CHAPTER

26

Slowing the flow for climate resilience in human-dominated riverine landscapes

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Introduction

Riverine landscapes in many ways represent the birthplace of intensive human settlement and development (Gregory, 2006). This long, ubiquitous and continually changing relationship continues to the present day. Considering the infrastructure associated with this high level of development (dams, diversions, roads, railways, farms, commercial and residential structures) is essential in the context of riverine landscape resilience. However, in spite of a heavy human footprint, almost all large river basins comprise a complex mosaic of highly and minimally developed land and water, generally distributed non-randomly throughout these landscapes and hydrologically connected at multiple scales. Incorporating this heterogeneity can help support approaches that maintain ecosystem services and natural resource values whilst protecting key infrastructure and goes to the essence of resilient riverine landscapes in the face of major environmental change.

Climate change poses challenges to riverine landscape resilience along multiple dimensions (Milly et al., 2008). Climate-driven increases in the frequency, magnitude and duration of hydrologic extremes – droughts and floods – have been observed in many parts of the world and are predicted to worsen over the next century, depending on the trajectory of greenhouse gas emissions and atmospheric concentrations (Seneviratne et al., 2012; Lane and Kay, 2021). These changes in extremes threaten human health, safety, and infrastructure. In contrast, natural systems are often well-adapted to hydrologic variation and in many cases require floods and droughts to generate suitable habitat, accommodate life-cycle requirements and mediate biotic interactions such as competition and predation (Naiman et al., 1993). However, changes in hydrologic regimes can have direct negative effects by forcing populations and communities beyond their capacity to accommodate losses and also by creating temporal and spatial mismatches with species requirements (Jonsson and Jonsson, 2009).

How water managers respond to these climate-driven changes in hydrologic variability and uncertainty will likely override the direct effects of changes in flood and drought risk on riverine species and ecosystems. Dams, impoundments, diversions, leveeing and dredging – sometimes collectively referred to as ‘grey’ or ‘hard’ engineering responses – have been perhaps the biggest driver of riverine ecosystem degradation and species loss at a global scale (Best, 2019; Poff and Zimmerman, 2010; McCluney et al., 2014). An expansion of this grey infrastructure will impose compounding stresses on riverine systems coping with other sources of large-scale environmental change. In contrast, approaches that take advantage of natural ecosystem storage – ‘green’ or ‘soft’ engineering – can, in theory increase the resilience of both human infrastructure and natural ecosystems. These approaches have been increasingly recognised and adopted as part of broader water management strategies (Keestra et al., 2018). However, because they encompass a diverse set of actions that are manifest in different ways and in different places, it has been a challenge to incorporate them into landscape scale management plans and strategies. Further, there have been relatively few attempts to link them into formal climate adaptation strategies or to quantitatively assess the extent to which they could mitigate climate-driven changes in hydrology.

In this chapter, we:

1. Discuss the resilience challenges posed by increases in the frequency, magnitude and timing of extreme hydrology in the northeastern United States.
2. Introduce the Slowing the Flow for Climate Resilience (SFCR) approach.
3. Present a case study on applying this approach to a specific river basin, combining hydrologic and hydraulic models with climate change projections to assess the role of floodplain forests in moderating climate-driven increases in flood frequency and magnitude.
4. Provide some considerations for future directions and science needs.

The resilience challenge

Effective riverine landscape resilience strategies are fundamentally context-dependent, requiring detailed and integrated knowledge of geographic setting, regional hydroclimatology and past, current and future stressors (Chapter 6). Here, we consider challenges to riverine landscape resilience in the New England region of the United States, which provides a prime example of these issues, both in terms of their impacts and efforts to address them on a landscape scale.

Geographic setting: The New England region of the northeastern United States comprises the states of Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island and Vermont and is embedded in large part within the Northern Appalachian/Acadian Ecoregion (Bailey, 1976). This is a well-watered area, averaging >1000 mm of annual precipitation, which falls as a mix of rain and snow, characterised by a cold-temperate climate. Although precipitation tends to be evenly distributed across the year, runoff tends to be highest in spring and late autumn, driven in large part by seasonal trends in evapotranspiration and snowmelt which reflect the climate regime and the strong influence of the current extensive forest cover in the region. Regional hydroclimatology demonstrates a strong north–south and inland to coastal gradient with more unpredictable patterns of runoff and more precipitation falling as rain versus snow (Magilligan and Graber, 1996). The human population and associated residential and commercial infrastructure follow these general gradients with large population centres occurring largely in southerly, lowland and coastal areas. Landscapes are characterised by low-moderate slopes and have been strongly influenced by Pleistocene glaciation (Davis and Jacobson, 1985). Tectonic and volcanic activity is minor. Many of the upland stream and river systems are poorly buffered and sensitive to chronic and episodic acidification (Likens and Bormann, 1974) and are frequently nutrient poor with low suspended sediment loads (Elliott et al., 1998).

As expected for coastal drainages unconnected with large continental river systems and lacking significant glacial refugia, aquatic biodiversity in New England is relatively low, although there is a diverse assemblage of diadromous fishes that provided important ecosystem services for original Native American inhabitants as well as European colonists (Saunders et al., 2006). Following early European settlement, large-scale land conversion (from >80% to <25% forest cover in some areas), along with major river engineering projects that fuelled early industrialisation, seriously compromised the ecological integrity of aquatic ecosystems in the region, altering landscapes and watersheds to the extent that 'reference' systems are essentially unavailable for comparison. Since then, major shifts away from heavy industry, agriculture and intensive forestry and an increasing understanding of the value of water resources have led to large-scale recovery of forestlands and major improvements in water quality. In addition, a public that increasingly appreciates the ecological values of aquatic habitats provides a strong public base of support for conservation. However, the legacy of land use (Nislow, 2005), atmospheric pollution (Driscoll et al., 2001) and hydrologic change (Magilligan and Nislow, 2001; Nislow et al., 2002), combined with emerging threats from climate change (Sharma et al., 2007), invasive species (Les and Mehrhoff, 1999), urbanisation and residential development (McMahon and Cuffney, 2000) remain significant challenges.

Geomorphic and disturbance context: Because of its mid- to-high latitudinal setting in northeastern North America, the New England region has a diverse geomorphic context driven, of course, by its diverse geologic history but also more recently by its Quaternary history. The current major drainage systems were established pre-Quaternary with minimal drainage shifts during Pleistocene glaciation (Denny, 1982). Glaciation, however, largely conditioned the sediment transport context, especially the predominant mode of transport where most of the rivers are gravel-bedded flowing on a thin alluvial cover. The highly resistant metamorphic and crystalline rocks throughout most of New England have led to steep channels and highly confined valleys, especially in northern, tributary settings. Post-Pleistocene isostatic rebound (Koteff et al., 1993) contributed to steep channels and frequent bedrock channel reaches especially in tributaries where knickpoint migration is still occurring.

That geologically controlled geomorphic setting with frequent cascades, confined valleys, and over-steepened channels also made it ideal for dam construction during the early Industrial Revolution (Magilligan et al., 2016a). The National Inventory of Dams (NID), a dataset compiled by the US Army Corps of Engineers, shows ~4400 dams exist in New England; however, compilations from state agencies with different height and storage criteria than the NID estimate that over 14,400 dams are scattered across the region, most of which are small dams lacking minimal flow regulation at high or low flows (Magilligan et al., 2016a) but that have significant impacts on lateral, vertical and horizontal connectivity (Wohl et al., 2017). The larger flow regulating structures, on the other hand, have had profound effects hydrologically and ecologically, especially on fish passage and fish and floodplain forest habitat (Magilligan and Nislow, 2001; Nislow et al., 2002; Magilligan et al., 2008). To help combat the ecological and geomorphological effects of dams, local, state and federal agencies and non-governmental organisations have spearheaded campaigns to remove dams. Although highly contested politically (Fox et al., 2016), more than 250 dams have been removed in New England over the past several decades (Table 26.1).

Besides its high density of dams, New England also suffers from other hard infrastructural issues that have significant impacts on riverine systems. Its industrial history and highly urbanised population (especially southern and coastal New England) mean the region has one of the highest incidences of road and railroad crossings intersecting with stream channels. In a broad assessment of infrastructural controls on riverine connectivity, Blanton and Marcus (2009) indicate that New England ranks high in US regions impacted by infrastructure with its overall length of railroads (6016 km), interstate highways (2680 km) and US/state highways (14,882 km) coinciding with its estimated 14,000 km river lengths.

TABLE 26.1 Dam removal totals in New England States (Magilligan et al., 2016a).

State	Removed dams
Connecticut	43
Maine	43
Massachusetts	72
New Hampshire	46
Rhode Island	7
Vermont	46
Total	257

Climate change and hydrology in New England: The New England climate has become warmer and wetter over the past 100 years, and these changes are forecasted to continue into the future (Hayhoe et al., 2007; Demaria et al., 2016; Ahn and Palmer, 2016). Annual temperature across the region has increased >1.5 C over the last century, which is the highest rate of regional warming in the continental US (Karmalkar and Bradley, 2017). Overall annual precipitation has increased, and more of this precipitation is falling as rain versus snow. The observed and forecasted trends all have substantial seasonal components with a large proportion of warming and increased precipitation expected in the winter.

These changes in temperature and precipitation have influenced riverine flow regimes and will continue to do so. Concordant with increasing precipitation and temperature, total runoff (Parr and Wang, 2014) and river water temperatures (Kaushal et al., 2010) have both increased. Reflecting warmer temperatures and reduced snowpacks, the annual peak discharge arrives later in the year and is becoming less predictable (Dethier et al., 2020). Warmer temperatures may also reduce the frequency and duration of river ice, which can be an important geomorphic agent in the northern part of the region (Prowse and Beltaos, 2002).

Perhaps most importantly, from a riverine resilience perspective, studies suggest that increases in intense precipitation events will substantially increase the frequency and magnitude of extreme events (Karmalkar and Bradley 2017; Huang et al., 2017). Although it is difficult to detect changes in flood regime from the instrumental record, high intensity, high-profile events such as Tropical Storm Irene in 2011 (Vidon et al., 2018) and Superstorm Sandy in 2012 (Halverson and Rabenhorst, 2013) have become emblematic of the risks posed by a changing climate. The heavily developed lowland coastal areas in New England and throughout the northeast US are particularly at risk given their exposure to both sea level rise and associated increases in storm surge damage and riverine flooding. With respect to the other hydrologic extreme − droughts and low flows − there is considerably more uncertainty. On the one hand, overall increases in precipitation will tend to increase low flows and reduce drought frequency and magnitude. However, increased evapotranspiration during the growing season associated with warmer air and soil/leaf surface temperatures, coupled with increases in the frequency and duration of summer high pressure events ('heat domes') does bring up the possibility that at least short-term droughts may be more prevalent in a warmer New England future (Bradbury et al., 2002). This is of concern given the reliance of both nature and people in the region on abundant, predictable supplies of water. This is evidenced on the human side by the preponderance of shallow residential wells and small municipal and community reservoirs with limited storage capacity. Similarly, the ability of small catchments to support diverse and valuable species assemblages associated with headwater streams and ephemeral pools is highly vulnerable to drought. Drought, interacting with increased temperatures, poses multiplicative threats to iconic species such as Sugar maple (*Acer saccharinum*) (Oswald et al., 2018), Atlantic salmon (*Salmo salar*) (Jonsson and Jonsson, 2009) and eastern Brook trout (*Salvelinus fontinalis*) (Williams et al., 2015).

Fostering resilience in riverine landscapes

Strategies to foster riverine landscape resilience in a non-stationary world encompass a diverse set of actions. In this section, we discuss two broad categories of approaches and introduce the Slow the Flow for Climate Resilience (SFCR) concept in the overall context of resilient riverine landscapes.

Infrastructure placement and design: Designing critical infrastructure that is resilient in the face of extreme hydrology and keeping vulnerable infrastructure out of harm's way is essential to riverine resilience in human-dominated landscapes. Efforts have increased along several dimensions of vulnerability in ways that are likely to increase both infrastructure and ecological resilience in the face of a changing climate.

In New England, the combination of high drainage density and high road density results in many road-stream crossings, a majority of which are already under designed for the current flood regime and likely to be at increased risk under future climate-exacerbated floods (Gillespie et al., 2014). Most of the New England states (states being a collection of counties) have enacted standards that now specify minimum sized and designs to both help protect roads and to ensure aquatic organism passage throughout river networks and empirical studies have demonstrated that crossings designed to allow fish passage were less likely to fail in an extreme storm event (Gillespie et al., 2014).

Floodplain zoning has become progressively more integrated in flood management and climate-smart infrastructure planning in New England. Vermont, for example, has had a longstanding initiative to enhance riverine health through its successful River Corridor Program. After a series of devastating floods in the 1990s − followed by the catastrophic Hurricane Irene flood in 2011 − the Vermont General Assembly passed four separate Acts to establish a River Corridor and Floodplain Management Programme. The goal of the Programme is to promote and encourage the identification and protection of flood hazard areas that reduce flood and fluvial erosion hazards. The Programme differs from many other states approaches as it highlights the hydrological (inundation) as well as the geomorphological (fluvial erosion) risks and damages associated with catastrophic flooding. Part of Vermont's visionary strategy was to focus on two inter-related components: establishing a holistic view of stream channels as situated within a spatially expansive river corridor and, secondly, to focus on the negative impacts of infrastructure and development. In addition to moving houses out of the floodplain and removing berms and other engineering structures that were increasing channel conveyance, they included a science-based 'river corridor' to make spatially explicit what was allowed in floodways (Kline, 2015). This river corridor mapping is further anchored with an ambitious flood buyout programme that has purchased more than 150 houses that were damaged by recent flooding. Vermont is now poised to have a programme that indeed makes more resilient watersheds that enhances riparian ecological integrity, reduces flood risk and is better adapted for what the future portends climatically.

The New England region has an exceptionally high number of dams, the vast majority of which are small, have limited current use, compromise ecological integrity and have substantial maintenance and safety concerns (Magilligan et al., 2016a). Dam removal has therefore emerged as a major river restoration and resilience strategy (Magilligan et al., 2016a). Regional research has revealed that streams recover quickly following dam removal (Gartner et al., 2015; Magilligan et al., 2015; Fields et al., 2021) with many benefits materialising within the first year (Magilligan et al., 2016b). This suggests that despite years of regional hydrologic and ecological shifts, rivers can quickly recover from 10^1 to 10^2 years of damming. Prior to the removal of the Pelham Dam in central Massachusetts, for example, the ~800 m reach below the dam was significantly armoured, but its removal in the fall of 2012 led to significant bed fining within the first year (Magilligan et al., 2016b), which has been sustained for 9 years post-removal (Fig. 26.1) (Magilligan et al., 2021a,b). At regional scales, the geomorphic and ecological impacts of these >250 dam removals are helping to achieve greater watershed resilience, especially as the climate changes. At present, these removals have opened up

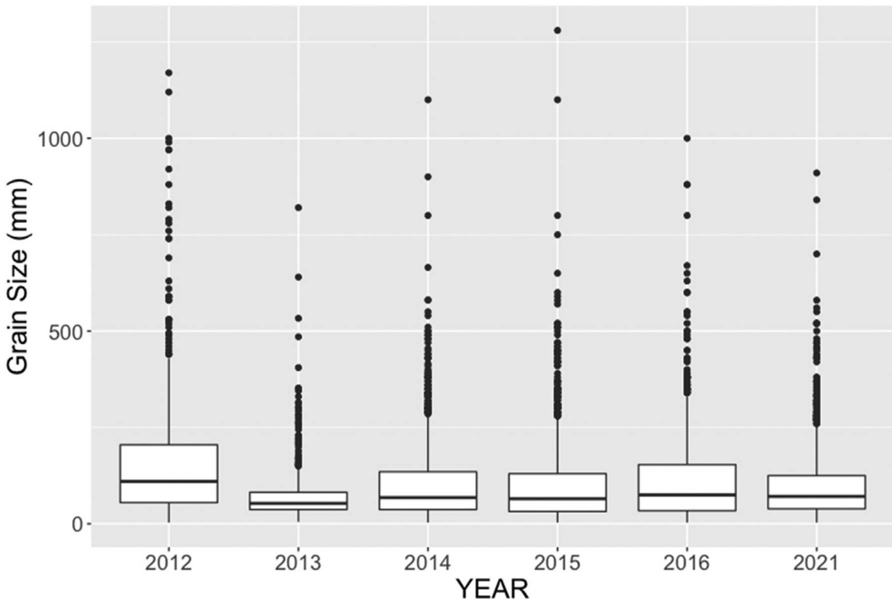

FIGURE 26.1 Box and whisker plots of grain size (b-axis) for years following removal (2013–21) of the Amethyst dam in Pelhams. MA. The lower and upper hinges correspond to the first and third quartiles. The upper whisker extends from the hinge to the largest value no further than 1.5 × IQR from the hinge. The lower whisker extends from the hinge to the smallest value at most 1.5 × IQR of the hinge. Data beyond the end of the whiskers are outliers.

>1700 km of free flowing rivers enhancing local and regional biodiversity (Magilligan et al., 2016a). The presence of dams has a significant thermal signal (Zaidel et al., 2021), so their removal will have an important thermal effect. Moreover, with many of the removed dams located in more upland and well-forested locations (Magilligan et al., 2016a), these liberated parts of the watershed offer critically important cold-water refugia for aquatic species already at their thermal maximum (Gillespie et al., 2014).

Moderating hydrologic extremes: While changes in the design and location of infrastructure can help to mitigate climate-driven changes in hydrologic regimes, dampening flow variability and extreme events can help make these and other riverine climate adaptation strategies more effective. We are *not* saying that high flows (and low flows) should be eliminated — they are essential to river and floodplain ecosystem function. What we *are* saying is that both the perception and the reality of increased risk (to both people and nature) *will* generate a response. 'Grey' infrastructure responses (e.g., dams, levees, impoundments, channelisation and dredging) can foster narrow-sense resilience focused largely on human infrastructure and water supply. This approach however can generate a 'vicious' cycle of grey infrastructure investment, associated environmental degradation and biodiversity loss and potential non-equitable shifting of losses and risks, necessitating more grey infrastructure costs and associated consequences. Green infrastructure responses (using, restoring and enhancing nature-based storage) can foster broad sense resilience (multiple dimensions including ecological benefits) via a 'virtuous' cycle of moderating changes in extremes, improving natural resource and environmental quality and building support for future efforts.

Nature-based solutions (Baliane et al., 2014), like river and floodplain restoration, are increasingly recognised as important components in responses to flood risk and many of these actions have been implemented (Keestra et al., 2018). For example, the Nature Conservancy (TNC) has incorporated nature-based solutions into the 'Water Quality Blueprint', plan for the Lake Champlain basin in northeastern North America. The plan prioritises the protection and restoration of wetlands, riparian corridors and floodplain forests to naturally filter sediment and nutrients from agricultural and storm water runoff. In addition to improved water quality in Lake Champlain, benefits include increased wildlife and fish habitat, flood resiliency and recreational opportunities (The Nature Conservancy, 2018). Internationally, but in similar mesic temperature cold-temperate ecoregions, the Ecosystem Restoration for Mitigation of Natural Disasters (ERMOND) project, established in 2014, studies the links between natural disasters and ecosystem conditions within Nordic countries. ERMOND advocates for the integration of nature-based solutions for strategic ecological resilience within national policies (Halldorsson et al., 2017). Additionally, restoration measures have been implemented within the lowland areas of Rangárvellir, Iceland, through the HydroResilience project. These intentional changes in vegetation and land cover alter the runoff dynamics of the Ytri-Rangá and Eystri Rangá watersheds. This ongoing project studies the increased field capacity of the watersheds and the change in seasonal water availability and flood risk within the system (Finger et al., 2016). These examples illustrate some of the ongoing and future research on nature-based solutions.

Historically, modelling approaches have been utilised to better understand and quantify the flood mitigation impacts of river restoration efforts. Multiple modelling studies have shown that river restoration techniques can provide flood management services across specific river reaches as well as entire catchments. Such studies have utilised a wide range of computer models and modelling approaches. Dixon et al. (2016) with an explicitly hydrologic modelling approach investigated the impacts of floodplain reforestation on the entire 98 km^2 catchment of the Lymington River, UK. Acreman et al. (2003) coupled a hydrology model with a one-dimensional hydrodynamic model to investigate changes in floodplain connectivity within an approximately 5 km section of the River Cherwell, UK.

Slowing the flow for climate resilience

Slowing the flow for climate resilience explicitly links the natural water storage capacity of watersheds and ecosystems to the hydrological and ecological impacts of a changing climate. Slowing the flow involves delaying the rate at which water moves through watersheds by increasing nature-based transient and long-term storage in soil, vegetation, surface water and ground water. Conservation and restoration of these natural storage compartments can, in theory, help to mitigate climate change-driven increases in the frequency and magnitude of floods and droughts that exacerbate risks to vital human infrastructure. If these actions also have positive effects on the structure and function of ecosystems that are threatened by a changing climate, slowing the flow for climate resilience will provide adaptation benefits along multiple social–ecological dimensions.

One of the clearest examples of this concept involves the ability to use nature-based actions to mitigate increased flood risks to what can be referred to as infrastructure nodes (e.g., homes, factories, farms, offices, roads and railways). Consider a hypothetical New England riverside town. Currently, the stage produced by the 10-year recurrence interval flood event produces only minor damages. However, forecasted increases in the intensity of extreme precipitation are projected to increase the discharge and stage of the 10-year flood to the point where substantial flood damages are likely. By increasing nature-based storage upstream of this node, it may be possible to flatten the flood hydrograph and decrease the likelihood that flood stage will exceed damage thresholds. Applying slow-the-flow principles to this hypothetical situation involves assessing appropriate nature-based solutions, analysing the scope for mitigation, modelling alternative scenarios and estimating corollary benefits to ecosystems and habitats. The slow-the-flow approach can also be applied in the other direction. Let us say that a management team has proposed a set of riparian conservation easements to provide habitat for an at-risk species. By using slow-the-flow approaches and analyses, it is possible to calculate the corollary downstream flood mitigation benefits of these actions.

Actions, processes and strategies that slow the flow

General considerations: A major challenge in developing and applying a slow the flow approach is the wide range of heterogeneous actions that affect storage and residence time (Table 26.2 and Fig. 26.2). For any part of the riverine landscape, only a subset of these actions would be relevant and appropriate. Further, the extent to which management actions confer corollary ecological benefits is highly context-dependent. While we can identify some relevant aspects for specific actions, there are also some general considerations for the approach.

TABLE 26.2 Types and characteristics of management actions that can slow the flow for climate resilience.

Management action	Scale	Setting	Slow the flow mechanism	Conflicts and constraints	Ecological targets
Large wood addition/ restoration	River channel	Small streams and rivers (wood less likely to be stable in larger rivers)	Increased channel roughness; aggradation (fostering floodplain-channel connection	Flood stage increase (very local); hazards to road-stream crossings when wood is transported by floods	Fish and aquatic invertebrate habitat; retention and processing of nutrients and materials
Impervious surface conversion	Watershed	Throughout, but developed landscapes often more common in valley/lowland settings	Soil and groundwater storage	Most relevant in developed watersheds with >20% impervious surface	Terrestrial – organic soils and vegetation support biodiversity and carbon/ nitrogen cycling and sequestration
Increasing channel sinuosity	River corridor	Throughout; but more scope for restoration in unconfined valleys	Increased effective channel length	Requires conservations set-asides and easements	Increases in aquatic habitat area and diversity; meander bends foster bar formation, provide sites for floodplain forest initiation
Floodplain/ riparian forest restoration and reconnection	River corridor	Throughout; floodplain forests more common and extensive in unconfined lowland and valley systems	Increased bank and floodplain roughness; increased hydraulic radius; flowpath complexity	Flood stage increases (local to more widespread); conservation set-asides and easements	Floodplain-dependent aquatic and terrestrial species
Forest restoration (outside of floodplains)	Watershed	Throughout, but more impact in watersheds that are not heavily forested	Canopy interception and storage; stemflow; transpiration and control of soil field capacity	Reforested sites in closer proximity to the waterbody more effective	Terrestrial forest biodiversity; carbon storage
Beaver restoration	River corridor	Small streams and rivers	Storage in wetlands and ponds	Local to widespread flood stage rise associated with dam and impoundment; loss of riparian trees due to foraging; dams as barriers to fish passage	Increased habitat for pond-dwelling species; nutrient retention and recycling; grassland and shrubland habitat-dependent species

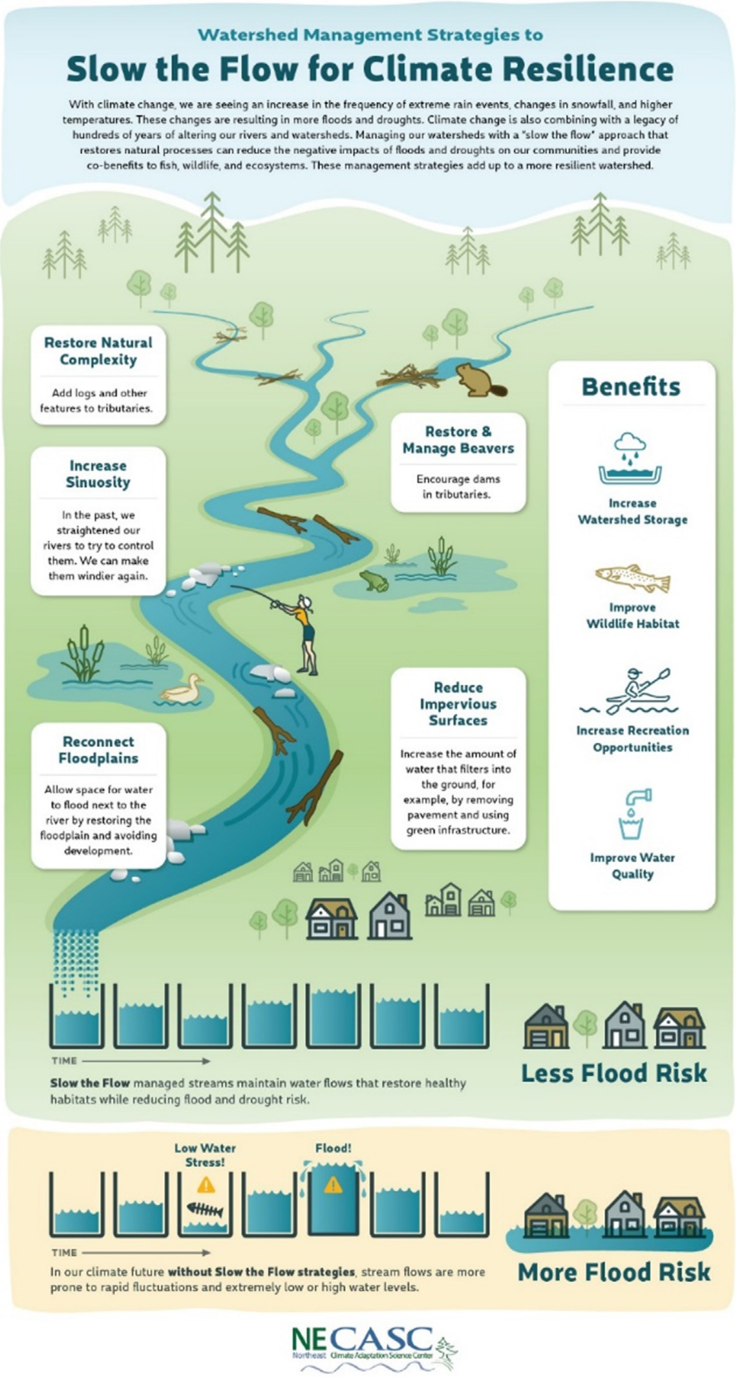

FIGURE 26.2 Slow the flow for climate resilience infographic.

Many of these are well summarised by Lane (2017) in a synthesis of catchment-scale natural flood mitigation approaches.

Characterising and integrating diverse actions: Most broadly, the importance and relevance of these different drivers of storage capacity generally exhibit predictable longitudinal patterns from headwaters to river mouth. These patterns have a strong influence on where, what and how to slow the flow. Let us go back to our hypothetical New England riverside town. At the river's origin, headwater catchments are likely to be highly forested and sparsely populated, flowing through small, constrained valleys. While this setting minimises potential conflict with human infrastructure, it also imposes constraints on the actions that are applicable. Clearly, the impact of mitigation via reforestation is minimal in already highly forested landscapes. Further, valley constraint limits the development and reconnection of extensive floodplains and the scope for re-establishing meandering and sinuous planforms.

The structure of stream networks generates additional considerations for longitudinal differences in the effectiveness of slow-the-flow actions. Given the high drainage density and large number of contributing small catchments and associated upland streams, actions in any given catchment will have a relatively minor effect on a downstream node like our hypothetical riverside town. At the same time, easier implementation in smaller streams and catchments may allow actions to be broadly spatially distributed and thereby have a substantial influence. In contrast, further downstream, individual actions on the mainstem and upstream proximate may have a more direct influence in mitigating the effects of hydrologic extremes on the infrastructure node. The potential for mitigation via floodplain reconnection and re-establishment of meandering planforms in less-constrained lowland valleys, and the opportunities to reforest previously converted agricultural and residential landscapes will likely increase. Unfortunately, conflicts with human infrastructure and competing land uses such as agriculture also tend to increase in the downstream/lowland direction, making it vital to identity and pursue the limited number of appropriate locations for implementation.

Even when scope and opportunity can be clearly identified, the diverse set of actions inevitably lead to challenges in working across governance structures and conservation entities. Slow the flow can involve actions that take place in-channel, within floodplains and riparian zones and even extend well into the uplands at considerable distances from the river network, and these different focus areas often involve distinct sets of practitioners. A major consideration in slowing the flow for climate resilience is the relationship between upstream flood accommodation and downstream flood mitigation. In general, actions that slow the flow by increasing hydraulic roughness/resistance to flow (Manning's n) will locally increase flood stage, extent and duration in the vicinity of the roughness elements. This generates a tradeoff between increased local flooding and decreased flood risk downstream, substantially complicating both planning and implementation. These and other considerations suggest that the social and organisational aspect of a slow-the-flow strategy may be as or more important than scientific and technical components.

Case study: Floodplain forests and flood mitigation under current and future climate conditions in Otter Creek, New England, USA

Physical setting: Otter Creek is the second largest river in Vermont and the largest tributary of Lake Champlain (Fig. 26.3). Located in the central New England region of the northeastern

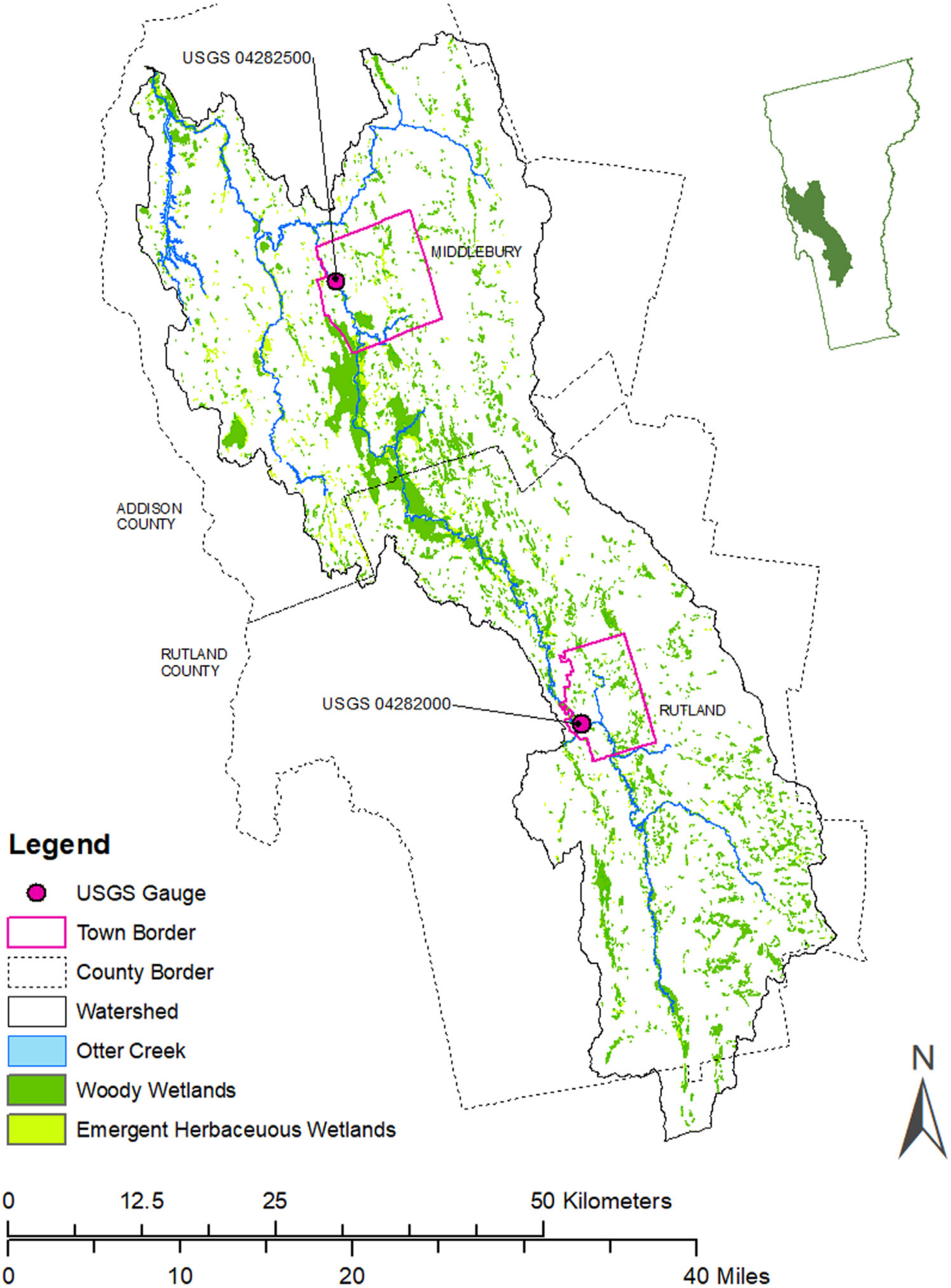

FIGURE 26.3 Map of the Otter Creek watershed (Vermont, United States), showing land use and USGS gage locations.

US, Otter Creek originates in the highland tributaries of the Green Mountains flowing down to and meandering through a montane valley before entering 7.28 km^2 (18,000 acres) of a well-connected, forested floodplain. The United States Geological Survey (USGS) measures hourly and daily discharge on Otter Creek upstream at the city of Rutland, Vermont (basin size = 795 km^2) and 75 km downstream at the town of Middlebury, Vermont (basin size = 1627 km^2), with an elevation differential of 44 m. The flood hydrograph responds sharply and rapidly to intense precipitation at the upstream gauge, while at the downstream site, the hydrograph has lower peak flows with slower rates of change (Rodríguez-Iturbe and Valdés, 1979). In part, this contrast derives from differences in basin size and topography, but the change between these locations is of particular interest when considering the lower Otter Creek floodplain, to which Watson et al. (2016) attributed significant flood peak attenuation.

Study approach: Our goal was to quantitatively assess the role of these forested floodplains in slowing the flow and providing flood resilience under both current and predicted future climate conditions. First, a watershed hydrology model is applied (Soil and Water Assessment Tool [SWAT]) was calibrated for observed flows at an upstream USGS gage location. An ensemble of downscaled climate projections from 13 general circulation models (GCMs) is used in the SWAT model to project changes in the recurrence interval of design floods. Second, a HEC-RAS hydraulic model is developed for the lower floodplain of the study region and calibrated against flow observations at a downstream gage location. Both historic high flow events (in years 1973, 1976, 1984, 1987 and 2011) and the sampled climate-driven design flood events are input into the hydraulic model. Three land-use scenarios are tested, and hydrologic response is measured at the downstream gage location. This combined modelling approach (Fig. 26.4) is applied within the Otter Creek watershed and used to address the following questions:

1. What future change in flood frequency is expected in Otter Creek under the effects of climate change?
2. What are the flood mitigation impacts of floodplain land-use on downstream river discharge during extreme flow events?
3. Will protection and restoration of riparian corridors significantly mitigate floods under the effects of climate change?

Otter Creek is an excellent study location because of the available fine resolution (0.7 − 1.7 m) LIDAR for the majority of the watershed and the extensive hydrologic records at the Rutland gage (USGS 04282000) and the Middlebury gage (USGS 04282500) (USGS

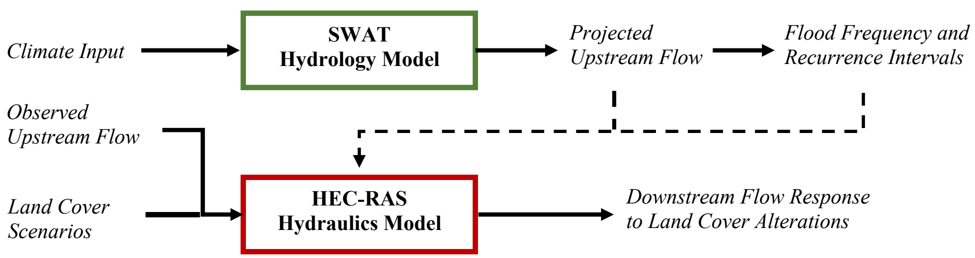

FIGURE 26.4 Flow diagram of the coupled hydrology and hydraulic modelling approach for Otter Creek.

Surface-Water Historical Instantaneous Data for Vermont: Build Time Series). Further, climate projections indicate that precipitation, especially for extreme events, is expected to increase in the northeast region of the United States (Huang et al., 2017). Understanding flood preparedness within the Otter Creek watershed can illustrate the importance of natural-infrastructure solutions in watersheds throughout New England where future extreme precipitation is a concern.

Hydrologic model: The SWAT was developed and calibrated (Arnold et al., 2012) with established procedures (see details in Saleeba, 2019). The model was run across a 35-year period (1979−2013). The calibration and validation period included the years 1979−2013. The National Centres for Environmental Prediction Climate Forecast System Reanalysis (NCEP CFSR) meteorological dataset serves as climate input for maximum and minimum temperature, solar radiation, wind speed and relative humidity (Fuka et al., 2014). Daily precipitation observations are sourced from 10 NOAA weather stations located within the watershed. Other major model inputs include a high-resolution digital elevation model (DEM) created from the available LIDAR, the regional SSURGO soil database (USDA, 2018), and the 2011 National Land Cover Database at a 30 m resolution (USGS, 2012).

Climate change scenarios: An ensemble of 13 downscaled GCM temperature and precipitation projections for the years 1981−2099 serve as input into the calibrated hydrology model (Taylor et al., 2012; more details in Saleeba, 2019). These GCM results were previously statistically downscaled to the New England region and selected for their satisfactory historical performance and diversity of climate scenarios (Karmalkar et al., 2019). The SWAT internal weather simulator provides inputs for solar radiation, relative humidity and wind speed data. Daily flow and flood projections are divided into three periods: the near-future (2025−49), the mid-future (2050−74) and the far-future (2075−99). The GCM ensemble data are presented as mean discharge statistics for each future period. After calculating the average projected 100-year flood for each future period, three upstream flow events are selected as representations of the projected 100-year flood events. For these projected flood events, the hydrology model results are imported into the HEC-RAS hydraulics model as input flows along boundary conditions for the analysis of downstream response to projected climate-driven floods.

Hydraulic model: To model the interaction between the river channel and floodplain between Rutland and Middlebury, we developed and applied a 2D unsteady-state hydraulic model using the United States Army Corps of Engineers' (USACE) Hydrologic Engineering Centre's River Analysis System (HEC-RAS) 5.05 to model the Otter Creek floodplain under existing and alternative land-use scenarios (details in Saleeba, 2019). Model inputs include river and floodplain terrain, land cover and associated Manning's roughness coefficients and SWAT-generated stream flows along boundary conditions (HEC-RAS, 2016). The floodplain terrain layer is developed using a high-resolution DEM, and a land classification layer is created from 2011 National Land Cover Database at a 30 m resolution (USGS, 2012), with each land cover type, is assigned a Manning's roughness coefficient (Chow, 1959; HEC-RAS, 2016). A 2D computational mesh is developed over the lower floodplain at a 50 m resolution within 1000 m of the channel and 300 m resolution further out. The model covers 300 km^2 and six inlets at major tributary confluences that provide input data. The largest five flow events between 1970 and 2018 (years 1973, 1976, 1984, 1987 and 2011) serve as input for large events. The historical observations of streamflow for these events are derived for the six major tributaries using the USGS StreamStats tool (Archfield et al., 2013). The DEM used to develop the model was created with LIDAR data that were hydro-enforced by the VT Centre of Geographic Information. Hydro-enforcement smooths the river channel and then removes obstructions along the river mainstem to properly simulate downslope flow through the system (Poppenga et al., 2014). The HEC-RAS model was calibrated by comparing simulated and observed data at the Middlebury USGS gage location using r^2 (0.86) and NSE (0.83). The 2D computational mesh resolution and Manning's coefficients were systematically altered under existing land-use conditions to attain calibration.

Land use change scenarios: Land-use scenarios are applied to the model to project hydrological responses to alterations within the riparian corridor of the main stem (Table 26.3). In the Field Buffer Scenario, all land cover within a 100 m of the Otter Creek main stem is transformed into NLCD land classes of grassland/herbaceous, pasture/hay and cultivated crops, using a representative Manning's roughness coefficient of 0.035. This scenario illustrates the flood mitigation potential of the Otter Creek wetland system under complete deforestation. In the Wetland Forest Buffer scenario, all the land within the 100 m channel buffer is transformed into NLCD land class 'woody wetlands' and is represented by a Manning's roughness coefficient of 0.12. The Wetland Forest Buffer represents the complete restoration of forested wetlands. These scenarios provide the upper and lower bounds of flooding impacts from floodplain development and restoration within the riparian corridor. The three land-use scenarios are run across the five historic flood events as well as the three projected climate-driven design flood events.

In addition to the hydrologic assessment at Middlebury, system response to land-use alterations is assessed with a longitudinal analysis of Otter Creek. Maximum discharge is extracted at every 7500 m along the river main stem, between the upstream and downstream boundary conditions. These maximum flow values map peak flow dissipation and flow alterations throughout the Otter Creek system. This separates the geomorphological and drainage network effects of flood pulse dissipation from those caused directly by the alteration of riparian corridor land use. This longitudinal analysis is only applied to the modelled historical flood events (years 1973, 1976, 1984, 1987 and 2011).

Flow projections: Linked RCP-SWAT models indicated substantial climate-driven changes in flow regime in the Otter Creek system. Flows are forecast to increase during the winter months of December, January and February across all recurrence intervals. In summer and autumn (July–September) flows >25th percentile are predicted to increase, with this increase

TABLE 26.3 HEC-RAS land-use scenarios.

Land-use scenario	Description
Existing conditions	No change to 2011 national land cover dataset
Field buffer	All land cover within a 100 m of the Otter Creek main stem is transformed into Field (Manning's roughness of 0.035)
Wetlands buffer	All land cover within a 100 m of the Otter Creek main stem is transformed into forested wetlands (Manning's roughness of 0.12)

most pronounced for extreme high flows (95th and 99th percentiles). In contrast, low flows (within the fifth percentile) are forecast to decrease in the far-future period by 20% and 15% in summer and autumn, respectively. Overall, floods >10-year recurrence interval are expected to significantly increase in frequency/magnitude, and shift from spring-season dominated to a more even and unpredictable distribution over the year (Fig. 26.5).

Downstream response to land use change: Results from the HEC-RAS model illustrate the effectiveness of downstream flood mitigation with changes in upstream land use (Fig. 26.6.) Increasing the extent of the forested floodplains (Wetland Buffer Scenario) substantially reduced both maximum discharge (average 23%) and maximum flow velocity (average 40%) with the greatest reduction associated with the far future climate projections. By contrast loss of existing forested wetlands via conversion to agricultural fields (Field Buffer Scenario) increased the discharge of current and future flood peaks. We did observe a relatively minor increase in stage under the Wetland Buffer Scenario in mainstem Otter Creek between the Clarendon and Neshobe River tributaries (maximum of 6% increase under the 2011 flood simulation). This affect was driven by the increased roughness values associated with the restored floodplain forest and would therefore generate a potential need for upstream flood accommodation.

Conclusions and implications of the case study: As broadly forecasted for both North American and European portions of the North Atlantic region, our research indicates that the intensity, magnitude and frequency of floods and droughts will substantially increase in the Otter Creek basin under future climate scenarios, threatening key infrastructure nodes such as the town of Middlebury, Vermont. While existing floodplain forested wetlands currently play a key role in moderating downstream flood risk in Otter Creek, our models suggest that expanding this role could help mitigate the impacts of climate-driven increases in flood magnitude and frequency, while reductions (associated with development or land-use conversion) might exacerbate flood risk. In terms of flood risk mitigation from floodplain

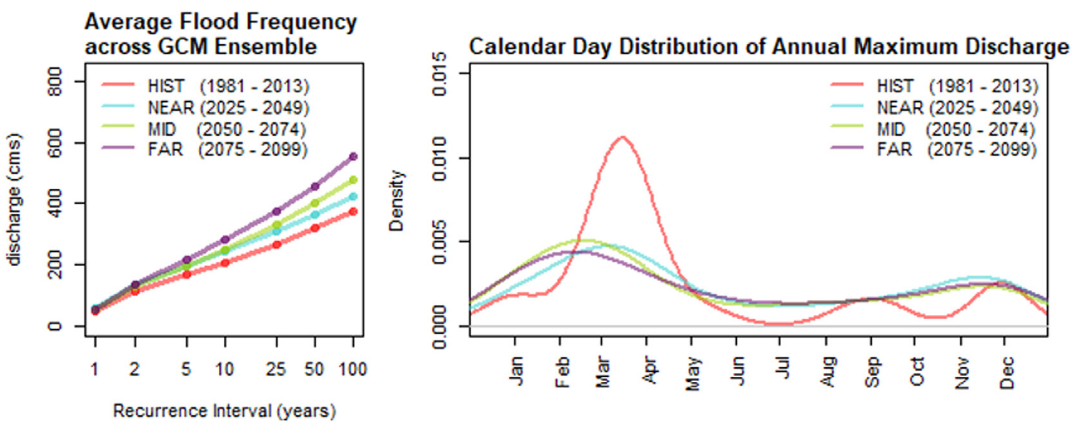

FIGURE 26.5 Flood frequency analysis of hydrology model results at Rutland, VT with climate input of RCP8.5 GCM ensemble precipitation and temperature data for historic (HIST), near-future (near), mid-future (mid) and far-future (far) projections (dates in parentheses). Averaged results are plotted on the bottom left. The bottom right plot displays the density distribution of the maximum annual flow events throughout the year.

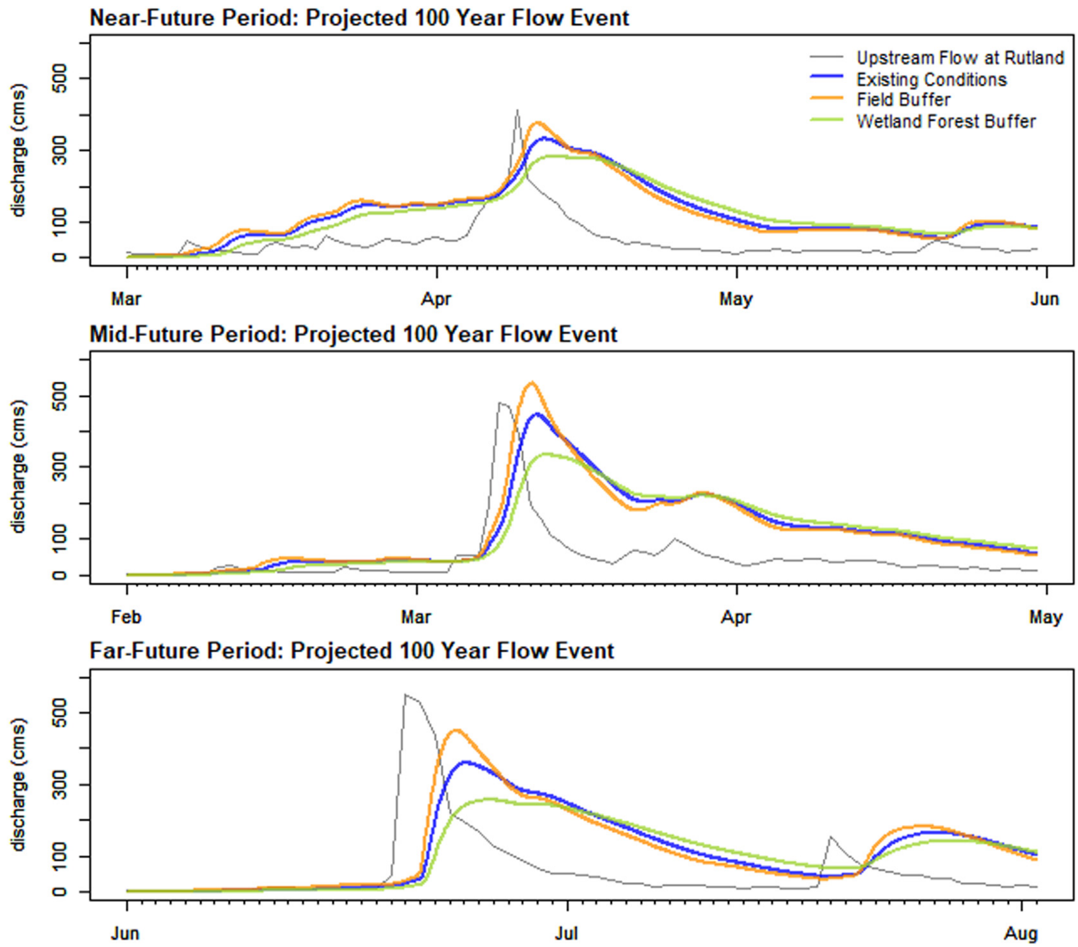

FIGURE 26.6 HEC-RAS results at Middlebury, VT: Simulated flows at Middlebury, VT across land cover alterations. The grey line displays the sampled climate-driven design floods at the upstream gage at Rutland, VT, the boundary condition for upstream flow along the main stem.

restoration and reconnection, these results are largely in accord with previous studies both in the Otter Creek basin (Watson et al., 2016) and in comparable systems (Acreman et al., 2003). However, by explicitly linking the effects of floodplains with forecasted hydrologic conditions, we provide quantitative estimates for how actions which influence floodplain extend and function can slow the flow and provide climate resilience.

The conclusions of this case study do come with some important caveats with respect to flood mitigation impacts. Perhaps, first and foremost, the modelling framework applied relies heavily on high-quality stream gauge data, which may not be available in many circumstances. Second, the hydraulic model represents land-use scenarios largely through land-cover specific adjustments to roughness and resistance to flow (Manning's *n*). While the complex relationship and natural alteration of geomorphology with land-use over time is not fully represented, the applied modelling efforts provide an initial analysis of downstream discharge relative to land-use changes. Further, while estimating the diverse effects of hydraulic roughness with a single parameter may be a bit fraught, the use of Manning's *n* has the potential to serve as a common currency across a range of management actions. Finally, our analysis focusses largely on a one type of action (floodplain, restoration and loss) in a specific part of the Otter Creek basin. A thorough slow the flow for climate resilience analysis would ideally incorporate potential actions and changes well upstream and more extensively in the basin. For example, legacies of intensive forestry in the New England region, including loss of the sources of large wood to stream channels and riparian zones, channel straightening and simplification associated with fluvial transport of logs, as well as associated channel incision, have likely reduced transient longer-term storage in lower order streams (Nislow, 2005). There is likely therefore to be an opportunity to further slow the flow for climate resilience with several actions (Table 26.2) applicable to upstream parts of this and similar basins.

An essential part of a slow-the-flow approach, which we did not focus on, was the corollary ecological and natural resource benefits of floodplain conservation and restoration. However, some of the hydrologic effects we observed are highly consistent with important and beneficial ecological responses. Floodplain forests in the northeast provide habitat for important and at-risk species (Nislow et al., 2002), so protecting and restoring these forests has direct ecological benefits. These effects are mutually reinforcing, as the flattening and extending of the flood hydrograph is actually a major factor in the establishment and maintenance of a distinctive flood-associated vegetation assemblage (Marks et al., 2014). Clearly, accommodating floods in places where they do maximum ecological good and minimal infrastructure harm helps to make linked human—ecological riverscape more resilient. Slowing the flow in this way also impacts other ecological dimensions of river systems. Migratory fishes are well represented in New England riverine assemblages and comprise important recreationally and economically important fisheries in the region (Nislow, 2005). The descending limb of the flood hydrograph is when most of these species move between their feeding and breeding habitats (Baras and Lucas, 2001) and extending the hydrograph extends the window available for migration. As migration is a critical life-history stage, managed actions which foster good migration conditions can contribute to species resilience as they face multiple stressors in a changing regional climate.

Slowing the flow for climate resilience: Prospects and consideration for the future

Slowing the flow for climate resilience, as a component of nature-based solutions for a nonstationary world, has a strong basis in fundamental hydrological, fluvial and ecological science. We suggest several emerging challenges and considerations for further implementation and extension.

Data-poor settings: The case study we present benefitted greatly from the availability of high-level data and technical expertise. Most potential settings and applications will not have these resources. While nature-based solutions certainly generate guidelines and rules-of-thumb to help advise practitioners in data-poor settings, is it possible to use an SFCR approach to generate specific recommendations that can be incorporated into adaptation and resilience plans?

From water quantity to water quality: sediments, nutrients and pollutants: The transport and fate of sediments, nutrients and pollutants is disproportionately influenced by high and low flows Doyle et al. (2005). Climate-driven changes in the frequency and intensity of floods and droughts will therefore additionally impact resilience via impacts on water quality. In some cases, hydrologic extremes such as floods may have complex effects. For example, while higher flows may dilute and lessen the impacts of pollutants within rivers, they may simultaneously increase loading rates to receiving waterbodies such as lakes and estuaries. Linked models will be increasingly necessary to fully capture the overall impacts of slow the flow approaches on watershed-scale resilience.

Droughts as well as floods: Our case study was focussed on climate-driven changes in flood regime, which is frequently the major concern in north temperate regions where overall precipitation is expected to increase. However, climate change even in these well-watered places may also result in increased risk of short-term droughts, as we observed in our modelling study of Otter Creek. As some, but not all, of the potential slow-the-flow actions can mitigate (via storage) both high and low flows, it may make sense to highlight these in adaptation planning for resilience.

Influencing plans and fostering communities of practice: Given the diversity of slow-the-flow approaches and settings, one of the most important elements of success may be simply bringing together practitioners, engineers and scientists. For example, as a long-term outcome of an introductory workshop, a slow-the-flow subcommittee of the Massachusetts Ecosystem Climate Adaptation Network (massecan.org) was formed and has been meeting monthly since 2019 to host speakers, discuss plans and share information. Similar communities of practice are well poised to make significant contributions to both the science and application of riverine landscape resilience in a changing world.

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Further reading

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