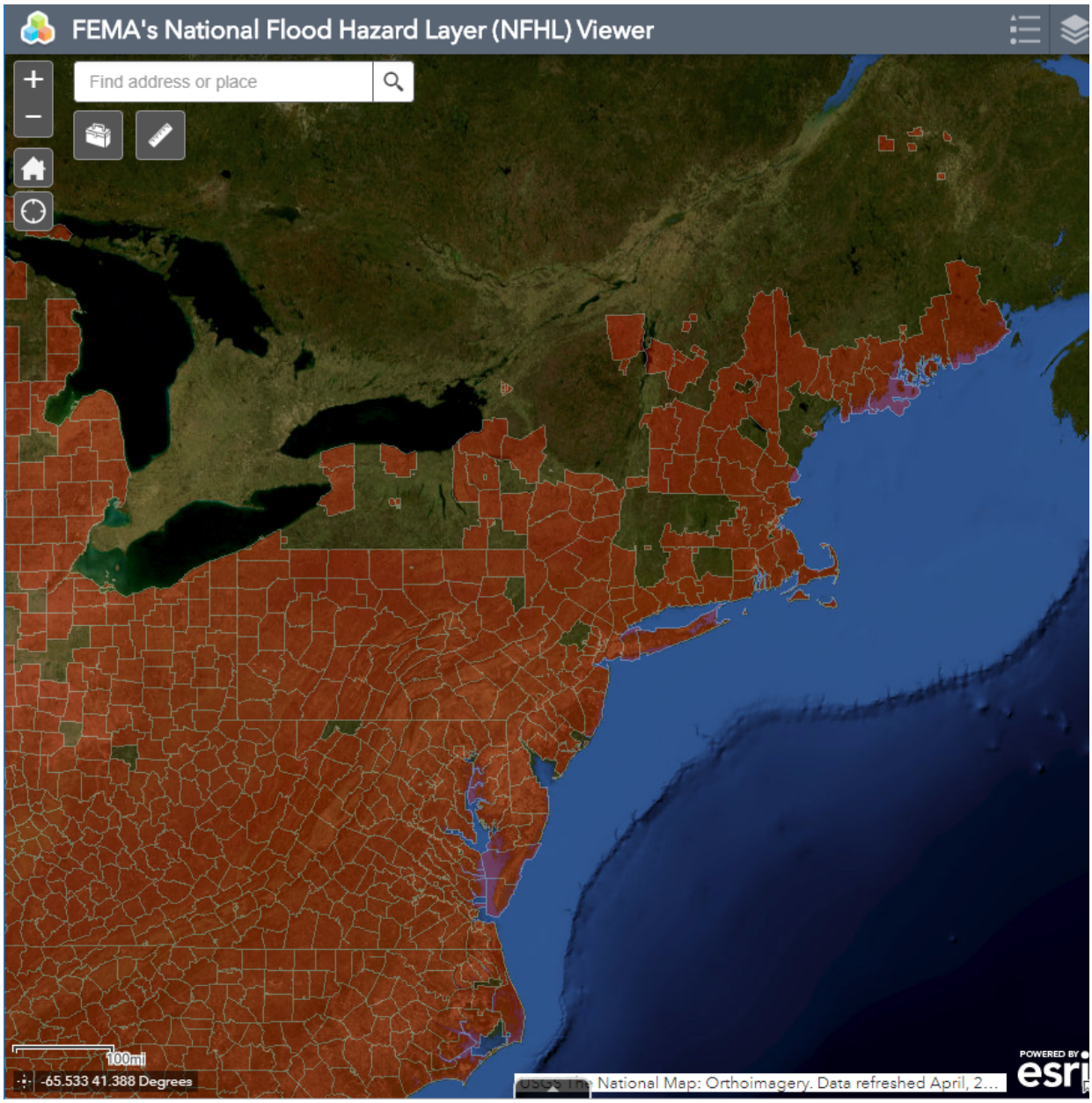


Figure 4. Red areas show available Federal Emergency Management Agency National Flood Hazard Layer (FEMA NFHL) maps in the Northeastern region of the U.S. as seen in the FEMA NFHL viewer. Note, there are some areas with no coverage.

Another source of uncertainty is that flood models represent a snapshot in time, and may not capture locations prone to floods as a river channel migrates, floodplains widen, or river discharges change. Incised channels may have a 1% AEP flood width that is substantially narrower than a channel not incised. Incised channels are prone to rapid geomorphic change, thus likely to have a changing width of

the 1% AEP. Some of the optional methods for mapping floodplains described below may overcome the limitations of the FEMA data snapshot.

It is for this very reason—the uncertainty of flood prone areas in future conditions—that prompted the development of the RPC and other river corridor methodologies. And it is likewise for this reason that the RPC includes more than just the flood process unit. Nonetheless, the 1% AEP flood provides critical information for predicting processes that will occur in the future and have rarely been observed in the past.

Data and Procedure: We use the FEMA Special Flood Hazard Area (SFHA) in the National Flood Hazard Layer (NFHL) database (https://msc.fema.gov/portal/home), and extract the polygons labeled as "T" in SFHA_TF column of the attribute table of the S_Fld_Haz_Ar layer. These polygons equal the Flood Processes Unit area.

Future Work, Model Refinements, or Other Data Sources: The widespread availability of FEMA maps is a major advantage for consistent mapping of RPCs across large regions. **Figure 4** shows the availability of FEMA flood data across the NALCC region. One limitation is that FEMA maps were not created for all areas. For example, roughly the western half of Massachusetts is not covered. Even in regions that are covered, the FEMA flood data typically do not show flood areas for small rivers, such as 1st and 2nd order streams. A second limitation is that the accuracy may be low when conditions have changed since maps were created. FEMA maps are being continually refined and improved by FEMA and private consultants.

We tested using surficial geologic maps in this area, because they show modern alluvium (yellow on surficial geologic maps, e.g. Massachusetts maps by Stone et al., 2018; **Figure 5**). However, the mapped alluvium often includes both the floodplain and the first stream terrace. So using the modern alluvium polygon from this source was often overly wide.

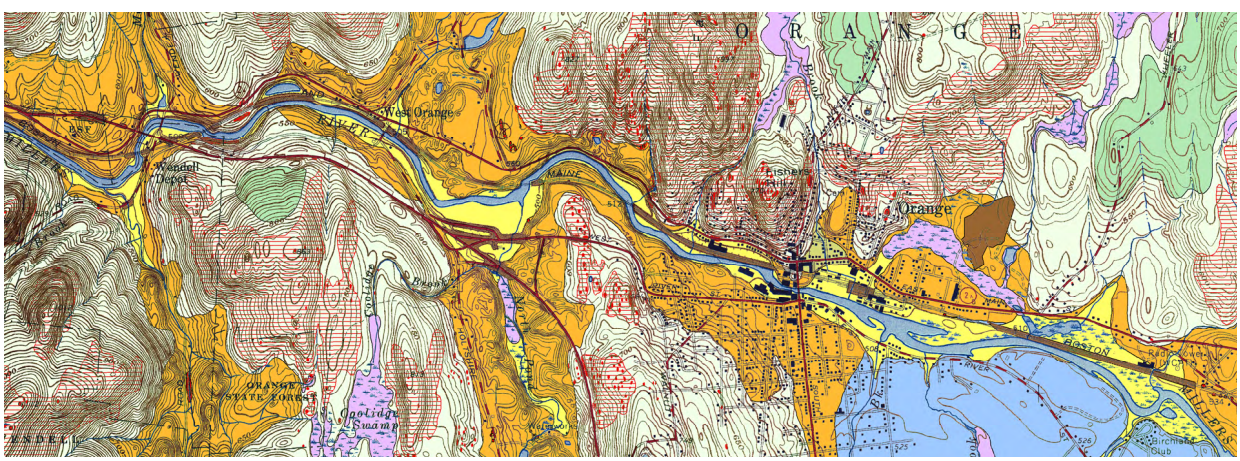


Figure 5. Segment of the Miller's River (blue) in Orange, MA showing the surficial materials mapped on top of the USGS topographic quadrangle map. Note that the alluvium (yellow) on either side of the river is a reasonable analog for flooding area. Clipped from Stone and DiGiacomo-Cohen, 2018 (quadrangle 54).

In addition to FEMA flood data, other options exist to determine probable flood extents. For example, computer generated maps derived from satellite elevation data show very good correspondence with FEMA maps (85-90% for 30-m and 1-km resolution data), do not skip headwaters, and do not require on-the-ground mapping and updating (Wing et al., 2017 and Sampson et al., 2015).

One emerging method utilizes soils data from the soil survey geographic (SSURGO) database to map the active floodplain where no flood studies have been conducted (Sangwan and Merwade, 2015). When did not have satisfactory results when we tested using soil survey data to delineate flood areas along the Nashua and Nissitissit Rivers in Pepperell, MA.

The USGS is creating flood-inundation maps in cooperation with FEMA in selected reaches (Bent et al., 2015; Lombard and Bent, 2015) as part of the Flood Inundation Mapping Program. These modeling efforts utilize high water marks from recent large floods, field-surveyed cross sections, and high-resolution topography from LiDAR to make very accurate maps of inundated areas in recently-flooded locations. These refinements are often incorporated directly into the FEMA data available online.

Another modeling option is to use HEC-GeoRAS, a hydraulic modeling program developed by the U.S. Army Corp of Engineers, in places where LiDAR data are available. This uses a method similar to the recent USGS efforts but without field data of the underwater stream bed or high-water marks. The modeled results are less accurate than the recent USGS efforts, with likely wider modeled flood areas. The procedure is not applicable for regional scale analysis because it is too time intensive to achieve suitable results, nor is it possible in areas without LiDAR data (Gartner et al., 2016). The accuracy is also not acceptable for the standards of FEMA maps that establish flood insurance rates. Yet the accuracy can be suitable for the planning purposes of reach-scale RPC delineation at sites of interest.

Another emerging option is to extract floodplain extents from topographic analysis of LiDAR data. Floodplains can be identified using automated extraction programs in areas with relatively flat surfaces that are slightly higher than channel elevations (Clubb et al., 2017; Samela et al., 2018). Initial results show good agreement with FEMA mapped flood areas. The limitation of this option is that LiDAR data are likely forthcoming (Massachusetts recently released data for the entire state) but not yet available to the public for the entire NALCC region.

At present, floodplains have been mapped globally using Shuttle Radar Topography Mission (SRTM) digital terrain data, but the data are too coarse of a resolution to be useful for the RPC (Nardi et al., 2019). The flood-prone areas are mapped in a grid pattern with 250-m resolution. This approach could potentially be used with finer resolution topography data to provide maps appropriate for the RCP.

Despite these alternatives to mapping flood-prone areas, at the time of this publication, FEMA data are the best available information, mapped consistently over most of the North Atlantic region, to show areas susceptible to beneficial and hazardous flood-related processes.

b) Steep Terrain and Landslide Process Unit mapping rules: This rule aims to map all river-adjacent land areas (within reasonable bounds) with slopes steep enough for rapid transport of materials downslope, using a slope angle that is a conservatively low estimate of the angle of repose, angle of internal friction, and the typical failure surface angle of landslides (**Figure 6b**).

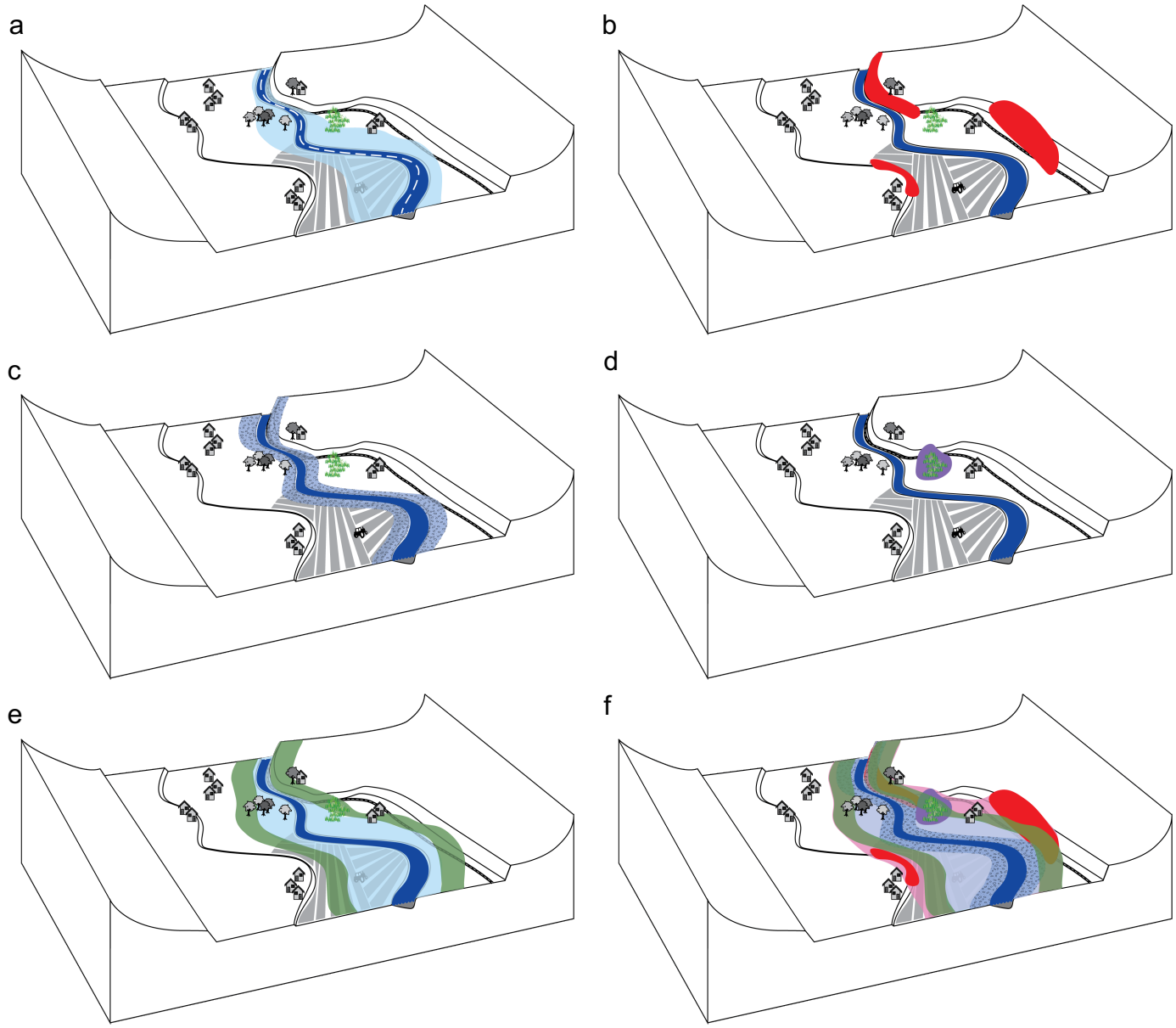


Figure 6. Schematic representation of how the five Process Units theoretically might appear on a generic floodplain as part of the River Process Corridor Modular Assessment Method (RPC). **(a)** Flood Process Unit. Note that this light blue inundation area barely extends beyond the banks of the deeply incised channel toward the top of the diagram, **(b)** Steep Terrain and Landslide Process Unit (red), **(c)** Channel Migration Process Unit (stippled blue), **(d)** Wetland Process Unit (purple), **(e)** Riparian Ecological Process Unit, and **(f)** the total River Process Corridor (RPC; pink), the sum of the five process units (these cover the same area shown only in outline in **Figure 1e**).

Data and Procedure: Include topography with a slope greater than 20 degrees and within 60 m (laterally) of the Flood Processes Unit. The data source for topography is the 1/3 arc-second Digital Elevation Models (DEMs), approximately 10-m grid size, from the USGS National Map (Gesch et al., 2002).

We set the 60 m lateral distance based on observations of near-channel landslides triggered by Tropical Storm Irene in Vermont and Massachusetts (Dethier et al., 2016; Gartner et al., 2015). We did not aim to capture every landslide across the entire landscape, but rather, specifically those landslides that were thought to have been caused by bank-undercutting, slope toe erosion, and other similar river-driven processes. Some steep slopes adjacent to channels extend continuously beyond 60 m, but the channel-proximal locations have more rapid and efficient delivery of materials than distal locations. The procedure fits with the guiding principles of being physically-based, simple, and easily reproducible.

Future Work, Model Refinements, or Other Data Sources: One shortcoming of this rule as currently configured is that steep areas are only captured if they are twice as wide as the resolution of the DEM, which would be more than about 20 m wide when using ubiquitous 1/3 arc-second DEMs from the USGS. As a result, the mapping rule may lead to missing some areas susceptible to landslides and other steep terrain processes. If the RPC were to be mapped for a smaller geographic area, however, where LiDAR or other high-resolution terrain data were available, a more granular representation of these steep terrain processes could be captured. On the other hand, because there is some overlap in the physical spaces where different processes occur, the Riparian Ecological Process Unit and Channel Migration Process Units are likely to also capture the steep terrain processes in areas less than 20 m from the channel.

Other more complex rules are available for mapping steep terrain processes. For example, stream power gradient analysis of large storm events shows that landslides and other steep terrain processes are more likely in river reaches that have downstream increases in stream power, modeled in GIS from 10-m digital elevation models (Gartner et al., 2015). An additional refinement could be to add a layer of analysis to the steep processes mapping rule to only include areas with downstream increasing stream power.

Another example of a more complex algorithm is a GIS-based model that predicts landslide locations in Massachusetts based on slope angle, soil properties, the angle of internal friction, cohesion, and wetness (Mabee and Duncan, 2013). Some elements of this work could also be included in this mapping rule. Even though the GIS-land failure model is potentially more accurate than the simple approach that we use here based on slope and distance alone, it was not parametrized for regions outside Massachusetts (originally developed for North Carolina), and lumps many values into a single, weighted parameter, reducing the method's flexibility. It may also give a false sense of accuracy for other regions within the NALCC, especially locations with different geology and glacial history.

c) Wetland Process Unit mapping rule: This rule is intended to include all known and mapped wetlands adjacent to the river within a reasonable distance (**Figure 6d**).

Data and Procedure: Include all wetland polygons in the National Wetland Inventory (NWI) database (Wilen and Bates, 1995) that intersect within 5 m of the flood process unit or intersect within a 5 m of the channel. The channel locations are obtained from the National Hydrography Dataset Plus High Resolution (NHDPlusHR) dataset (McKay et al., 2012). Specifically, we use the "Wetland" layer from the wetlands database, and the "NHDflowline" and "NHDArea" layers from the NHDPlusHR geodatabase. The NHDPlusHR dataset provides geospatial data of channel centerlines and channel areas, available for download at (https://nhd.usgs.gov/data.html). The original source is the USGS 1:24,000-scale printed topographic maps, which have a locational accuracy standard requiring ninety percent of well-defined

features to lie within 40 ft of their true geographic position based on the date of collection. As with any large dataset, these data are not a perfect representation of the drainage network, but ongoing efforts to publish NHDPlusHR data across the U.S. have improved the accuracy of these products. NHDPlusHR data mimic the depiction of streams and rivers of the printed topographic maps. Blue lines show centerlines of all streams and rivers. Blue polygons show the channel extent only of rivers greater than a few meters wide (such as the Connecticut River, as shown in Figure 5c). The buffer is applied starting from the channel edge for larger channels where the NHDPlusHR dataset depicts the channel area, and from the channel centerline for channels less than a few meters wide where the NHD dataset depicts that channel location only as a line. Because the buffer we use is applied to the centerline for very small streams, not the channel edge, this could potentially underestimate the buffer by a few meters.

The NWI is a digital database of wetlands developed and maintained by the USFWS, available for download at https://www.fws.gov/wetlands/data/data-download.html. Wetlands were initially mapped for most of the coterminous U.S. using mid-1980's color infrared photos from high-altitude aerial photography (Cowardin et al., 1979). Digital data of wetland locations are available for 81% of the U.S, and 100% of the continental U.S. The NWI is now being updated at a rate of 2% per year.

Future Work, Model Refinements, or Other Data Sources: As with any digital dataset of land surface characteristics that cannot be directly observed, there are errors and inaccuracies. Local wetland delineations are often conducted for land use permitting and may include more accurate data or detail than the NWI database. However, for broad-scale delineation of RPCs, the NWI is a fortuitous and broad-reaching dataset. For the reach scale delineation of RPCs, it may be preferable to use more detailed wetland map data based on field observations of soils, hydroperiods, and vegetation.

In theory, stream centerlines could be detected from computer-generated digital elevation models from highly accurate data sources such as LiDAR or Unmanned Areal Sensors, but in practice, and especially in flat terrain, the NHDPlus data have been quality controlled and tend to be much more accurate.

Some states, such as Vermont and Massachusetts, maintain additional inventories of wetlands that are regulated under state statutes in addition to federal laws. These do not necessarily share consistent database formats, but could be added to improve this process unit for smaller regional studies.

In addition, it is worth noting that despite its vast coverage, the National Hydrography Dataset Plus High Resolution (NHDPlusHR) dataset has limited coverage of headwater streams, which was studied in detail by Villines et al. (2015).

d) Channel Migration Process Unit mapping rules: The mapping rule for channel migration is to capture an area large enough to accommodate present and future migration of the river channel. The challenge for the channel migration process unit is that it is extremely sensitive to the condition (e.g. channel location) that comes immediately before the prediction, and becomes less accurate with time after that. While this problem is widely recognized, few solutions are forthcoming. A productive collaborative effort to address specifically erosion hazards from rivers has produced a helpful and informative white paper (ASFPM, 2016). Future solutions notwithstanding, for the present version of this mapping rule, we propose that most channel migration occurs predominantly in the alluvial area, which also corresponds to the Flood Process Unit. But channels can be close to the boundary of the flood unit, perhaps abutting the edge of historical river terraces that are high enough not to be mapped as flood-prone, but still comprised of easily erodible and/or unconsolidated material. A margin of safety is

therefore needed to help capture this type of bank erosion (particularly prevalent in incised streams) and migration processes beyond the flood area. To do this, we take the mapped channel edge, and add an additional buffer to it. The buffer plus the Flood Process Unit captures the likely meander migration area (**Figure 6c**).

Data and Procedure: Compute a 40 m buffer from the channel edge in the NHD dataset, and combine this area with the area of the Flood Processes Unit to delineate the Channel Migration Processes Unit. The channel edge in the NHD database is described in the Wetlands Process Unit rule.

Future Work, Model Refinements, or Other Data Sources: This rule is guided in part by the goal of keeping mapping rules simple and as straightforward as possible, so that RPCs can be mapped efficiently over large regions. River migration is a very complex process to predict, with a large range of migration rates in different settings. Rates of average bank retreat range from 0.0 to 7.3 meters per year in locations in the U.S. and Europe (as observed by Knighton, 2014). The rate of river migration is influenced by channel curvature, channel width, erodibility of adjacent material (consider bedrock versus sand, as well as variability in riparian vegetation), and the sequence of storm events (Buraas et al., 2014; Hickin and Nanson, 1984; Schwenk et al., 2017). Not only are these factors highly variable naturally in any given watershed, but also these factors are highly influenced by human activities that straighten channels, reinforce banks, remove riparian vegetation and woody debris, and curtail flood flows. If we then add within-watershed variability, and climate change to the equation, the complexity of river migration quickly gets computationally expensive and infeasible.

While in theory it is possible to use existing bank retreat rate data to determine and model likely or potential meander migration, the process of doing so may be inordinately time consuming, data intensive, and poorly constrained. One might be tempted to use a maximum known migration rate as a "worst case scenario", but it would not be appropriate to compute a channel migration area by assuming that rivers could migrate laterally at a rate up to 7.3 m per year. This approach would equate to 730 m swath on each side of the channel over a century timescale! Furthermore, it would not be accurate: rivers do not simply move laterally in the same direction indefinitely. Instead they meander back and forth, typically across the area of modern alluvium. In addition, as noted above, the best predictor of where the channel will move next, is where it is now – and over 100 years, that position (and our ability to predict it) can change significantly (see **Figure 10**).

Other approaches to predict areas of channel migration exist, but they are better suited for analysis of a single reach or a single river rather than region-wide predictions. Recent studies have used channel curvature together with channel width and erodibility of adjacent materials to predict the rate of river migration (Buraas et al., 2014; Schwenk et al., 2017). This approach can produce accurate predictions, but it is data intensive and highly dependent on initial conditions. Another approach is to assume that future channel migration will follow in a similar area as past river migration, and use historic maps of former channel locations to estimate a historical meander area. Many methods of river assessment utilize the historical data approach to varying degrees (Washington State's program relies heavily on it, for example; Rapp and Abbe, 2003a). While time- and data intensive, and dependent on sometimes limited historical maps or imagery, this approach can yield very helpful maps. What it does not often address are the human-built infrastructure and impingements that accumulate in the floodplain over time that are unlikely to change in the future, e.g. a major interstate, but historical information gives

great insight into the width needed to accommodate the river's natural movements in the absence of these features.

Incised channels can result from urbanization, grazing, or other watershed changes that alter the balance between sediment transported into and out of river reaches. After incision, rivers are prone to bank failure. The area prone to these bank failures could extend beyond the limits of the RPC Flood Processes Unit, but would likely be included in the Channel Migration Unit and the Landslide and Steep Processes Unit. Channel incision, or vertical erosion, would be unlikely to change the 2-dimensional map view of the stream. In systems where upstream sediment supply is significantly less than the sediment transport, erosion can cause vertical change in the channel height. Rivers downstream of dams that trap sediment may be "sediment starved".

As part of the development of the threshold values for the Channel Migration mapping rule, we explored using a different algorithm for determining the buffer width. Initially, we applied the 40 m buffer because it mirrored the Massachusetts Clean Water Act buffer width for pristine streams and effectively captures large regions surrounding headwaters, which are important upland habitats. That said, we recognize that 40 m might be disproportionately large for very small streams, and so we experimented with a buffer that scaled up with increasing channel width. Unfortunately, channel width estimation also presents challenges and potential inaccuracies. Channel width can be estimated from regional curves that relate drainage area to channel width. Deciding which regional relationship to use, and how to flag an automated program to use the correct equation presented a problem, since there are more than 20 published studies on regional relationships across the 13 states in NALCC area (Bieger et al., 2015). As we discovered, the analysis quickly became more complex and computationally intensive without clear improvements in accuracy, so it was abandoned, but could be revisited at a later date.

Other approaches to determine the likely area of channel migration exist that utilize channel curvature, channel width, erodibility of adjacent material and/or critical stress calculations to predict channel movement. But, neither of these are easily automated, independent from initial conditions, or widely applicable across a geographically and geologically diverse region.

This process unit could also be replaced by a locally-derived, locally-relevant zone subject to narrower jurisdictional bounds (e.g. a single state), such as the Vermont River Corridor, the Washington State Channel Migration Zone, or the Colorado Flood Hazard Zone (Kline and Cahoon, 2010; Vermont Rivers Program; Rapp and Abbe, 2003a; ASFPM, 2016; CHAMP, 2013; Olsson Associates, 2016). In addition, theoretical layers such as "freedom space for rivers" (Biron et al., 2014; Buffin-Belanger et al., 2015), "fluvial territory" (Ollero, 2010), or the "erodible corridor" (Piegay et al., 2005) would also fit the definition of the Channel Migration Process Unit.

e) Riparian Ecological Process Unit mapping rules: The mapping rule for the Riparian Ecological Process Unit is to capture the unique riparian area ecology by adding a buffer to the existing mapped river channel edge. This step allows practitioners a particular process unit within which to define a parameter of interest and include it in the total RPC to suit their specific needs. Here, we define the riparian area as the vegetated strip adjacent to channel and floodplains comprised of diverse and complex habitat for many species. This area also helps stabilize river banks, slow down high flood flows, and filter pollutants through overland flow.

Data and Procedure: Add a 40 m buffer from the channel edge (the channel edge as defined by the NHD database is described in the Wetland Process Unit rule). This buffer is combined with the Flood Process and Wetlands Process Units to create the Riparian Ecological Process Unit (**Figure 6e**).

Natural and human-altered waterways exhibit great variability in the distance that riparian vegetation extends from the edge of channels and floodplains, and the value of 40 m is supported by studies that have examined or proposed riparian buffers of 10 to 40 m (Castelle et al., 1994; Fischer and Fischenich, 2000; Lee et al., 2004; Micheli et al., 2004). Other existing river protection programs use a variety of setbacks or buffers, ranging from 7 to 22 m, including the USDA Conservation Reserve Enhancement Program (10 to 55 m), Massachusetts River Protection Act (15.2 to 61 m), Vermont Small Stream Setback (15.2 m) the Wild and Scenic River Act (75 to 122 m). We recognize that riparian ecologic processes are diverse, and the locations of these processes are difficult to predict and/or data and time intensive to measure.

In practice, this mapping rule ensures a minimum 40 m buffer on all streams, even if there are no wetlands, steep areas, or flood extents mapped along a given reach. This may not capture the extent of ecologic processes perfectly, and there is the possibility that riparian ecological areas exist outside of the 40 m buffer from the channel, but we must select a value for practical purposes, so we've chosen a very inclusive value, one of the larger included in published studies.

Future Work, Model Refinements, or Other Data Sources: More sophisticated, and potentially more accurate, methods exist for designating the location of crucial, existing riparian species. Detailed field studies of specific species, remote sensing analysis, and ecologic modeling can be conducted at specific sites of interest. For example, the USFWS has developed methods for delineated riparian areas in arid regions based on vegetation abundance (USFWS, 1997) but these strategies are not as applicable in humid areas with more abundant vegetation in both riparian and upland areas.

Historical human settlement sites are often found along rivers and on abandoned river terraces. Because river terraces are often comprised of the easily-erodible unconsolidated materials that make up the riverbed, these historical resources can be very vulnerable to getting eroded away. While not explicitly "Riparian Ecology", this kind of archeological resource is an example of the kind of user-defined parameter that could be added to this mapping rule to map and protect a resource of interest.

7. Developing the RPC: Combine polygons to create RPC

Overlaying the process units is a straightforward step completed in ArcGIS or other GIS programs. The work flow is depicted in **Figure 7**. Essentially, the channel area, flood area (a), steep/landslide area (b), wetland area (c), channel migration area (d), and riparian ecological area (e) are combined into a single polygon that is the sum, or union, of all five of these areas.

Once completed, we smooth the edges. The summed polygon often has some sharp edges, rough pixelated corners, and small holes along its boundaries. If left as-is, this would create the impression that the map has a very high degree of precision, even if many of the pieces are estimates. In addition, floodwaters will not "skip" a pixel even if it is a tiny bit higher in the middle of a flooded area. In ArcMap, we apply a positive 40 m buffer then a negative 40 m buffer. The positive buffer first adds a smooth

outline to the total RPC, that is +40 m from the corridor edge. Next we subtract the excess width, but maintain the filling and smoothing, by subtracting 40 m from new smoothed outline. This two-part smoothing step effectively removes the sharp edges, small holes, and pixelated corners along the boundaries, so as not to imply a greater level of precision than is warranted (**Figure 6f**, or, without all of the process unit layers shown, **Figure 1e**).

In addition to generation of the total RPC, we preserve each of the process unit's polygon layers (**Figure 6f**). This way, a user can investigate layers individually, weight the layers differently, or hone in on a particular layer for more fine-tuned assessment or management.

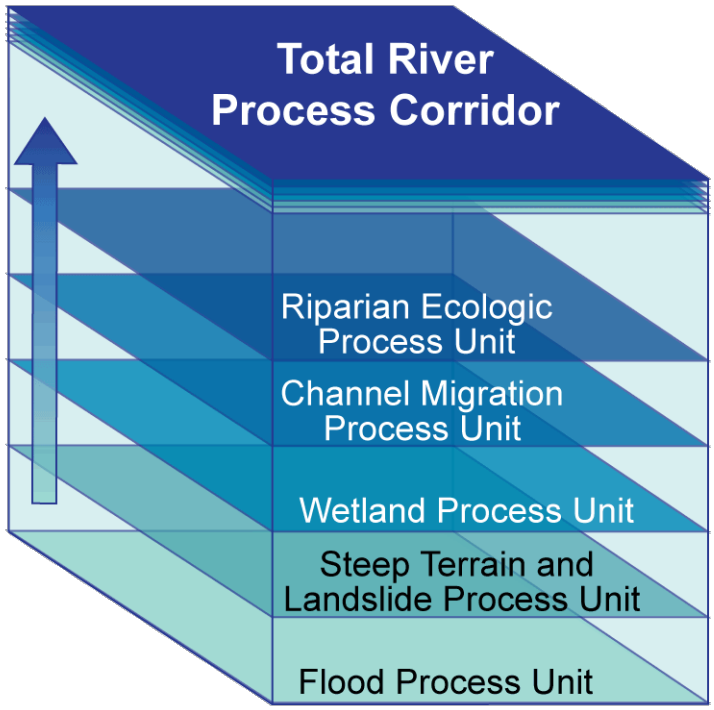


Figure 7. Schematic representation of how individual modular process units are mapped, overlain and summed to form the total River Process Corridor.

8. Developing the RPC: Refine and Modify

Modifications to the RPC can occur in three distinct ways, including (a) improving a mapping rule that is developed for a specific river process, (b) adding an additional river process—and develop an associated mapping rule to add to the analysis, if desired by the users of the RPC, and/or (c) incorporating site-specific knowledge and field evidence to yield higher-resolution data analyses, if desired.

Altering individual rules: The fields of hydrology, geomorphology, and ecology are continually progressing. Some of the progress comes from improved data sets, such as the increasing availability of high-resolution topography in 1-m gridded DEMs from LiDAR. Some of the progress comes from our increased ability to predict future conditions.

The RPC allows integration of improved information because the process units are modular and computer generated. One can update the mapping rule for one of the process units and recalculate the extent of the RPC. One of these possible alterations is using a different, or more precise data source. Others include using an improved model, different equation, or updated methodology for determining that unit. And finally, the least substantial alterations include changing the distances or thresholds used in the GIS algorithm to make the maps. Within each of the Process Units, as well as summarized in **Table 3**, is a discussion of *Future Work, Model Refinements, or Other Data Sources* which addresses this mode of refinement.

Adding process units: The PURE method is not limited to the five process units included here. If land managers were to have a heightened interest in, for example, depicting the habitat for riparian birds within river corridors, a riparian bird movement unit could be added. Other users may have a heightened interest in pollutant transport or geochemical cycling in river corridors. In such cases, a pollutant transport processes unit or a geochemical cycling processes unit could be added with accompanying mapping rules. The delineation procedures we present here do consider these processes, but not in specific detail. Pollutant transport, for example, typically occurs in conjunction with sediment transport (Landis et al., 2012), and our procedure specifically investigates sediment transport.

For cultural resources, users may desire to overlay different historical, recreational, or cultural resources maps with the river corridor. These could be derived according to their own sets of mapping rules, and then added to the total corridor for land management and resource protection.

Site specific information: The RPC allows for finer resolution mapping with site-specific information while still following the general procedure of listing key processes, developing mapping rules, and overlaying polygons. For example, there may be detailed mapping of bank swallow (*Riparia riparia*) nesting habitat or landslides in a particular watershed that could be interjected into the RPC. There may also be reach-scale, watershed-scale, or state-wide mapping of river hazards, such as the channel migration zone used in the Vermont River Corridor or Colorado Fluvial Hazard Zone. This could also be interjected into the RPC, perhaps in the place of or in addition to the river migration process unit.

When we developed this method, we examined a wide range of example watersheds and selected the parameters and thresholds that work best across the northeast region. However, these thresholds could be adjusted for specific regions. For example, a 50-m buffer for the river migration mapping rule could be applied to rivers known to shift especially rapidly. This substitution could improve the accuracy of the RPC for that location. The downside is that the corridor would now be site-specific and not perfectly uniform with regional RPC maps.

9. Using the RPC: GIS steps for practitioners

The preceding sections lay out the conceptual steps that lead to the development of the RPC, including a) choosing river-related processes, b) grouping processes based on similar forcing mechanisms, c) developing mapping rules for each process unit (or process group), d) overlaying the mapped process groups, and e) refinements.

This section shows the GIS steps that a user would follow in order to create their own map of a River Process Corridor (See Table 2). Table 3 lists the data sources that are the inputs for this geospatial analysis. Table 3 also summarizes the limitations of the input data, additional sources of data, some sources of error, and possible refinements for the mapping rule for each process unit.

Table 2. Steps to Map the Total River Process Area by assembling the five Process Units included in the River Processes Area Assessment Method

Step	Action
1	For the **Flood Process Unit**, acquire the FEMA 1% Annual Exceedance Probability (AEP) flood extent from the National Flood Hazard Layer (NFHL) database.
2	Open the attribute table of the S_Fld_Haz_Ar layer, and extract the polygons labeled as "T" in SFHA_TF column.
3	Merge these polygons to complete the **Flood Process Unit.**
4	For the **Landslide and Steep Terrain Process Unit**, acquire the USGS National Map 1/3 arc-second Digital Elevation Model (DEM) for the area of interest.
5	In GIS, identify all areas that have a steep slope within a range of influence of the channel. Default values are slope > 20° that are within 60 m of the outer bounds of the **Flood Process Unit**.
6	Merge these polygons to complete the **Landslide and Steep Terrain Process Unit.**
7	Map the ***stream channel***. Acquire the linear centerlines of mapped small stream channels (NHDflowline) and the filled polygons of mapped larger stream channels (NHDArea) from the USGS National Hydrography Dataset Plus High Resolution (NHDPlusHR).
8	Merge these lines and polygons to complete the ***total stream channel***.
9	For the **Wetland Process Unit**, acquire the wetland layer from the USFWS National Wetland Inventory (NWI) database.
10	In GIS, identify all known and mapped wetland polygons that intersect or are very close to the channel. Default value is wetlands within 5 m of the outside edges of ***total stream channel*** or **Flood Processes Unit**.
11	Merge these polygons to complete the **Wetland Processes Unit**.
12	Create a ***40-m buffer*** from the channel as an intermediate step. Default value is to add a 40-m buffer beyond the mapped edge of the ***total stream channel***.
13	For the **Channel Migration Process Unit** overlay and merge polygons and lines from the **Flood Process Unit**, the ***40-m buffer***, and the ***total stream channel.***
14	For the **Riparian Ecological Process Unit**, overlay and merge polygons and lines from the **Flood Process Unit**, the ***40-m-buffer***, the ***total stream channel*** and the **Wetland Process Unit**.
15	For the ***total river process area***, overlay and merge polygons and lines from the **Flood Process Unit**, the **Landslide and Steep Terrain Process Unit**, the ***total stream channel***, the **Wetland Process Unit**, and the **Riparian Ecological Process Unit**.
16	Finally smooth the outer edge of the ***total river process area***, by applying a positive-40-m buffer on the ***total river process area***, and then a negative-40-m buffer. This creates the **River Process Corridor**.

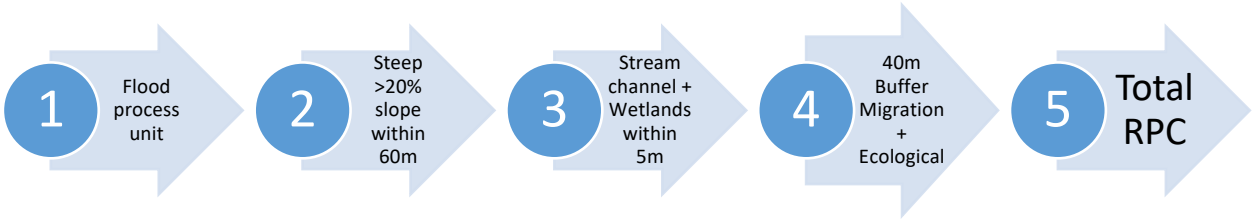


Figure 8. Conceptual Map of Steps for the River Process Corridor.

Table 3. Limitations, Sources of Error, Model Refinements and Other Data Sources for the five Process Units included in the River Processes Area Assessment Method

Process unit	**Data source**	***Limitations and Sources of Error***	***Model Refinements or Other Data Sources***
Flood	FEMA Special Flood Hazard Area (SFHA) in the National Flood Hazard Layer (NFHL) database (https://msc.fema.gov/portal/home)	• Incomplete coverage across entire North Atlantic Region, especially in rural areas • Maps represent a snapshot and may not account for change in land use, climate, channel position, or channel dimensions • streamflow uncertainty • topographic resolution	• USGS Flood Inundation Mapping Program (high water marks from select stream reaches) • USACE HEC-GeoRAS Hydraulic Modeling • State/ USGS/ Geological maps of modern alluvium or soil surveys. • Map floodplain extents from topographic analysis of LiDAR (where available) data using automated extraction programs
Landslide and Steep Terrain	USGS National Map 1/3 arc-second Digital Elevation Models (DEMs), approximately 10-m grid size , (https://viewer.nationalmap.gov/basic/)	Mapping every landslide or steep slope could eventually include the whole watershed – limited to near-channel. Steep areas are only captured if they are twice as wide as the resolution of the DEM, thus are resolution dependent	• LiDAR with 1-m or finer resolution DEM grid may be preferable for site-specific mapping • Stream power gradient analysis: identify river reaches downstream increases in stream power and other risk factors (Gartner et al., 2015) • GIS-based model that predicts landslide locations in MA based on slope angle, soil properties, the angle of internal friction, cohesion, and wetness (developed for NC; could be applied elsewhere) (Mabee and Duncan, 2013).

Table 3. (Continued)

Process unit	**Data source**	***Limitations and Sources of Error***	***Model Refinements or Other Data Sources***
Wetland	USFWS National Wetland Inventory (NWI) database, wetland layer from (https://www.fws.gov/wetlands/data/data-download.html); National Hydrography Dataset Plus High Resolution (NHDPlusHR from https://nhd.usgs.gov/data.html), NHDflowline and NHDArea layers	The original source of the NHDPlusHR is the USGS 1:24,000-scale printed topographic maps. Locational accuracy: 90% of well-defined features lie within 40 ft of their true geographic position based on the date of collection. NWI was mapped using mid-1980's color infrared photos and is updated at 2% per year	• Some states, such as Vermont and Massachusetts, maintain additional inventories of wetlands Site specific mapping can be done by wetland scientists for areas of high concern
Channel Migration	NHDPlusHR, NHDflowline and NHDArea layers; Flood Processes Unit	River migration rates are hard to predict and range from 0 to 7 m/yr. Future locations are extremely dependent on prior locations. The 40-m buffer may be too large for very small streams and could benefit from some width-informed scaling factor. However, in small streams, the 40-m distance is always included in the RPC due to the riparian ecologic unit.	• Map the past meander locations to constrain the historical meander area and assume future migration will remain in a similar area (does not consider accumulation of human-built infrastructure or channel modifications) • Regional studies incorporating channel curvature, channel width, erodibility of adjacent materials, and/or critical stress calculations
Riparian Ecological	NHDPlusHR, NHDflowline and NHDArea layers; Flood Processes Unit; Wetland Processes Unit	This mapping rule is based on locations on where river-related physical processes are common, with the idea that the physical processes create conditions favorable to riparian and aquatic species. This setback is intended to encompass user priorities and ensure that every river, no matter how small, has a minimum mapped buffer. Buffer width and scaling should be determined by specific application.	• USFWS Riparian vegetation mapping (more suitable in arid regions) • Map archeological or other resource of interest and include this in the protected area • USDA Conservation Reserve Enhancement Program (10 to 55 m) • MA River Protection Act (15.2 to 61 m) • Vermont Small Stream Setback (15.2 m) • Wild and Scenic River Act (75 to 122 m)

10. Testing the RPC

Our final step was to perform the previous four steps and map all process units in three locations across the NALCC and then evaluate the delineation method's effectiveness.

Our evaluation criteria were those that guided the development of our approach. We aimed to develop a terminology, method, and mapped area that had the following:

DEFINITION / SCIENTIFIC GOALS:

1. Are scientifically based, with delineated geographic areas defined by the areas in which river and floodplain processes occur.
2. Encompass nearly all river and floodplain processes and thus can be predict the vast majority of past and future erosion, deposition, channel migration, near-channel landslides and other river-related geomorphic processes;
3. Include the river process areas that are most likely to be hazardous under future climate change.

USABILITY GOALS:

4. Are clear and accurate at both large and small geographic scales, across the Northeast United States;
5. Can be performed with readily available data for relatively low cost, consistently and accurately by non-experts;
6. Are modular, with different procedures to map polygons for specific hydrological, geomorphological and ecological processes.

While we can't predict the future, as we generate more maps we can certainly test the effectiveness of our predictions against actual mapped river hazards. Until we have such data, we can test our broad theoretical goals against specific locations where we have these types of data to assess the RPC against. For this purpose, we consider three test locations. First is the Upper Connecticut River watershed on the border of Vermont and New Hampshire (**Figure 9**). We use the site as both an example of how the different layers of mapped process units are added together to create the RPC and as a location to test how well the RPC performs against areas of known changes at the site, especially river migration.

The second site, the Baker River within the White Mountains of New Hampshire, is used to test a rapidly shifting river channel where we have abundant imagery of channel location through time (**Figure 10**).

The third site is the White River watershed central Vermont (**Figure 11**), which experienced extreme flooding during Tropical Storm Irene in 2011. We test how well the RPC, generated from data available before the flood, predicted the location of numerous landslides and floodplain deposition zones during the flood.

*Example 1: Northern Connecticut River Valley (**Figure 9**)*

This test location serves dual purpose. One intent is to exhibit how the different Process Units are mapped and expressed on the landscape. The other intent is to examine how well RPC captures the area prone to channel migration. The site region is a mixture of forest and farmlands, with rolling topography on both sides of the broad Connecticut River valley situated in Haverhill, NH and Newbury, VT.

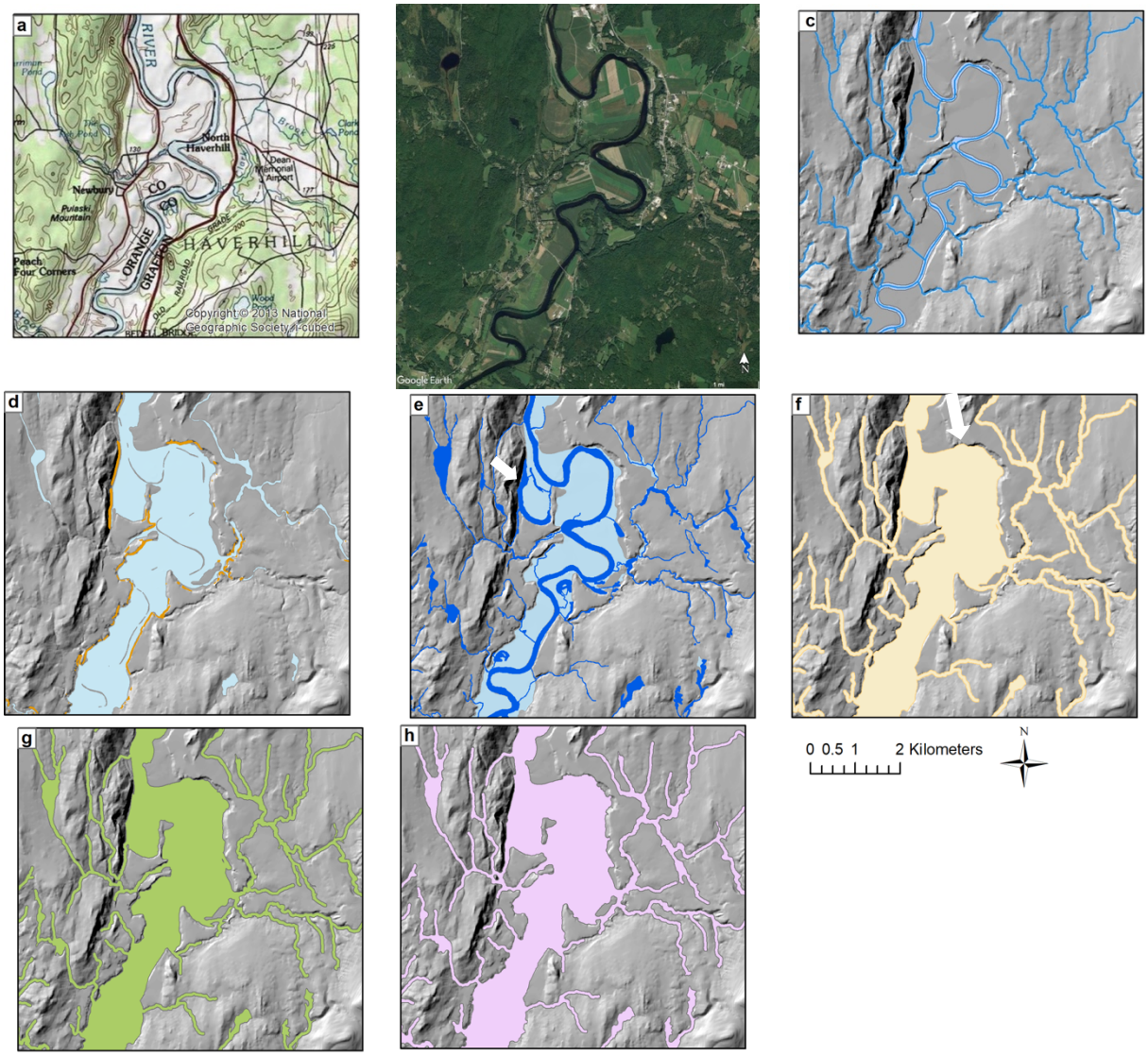


Figure 9. The upper Connecticut River test location near Haverhill, New Hampshire. **(a)** USGS Topographic Map. **(b)** Google earth satellite imagery. Remaining panels all have, as a background the GIS Layer showing USGS Digital Elevation Model (DEM) hillshade basemap, and are overlain by **(c)** the National Hydrolography Dataset (NHD) channel flowlines (dark blue) and, for wide channels, channel area (light blue), **(d)** River Process Corridor (RPC) layers: Flood Process Unit (light blue) and Steep Terrain and Landslide Process Unit (orange), **(e)** RPC layers: Flood Process Unit (light blue) and Wetland Process Unit (dark blue), **(f)** RPC layer: River Migration Process Unit (light yellow), **(g)** RPC layer: Riparian Ecological Process Unit (olive green). The sum of the five process unit layer equals **(h)** the total River Process Corridor layer (pink, on top of NHD channels). Refer to text for a description of arrows in panels e and f.

It contains a mixture of 1st to 4th order tributaries that lead to the 7th order Connecticut River (**Figure 9c**). This large river forms the boundary between Haverhill, NH and Newbury, VT in the test area (**Figure 9a, 9b**). The region was glaciated during the last glacial maximum, and the valley bottom was occupied by post-glacial Lake Hitchcock from approximately 15,600 to 12,900 B.P. (Ridge and Larsen, 1990).

The following five paragraphs describe each process unit at this site. The methods to map and layer the five process units follow the standard procedures without refinements.

The Flood Process Unit (**Figure 9d**)is equal to the FEMA 1% AEP flood extent. It varies in width along the Connecticut River and is discontinuous in smaller tributaries, with no flood extent mapped for the smallest streams. The Flood Process Unit is discontinuous in part because it was derived from the FEMA 1% AEP flood extent map data, which are discontinuous, and in part because the smallest streams have little space for broad inundation and pooling near their origins in steeper areas. The discontinuities in the FEMA source data highlight why a single source can be problematic, and lack coverage in areas of concern. Ideally, we would use additional sources of data such as more detailed hydraulic mapping, surficial geology maps (specifically the location of Quaternary alluvium), or channel and valley-floor dimensions to verify the flood area for the missing areas before moving on to the next unit. However, since we have additional buffers in other Process Units, most of these areas will be filled in through the following mapping steps.

The Landslide and Steep Process Unit (**Figure 9d**) is derived from slope analysis of 1/3 Arc-second DEMs and includes hillslopes greater than 20 degrees that occur within 60 m of the Flood Process Unit. This encompasses terraces on the eastern side of the Connecticut River and other steep hillslopes scattered throughout the view. The unit does not include steep hillslopes adjacent to the smallest tributaries, because of discontinuities in the flood process unit. However, locations of potential steep processes adjacent to small tributaries are effectively included in the total RPC through other overlapping process units such as the channel migration and riparian areas.

The Wetland Process Unit (**Figure 9e**) was derived from the NWI and includes mapped wetland areas within 5 m of the flood process unit or within 5 m of the NHD mapped drainage network. The NWI data generally show present-day channels, for example the present-day Connecticut River channel seen in this figure. Many wetlands within the NWI are in the uplands and do not intersect within 5 m of the channel or Flood Process Unit. While important for ecological processes of wetlands in the overall watershed, these upland wetlands are not included in the RPC because they do not regularly and directly interact with the river nor influence river processes on the human timescales that are the focus of this RPC delineation effort.

The Channel Migration Process Unit (**Figure 9f**) is the sum of the Flood Process Unit plus a 40 m buffer from the channels in the NHD dataset. The buffer is applied starting from the channel edge for larger channels where the NHD dataset depicts the channel area, and from the channel centerline for channels less than a few meters wide where the NHD dataset depicts that channel location only as a line. The white arrow in this panel shows a location where the Connecticut River channel is adjacent to the eastern margin of the Flood Processes Unit, and the 40 m buffer expands the width of the total RPC in this location. The 40 m buffer of the Channel Migration Process Unit also expands the width of the total RPC along the smaller streams which do not have flood-prone areas mapped by FEMA. The Channel Migration Processes Unit also shows narrow sinuous wetlands in some swales that do not have mapped channels in the NHD dataset. Some of these appear as narrow spurs in the total RPC (Figure 5h).

The Riparian Ecological Processes Unit (**Figure 9g**) is the sum of the Flood Processes Unit, the Wetland Processes Unit, and a 40 m buffer on the channel edge. In some areas, such as along the Connecticut River, the 40 m buffer is less than the flood-prone area, and it does not add to the width of the RPC. In

other areas, for example small tributaries without wetlands or FEMA flood-prone areas, the 40 m buffer on the channel edge is as wide as or wider than any other unit.

The ***RPC*** is the combination of all 5 process units (**Figure 9h**) with a smoothing algorithm as the final step. We did no refinements to the RPC. Note that the RPC is a minimum of 40 m wide in all locations with channels mapped in the NHD due to the 40 m minimum of the Channel Migration Process Unit and the 40 m minimum of Riparian Ecological Process Unit.

Another observation is that there is a physically based explanation and a transparent rationale for why areas are included in RPC. For example, a white arrow (**left side of Figure 9e**) near the Connecticut River shows a broad area in the RPC because it is within the area of the Flood Process Unit depicted in **Figure 9d** and is susceptible to flooding via inundation. By examining the component layers, or Process Units, from the RPC, we can easily see that this a wetland (**Figure 9g**), and therefore of interest for the wetland-specific processes present in this location.

How well does the RPC perform against locations of known river corridor processes? The *Channel Migration Process Unit*—which is a prediction of where shifting channel positions may occur—encompasses the former shifting locations of the Connecticut River in this test location. Historic maps and modern aerial imagery show from 0 to 90 m of channel migration in the reach between 1935 and the present. However, the NWI data (**Figure 9e**) show oxbow-shaped wetlands along the Connecticut River Valley that were likely former channel locations, suggesting between 250 and 1000 m of lateral movement. Scroll bars are evident in the aerial imagery (**Figure 9b**) between some oxbow-shaped wetlands and the modern channel.

The spatial domain of the *Channel Migration Process Unit* (**Figure 9f**) encompasses 100% of these features in this 15 km segment of the Connecticut River Valley. The overlap is evidence that channel migration has occurred primarily within the floodplain, within the erodible alluvium, and supports our use of the floodplain as a first order indicator of where channel migration occurs. Regarding future conditions, this site also exhibits areas where the 40-m buffer in the Channel Migration Process Unit is intended to account for possible migration into erodible terraces which may lie above the elevation of the flood-prone areas mapped FEMA (white arrow, top of **Figure 9f**). Locations like this terrace are precisely why the 40-m buffer term is included in the *Channel Migration Process Unit*.

*Example 2: Baker River (**Figure 10**)*

This second test location (Figure 10) was chosen to assess the accuracy of the Channel Migration Process Unit in an active setting where the channel position changes frequently. The site is located along an approximately 1.5 km reach in Warren, NH where the Baker River transitions from the steep headwaters on the flanks of Mount Moosilauke to less steep terrain in a broader valley. In some places the river is braided, an indication of high sediment loads.

To assess how well the RPC performed in an area with a rapidly shifting channel, we digitized the channel locations over the last 25 years from historic imagery available from Google Earth (1993, 2003, 2011, and 2013) and ESRI (2015). To delineate the RPC, we used the standard procedure without refinements to the method. We used no site-specific information to adjust be boundary of the RPC. **Figure 10** shows the former channel locations and the extent of the RPC.

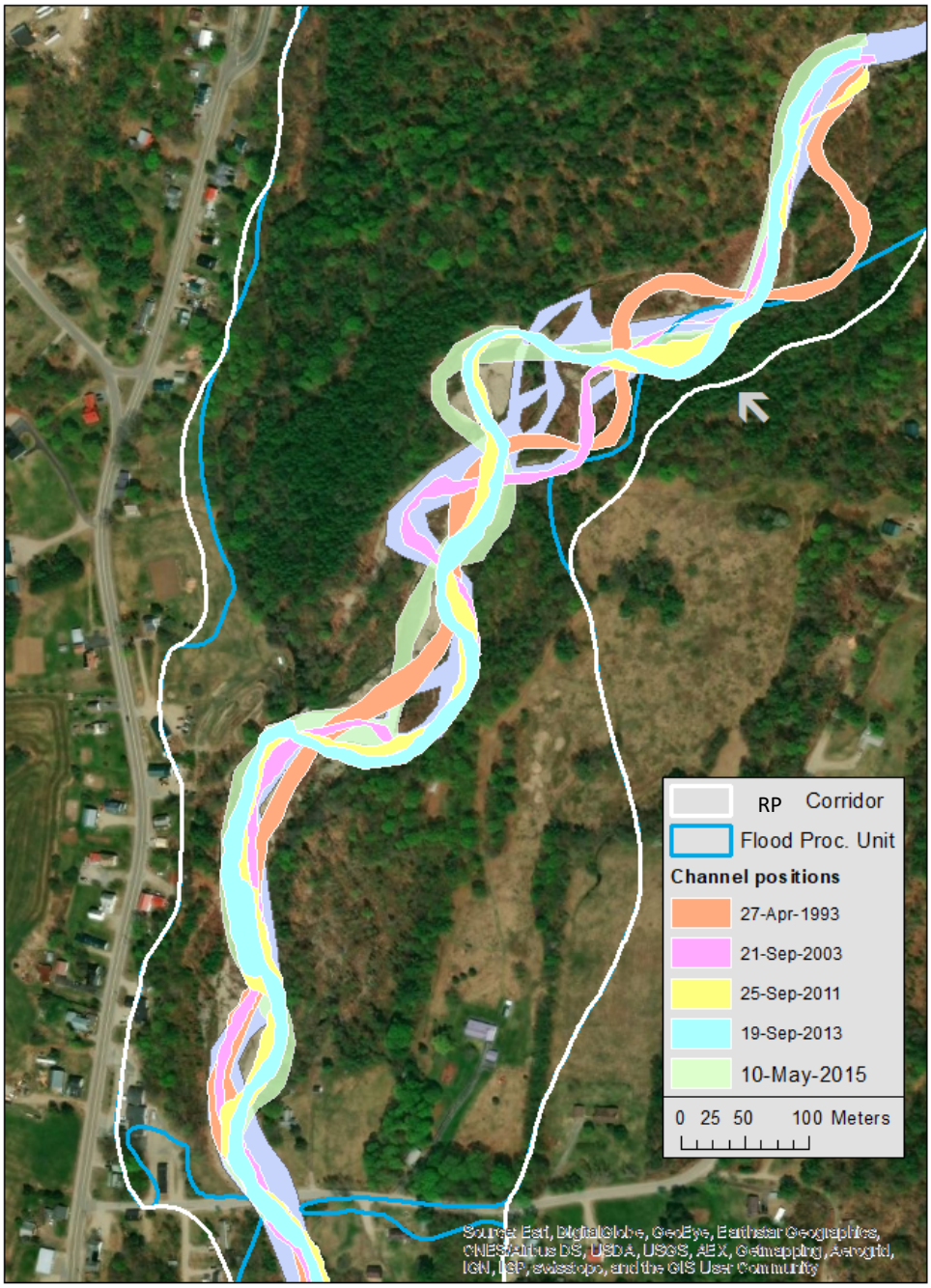


Figure 10. The Baker River test location, near Warren, Vermont. Google earth satellite imagery overlain by historical channel positions from 1993 (orange), 2003 (pink), 2011 (yellow), 2013 (blue) and 2015 (green). The total River Process Corridor layer is outlined in white, and the RPC Flood Process Unit alone is outlined in blue.

The Baker River site is especially informative for evaluating the RPC's ability to capture shifting stream locations during flood events. It has experienced several high water events in recent years, notably during Tropical Storm Irene in 2011, and during a storm on October 30, 2017. In the 2017 storm, channel migration undercut the eastern bank below a home, and carried it downriver to where it was

destroyed when it smashed into a bridge. (Video available online at https://abcnews.go.com/US/video/house-washed-hampshire-flooding-50825411).

The data show that despite rapidly changing channel positions, all known former channel locations are located within the spatial domain of the Migration Process Unit of the RPC. Through most of this study site, the channel positions are located within the predicted flood area from FEMA, evidence that channel migration occurs primarily within the floodplain. However, highly erodible terraces and alluvium may fall outside of the FEMA area. For this reason, it is noteworthy that the RPC captures some of these vulnerable reaches, including a 100 m segment (white arrow, Figure 6) where recent, former channel locations are beyond the limit of the FEMA flood area.

If a site-specific RPC delineation were undertaken along this reach, we might refine the mapping rule for this unit. A possible refinement would be to apply the 40 m buffer to the most recent known channel position (rather than whichever channel position is in the NHD database) as ascertained from drone photogrammetry, satellite imagery, or field surveying.

*Example 3: White River Watershed (**Figure 11**)*

This test location is used to examine how the RPC compares with evidence of geomorphic change during a major storm, Tropical Storm Irene in 2011, a large flood that did a great deal of damage in Vermont. Since the RPC is created using data available before Irene, we can evaluate how well our method predicts areas that are susceptible to natural hazards and other important processes of material transport during the flood.

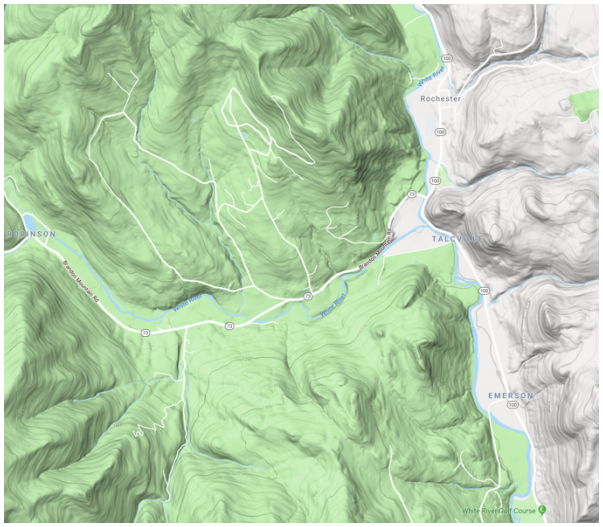
The White River watershed has the largest free-flowing river network in Vermont, with a combination of forest and farms, wide and narrow valleys, and small towns among the Green Mountains (**Figure 11a, 11b**). In August 2011, Tropical Storm Irene produced abundant floodplain sedimentation, hundreds of landslides, and record-breaking high flows at many gaging stations in Vermont (Magilligan et al., 2015). Floodplain deposits and landslides from Irene were mapped by Gartner et al. (2015) along about 50 km of the White River and the West Branch of the White River, and landslides from Irene were mapped by Dethier et al. (2016) across much of Vermont and Western Massachusetts. The study area examined here is the southern 955 km^2 of the White River watershed for which FEMA flood data are available.

For methods in this example, the RPC was delineated using the standard procedures without refinements. As in the previous test sites, no site-specific information was used to delineate the RPC.

Across the entire study area, the RPC overlaps with 86% of the area of floodplain deposits and 92% of the area of landslides. These data show that the RPC is a successful predictor, even in an extreme event, of a majority of the areas prone to river-related geomorphic processes. These geomorphic processes mobilize materials, shape the landscape, and sometimes create natural hazards that threaten roads, agricultural land, and structures. **Figure 11** shows a detailed view of a representative portion of the study area, where the West Branch of the White River meets the main stem of the White River in Rochester, VT. The sediment deposited on the floodplain during Irene is shown in yellow, and landslide areas are shown in red. The RPC encompasses most, but not all, of the areas with floodplain deposits and landslides (**Figure 11c**).

a

b



c

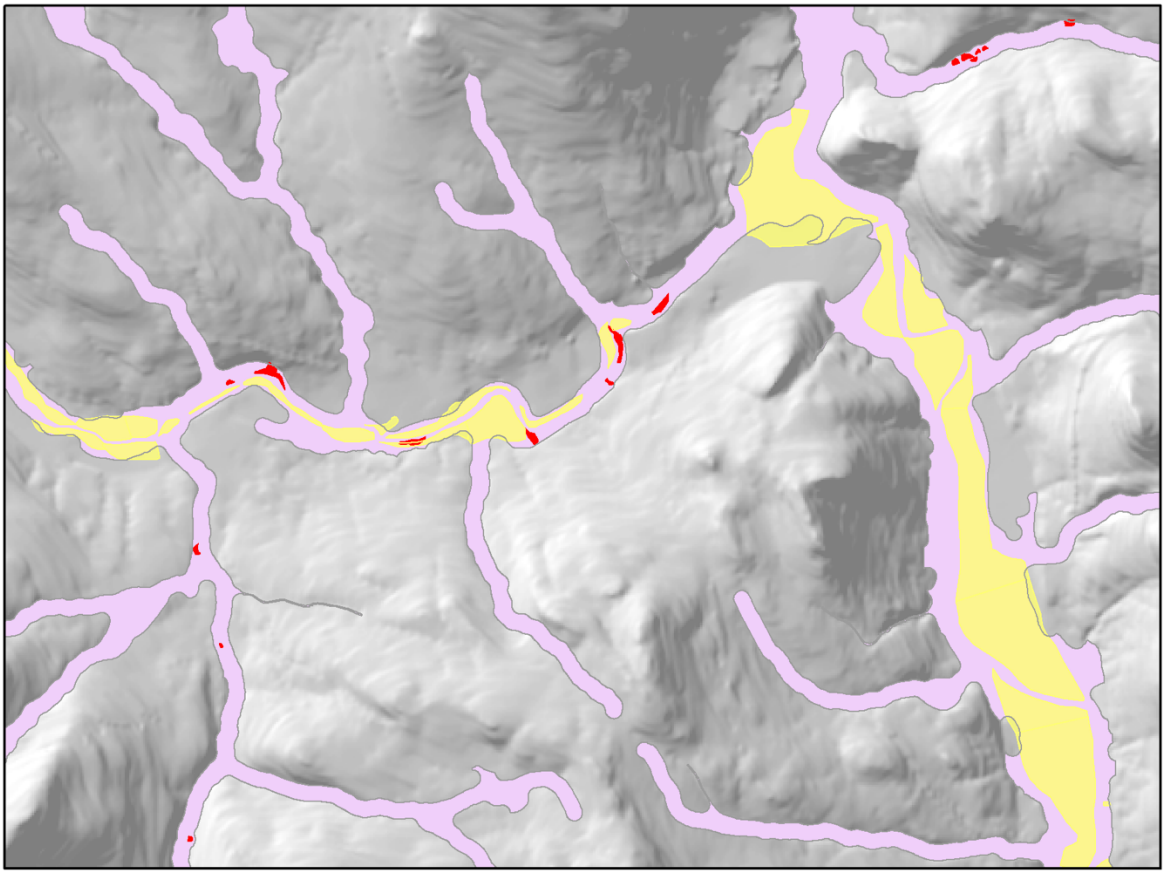


Figure 11. The White River test location near Rochester, Vermont. **(a)** Google earth satellite imagery. **(b)** USGS Topographic Map. **(c)** GIS Layer showing USGS Digital Elevation Model (DEM) hillshade basemap overlain by the field-mapped extent of features that occurred as a result of Hurricane Irene in August 2011, including: erosion from landslide scarps (dark red) and sediment deposition (yellow). Underneath these features, for comparison, is the total River Process Corridor layer (pink).

It is interesting to note that the RPC performs well at delineating areas of interest along all streams in the NHD dataset, including the many first order streams and the largest streams. Most other automated and semi-automated river corridor maps do not delineate a river corridor in the first order streams, and some other maps have not yet developed protocols for mapping large rivers (Kline and Dolan, 2008; Smith et al, 2008). The RPC will delineate corridors for rivers of all sizes. By virtue of the mapping rules, the minimum corridor is width is 40 m.

11. Effects of Climate Change

How will the extent of river corridors change with changing climate? In brief, we anticipate that the boundary limits of the river corridor may not change much; however, the frequency and intensity of many river-related processes are likely to increase. In other words, the largest floods may not get substantially larger, but small, medium, and large floods could get larger too, leading to more "extreme" events. We do not expect that new river-related processes will occur, just that the existing process will be more active. Overall, the changing conditions suggest a greater need for river corridor maps as planning and management tool.

The GIS steps used to create the RPC do not inherently consider changes in hydrologic regimes that are expected with climate change. Yet a central tenet of the RPC is that it can be refined rapidly, owing to the modular, computer generated mapping. If future research shows, for example, that the future 1% AEP flood has a larger discharge than before, then the revised Flood Processes Unit can be mapped and substituted for the outdated Flood Processes Unit.

The NALCC region is predicted to have continued trends of increased precipitation, more rainfall compared to snowfall, increased individual storm intensity and increased variability in precipitation that could lead to strengthened wet periods as well as longer dry and/or drought intervals (Parry et al., 2007; Stocker et al., 2013). One specific example of an observable shift toward increased risk of flooding due to climate change is documented by Yellen et al. (2016), whereby soils are saturated 4 times more often in advance of and during hurricane season in the northeastern U.S. This means that the land has less capacity to absorb intense quantities of rain from these storms (even *if* they were exactly the same magnitude; though future predictions show them also being larger and more intense), and risk of overland flow and flooding increases up to four times. Thus, climate change is most likely to exacerbate *existing* river and floodplain processes, increasing the frequency by which processes happen at extreme volume and strength, rather than add new processes.

All of these predictions point to an increased need to incorporate river corridors into natural resource planning and management because the RPC includes the areas we know to be most susceptible to climate changes. Flood mapping alone is a static snapshot of conditions at present time (more commonly, a moment 5 to 40 years ago when many FEMA flood maps were made). River corridors explicitly consider the potential for channel movement and other physical changes. Thus they provide a more accurate map of where river-related processes will occur in the future, compared to the FEMA floodplain maps alone.

12. Applicability

A major threat to earth sustainability is the loss of places where natural physical and ecological processes can occur untrammeled (Watson et al., 2018). This is a key factor in the decline in biodiversity and the drop in some animal populations. For example, there has been a 29% decline in bird populations during the past half century (Rosenberg et al., 2019). Freshwater mussels are the most common group of animals on the US Endangered Species list due to the fragmentation and pollution of river habitat, with 70% of North American freshwater mussel species either extinct or imperiled (https://www.fws.gov/midwest/endangered/clams/mussels.html). This loss of natural places is occurring independent of climate change; however, changes in precipitation, temperature, floods, and land surface processes may compound the effects of direct habitat impacts. Accordingly, it is vital for natural resource managers to understand what these natural processes are and where they are likely to occur, both frequently and infrequently.

An understanding of natural river processes – and the locations they are likely to occur – is it vital information for natural resources managers. This information helps target areas of special interest that warrant protection, specifically the places where we should allow the natural processes that many species depend upon. More importantly, it gives managers a justification for letting these natural processes prevail, even when some people might not quickly see their benefit. After floods, many people focus on the damages of that event. Yet river scientists also see the natural process during infrequent floods that are vitally important for fish, stream macroinvertebrates, riparian vegetation, and a suite of other species. A RPC map communicates where we expect to have natural river processes, and can communicate that these natural processes are beneficial to fish and wildlife. It helps justify that we don't need to "clean up" after a flood, even a major flood.

On the flip side, these river processes can be hazardous to humans and human structures. The RPC can help land managers plan where we should avoid placing new infrastructure out of harm's way and maintain healthy river ecology at the same time.

13. Discussion

The scientific foundation of the River Process Corridor is the notion that a suite of physical and biological processes interacts with and alter the landscape in river and floodplain areas. We strove to incorporate those processes into a single, unified river process corridor, or RPC. The aim was to use easily available data and relatively simple, transparent, and physically and science-based mapping rules that could be applied consistently, in order to develop a method of delineating a local-scale and/or regional-scale RPC that is comprehensive, reproducible, and usable across the North Atlantic region. Additionally, we wanted to make the system modular, for three reasons: so the spaces of different processes could be visualized; so states, local governments, NGOs and other entities could substitute in their own data as they desire and are able, to meet their own distinct purposes and goals; so different processes could be weighted differently, to suit specific applications, and could be updated piecewise as new approaches become available.

In verifying our mapping rules and the overall approach, our test was to examine how well the delineated RPC matches with physical evidence of these processes.

In three case studies, we took several angles to analyze the efficacy of the RPC in various settings, and the initial results are promising. The results show that the RPC is useful for watershed and reach scale analysis. The Baker River and Connecticut River examples show that the RPC encompasses all of the historic channel locations of this actively migrating and avulsing river. The White River example show that the RPC predicts 87% of areas susceptible to floodplain sedimentation and 92% of areas susceptible to landslides adjacent to river channels in an extreme flood which had, in most places where it was calculated in Vermont, a recurrence interval much, much longer than 100 years. Overall, the RPC incorporates and covers 100% of the mapped channels longitudinally up watersheds.

As suggested by the White River example, the RPC considers the effects of changing climate on the landscape because it depicts areas where increased flooding and surface runoff are most likely to accelerate the transfer of material between river channels, floodplains, and the broader landscape. Similarly, the RPC helps predict areas along river networks most susceptible to increased hazards, including landslides, river migration, and floodplain sedimentation. With changing climate, rivers in the NALCC region are predicted to have more frequent flooding and associated geomorphic change (Huang et al., 2017). Current predictions of climate change do not yet warrant changes in the width of RPCs as we map them. This is due in part to the uncertainty in how climate change predictions will bear out in river systems. For example, the NALCC region is predicted to have continued trends of increased precipitation, increased rainfall compared to snowfall, increased individual storm intensity and increased variability in precipitation that could lead to strengthened wet periods as well as longer dry and/or drought intervals (Parry et al., 2007; Stocker et al., 2013). Increasing groundwater levels across the northeast region point to a long trend of increasing precipitation in the region over time (Weider et al. 2010). However, precisely how and when these increases in precipitation and variability will occur and change both large and small floods is uncertain. The uncertainty is coupled with the existing uncertainty in modeling the extent of flood-prone areas. The RPC includes the areas we know to be most susceptible to climate changes.

In the RPC we explicitly include two new processes that, to our knowledge, have not been included in any other delineation methodology: (i) Wetland Process Unit and (Iii) Steep Terrain Process Unit. We feel that these are important additions, because of the well-established benefits of channel-proximal wetlands, the rapid delivery of materials to rivers from steep areas, and the hazards of presented by landslides in steep terrain. In addition, the Steep Terrain Process unit captures the very near-channel areas adjacent to incised rivers, which often fall outside of mapped inundation areas but can be extremely vulnerable to the erosive power of fast-moving floodwaters.

In contrast, as stated earlier, we did not specifically consider anthropogenic processes, nor how physical processes may be altered and reshaped by the presence of human-built structures and land use change. The RPC aims to encompass the area where river processes will occur over longer time spans. Here we explain a couple important implications for managers.

First, in some cases human structures like buildings, berms, dykes and roads, or human land use like river excavation, deforestation and afforestation, shift or redirect the biophysical processes in riverside areas. In other words, within the timespan considered by land managers, the RPC may include

structures that successfully block floods, erosion or other processes from part of the RPC. In such cases, the RPC is still informative as it highlights structures that a) may experience significant force during a flood, sediment movement, or other process; and b) if they do withstand the flood successfully, they will shift that force elsewhere – which means managers need to consider where else in the RPC that force will go.

In addition, some human alterations are reflected in how the process units are mapped, and others are not. For example, the area of flooding can be greatly diminished by dams that alter river flows for flood control or hydroelectricity. Typically flood maps specifically consider the reduced flood areas, and our mapping of the RPC typically reflects this reduced flood area. In contrast, near channel landslides can be diminished by human-made revetments, but this reduced likelihood of landslides is not specifically included in the RPC mapping rules, describe below. Refinements of the RPC, as described in the section in this document on refinements, would allow more detailed analysis of the anthropogenic influences on the extent of the RPC. One could model flood extents with and without the effect of flow-regulating dams to investigate how wide the pre-industrial river corridor would have been. One could also incorporate human structures into the landslide mapping rule for more detailed site-specific mapping of the RPC.

Related to this, the second significant implication of not considering anthropogenic processes and structures is that there can be special situations in which the RPC may not include all potential at-risk areas. In Vermont, for example, managers have found that many straightened, armored channels have incised, i.e. deepened. As a result the 1% AEP flood is relatively narrow. One component of the RPC, the Flood Process Unit, may also be narrow. However, over time, as the river continues to incise, it can cause bank collapse. The RPC includes 40 m width for potential bank collapse in this situation via the Channel Migration Process Unit, but that may not be enough width. The RPC has not been thoroughly tested in locations with highly incised channels.

Overall, the RPC appears usable and successful, and to be a promising tool for landowners, managers, planners, developers, and others.

14. Conclusion

This document focuses on the geographic extent of river process corridors. We describe the important river-related physical processes in river corridors, and introduce a new method that allows for rapid, uniform, and scientifically-based delineation of critical areas along and adjacent to rivers. We show the results in test locations in the North Atlantic area of North America. The results have an added benefit for land managers, government agencies, and individuals to help them understand not only important river-related habitat, but also river-related hazards that arise from the erosive force of floodwaters.

The RPC shows promise as a method and mapped area that can demarcate zones of both ecological value and river flood hazards, and potential areas to look for conservation opportunities that can attenuate flood risk elsewhere. Additionally, because one of the chief observations of climate change in the Northeast is increasing frequency of large river floods, the RPC functions as a good predictor of future areas susceptible to increased hazard risk from climate change as well.

Further testing of the methodology is warranted, including how well the RPC delineation strategy predicts locations of riparian ecological processes that are not strictly tied to flooding, floodplain sedimentation, river migration, and steep terrain physical processes. Broader testing is also warranted for the emerging strategies to predict the flood prone areas uniformly over large regions (Wing et al., 2018; Sampson et al., 2015; Bent et al., 2015; Clubb et al., 2017; De Roo et al., 2000; and Durand et al., 2010). Additionally, future testing by non-scientists is important to test its usability goals.

As improved and alternative mapping rules and data sources are developed, they can be incorporated into each respective module of the process units approach, either by individual users, or as part of the default practice.

Because our initial focus was specifically on river processes and how best to map each of them, our process units approach is not influenced by the practical or political feasibility of legislating activities within the RPC, and should not be considered a proposed management or regulatory area. However, like other delineation strategies that incorporate the dynamic nature of rivers, we hope that in the future RPC maps could be applied for a wide array of planning and management purposes to avoid natural hazards, allow natural river processes to occur unimpeded, and to protect and conserve fish, wildlife, and the environmentally sensitive riparian habitats they occupy. Because of this, and because of its emphasis on wide usability and applicability, we believe the RPC can serve as a useful complement to other existing regulatory and scientific assessment tools.

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