US Route 4 in Vermont was no match for the force of water, sediment and debris raging down into and along the Ottaquechee River during Tropical Storm Irene.

II. River Science, River Floods, and River-Smart Management

Why Should We Care About Rivers and River Management?

Rivers are vitally important resources in New England. Many of our towns and cities get their drinking water from the region's clean, bountiful rivers. Rivers sustain fish and other animals, myriad plants, and a range of ecosystems. New England's rivers powered our nation's earliest factories, and still produce electricity. Rivers connect us – from mountain to sea, from rural countryside to urban metropolis. Rivers are also places – they provide some of the most iconic landscapes in New England, many of our most beloved destinations, for locals and tourists alike.

Rivers are also active participants in making our landscapes richer and more productive. Rivers transport sediment and nutrients from hill slopes to valleys, down to floodplains, broad lakes and larger rivers, and finally out to the sea. These processes nourish floodplains, farms, and riparian areas, and provide benefits all the way to the coast, helping to maintain sandy beaches and barrier islands (thus reducing the negative effects of sea level rise). Rivers move gravel into stream reaches to form spawning habitat for fish, and dig pools where aquatic creatures can hide, find cool water, and grow. They carve meanders, pools, rapids and embankments where people love to recreate. Rivers even allow species to go up hill – creatures as diverse as insects, salamanders, raccoons, and people follow river meander corridors upward as well as downward to find new habitats, homes, mates, and communities.

However, rivers are powerful natural entities. They can cause damage to life, property, and habitat when they flood. This is especially so if we do not understand or appreciate, and are unprepared for, the ways rivers move and change over time and space. It is vital to interact with rivers mindfully when building and living near them.

The Science of Fluvial Geomorphology: Understanding Why and How Rivers Move and Interact With Their Landscapes

Rivers and landscapes shape one another. The study of how a river moves and interacts with its landscapes is called fluvial geomorphology. "Fluvial" means "relating to rivers and streams." "Geomorphology" is the study of the shape of the landscape, and the dynamic physical and chemical processes that form and change it.

This section outlines some general dynamics and processes of fluvial geomorphology, and lists several key insights about river floods.[17]

Dynamics and Processes: How Rivers Move and Shape the Landscape

The two starting points for understanding how rivers move and interact with their landscapes are first, that streams and rivers include sediment and debris as well as water; and second, that as they flow, they apply force on, and release material to, the landscapes around them (see Example 2: Inundation Hazards Versus Fluvial Hazards, p. 16).

As the water in a stream or river travels, it pushes on the rocks, sands and silts in its bed and bank. Often it dislodges some of these sediments, and carries them into the channel and downstream. The faster the water in the river moves, the bigger pieces of rock and sediment it can carry. Most rivers can move sand and silt under normal flows, and when moving very fast during high flows, they can carry bigger rocks and boulders. When the river carries a lot of water, it can also carry more sediment.

Key Insight #1:
Rivers carry more than water. Rivers in flood carry and move large volumes of sediment and debris, and travel with tremendous velocity and force.

Example 2. Inundation Versus Fluvial Hazards: Different Kinds of Flood Hazards

Downtown Wilmington, Vermont at the height of Tropical Storm Irene

A house destroyed by Tropical Storm Irene hangs over Marshs Brook, a tributary of the White River in Rochester, Vermont

The most common notion and image of floods is of rising water. Rising water causes inundation, or immersion in water. Many times, though, the most damaging aspect of river floods, and the one that takes people by the greatest surprise, is fluvial damage – either **fluvial erosion** or **fluvial deposition**. This is not caused by rising water, but by the power and force of moving water, sediment, and debris.

If the main threat of a flood is inundation, or rising water, the key variable that affects flood risk and damage is the elevation of lands, homes, and structures. Lower elevation areas are more likely to be inundated, like a bathtub might fill with rising water. The solution is to move structures to higher ground, to elevate homes and structures, and, where needed, build protective structures to keep out water.

However, there are many areas of higher elevation that may be safe from inundation, but are at great risk of fluvial erosion. This is because flood waters can undercut banks and hill slopes, causing small and large landslides. For example, this home along Vermont's White River near Rochester was likely at high enough elevation that rising water never touched it, but the damage it suffered from the bank eroding beneath it is clear. Some areas that are at risk of inundation may also be at great risk of fluvial deposition (see photos pp. 9 and 10).

New England communities remain ill prepared for the **fluvial hazards** that come with river floods. It is time we stop seeing floods only as inundation. Predictions of inundation risk, and mitigating for inundation, cannot prepare towns or property owners sufficiently for problems like catastrophic streambank collapse, or inches to feet of deposited sediment. Some measures used to protect against inundation – like building berms and levees – can make fluvial hazards worse.

The long-term, cost-effective solution to reduce fluvial hazards and damage is to allow rivers room to move as much as possible – to flood their floodplains, and to meander and braid. Where this is not possible, it is important to mitigate, by allowing rivers to move in other locations.

When a river slows, sediments settle out. The smaller the particles are, the farther the river can carry them downstream. The settling out of sediment, called deposition, can occur on the stream bed, on the inside of river bends, and on flatter areas next to rivers and streams.

Watershed patterns: The power of gravity and slope

In a watershed – that is, in an area of land which drains into a particular river – these dynamics play out in reasonably predictable patterns. In the steep hill slopes, more sediment is eroded than deposited. In flat valleys, more sediment is deposited than eroded. Over long time periods, material from hill slopes travels down slope to become stream bed gravel and floodplain soils. Eventually – over decades, centuries, millennia, or sometimes just days or hours – it is carried out to the sea.

The downstream movement of sediment is a long-term pattern, and is accelerated during river floods. When it rains in mountainous areas, water runs down the hill slopes. When rain water first enters a stream channel, the streams are often steep, small, and fast-running. Several of these soon join to form slightly larger streams. When there is a lot of rain in a

In this watershed, all land in the dark green area drains into the same river.

short amount of time, these small streams can swell enormously, quickly reaching the volume normally found in the mainstem river in the valley far below.

Key Insight #2:
Small streams can swell enormously during floods, rising much higher than their banks.

As these swollen mountain streams run downhill, they exert tremendous force on their stream banks and beds, and on any trees, structures, or other normally fixed-in-place parts of the landscape. Stream banks slump into the river. Bridge abutments crumble. Trees topple over entirely. Now, rocks, soils, bridge abutments and trees all become part of the raging torrent, and they also exert force, smashing into further roads, stream banks, and trees.

Key Insight #3:
High, fast, powerful flood flows can rapidly erode, undercut, and carry away parts of their landscapes.

Only when the river finally reaches an area where it can spread out, or the slope decreases, does the water slow down and lose energy. The immense quantities of sediment and debris carried downslope can no longer be carried by the slower, less powerful water, and the river drops its load. Several hours or days later, as the flood recedes, it leaves behind much of what it took from the upstream hill slopes and stream banks (see photos pp. 9 and 10).

Key Insight #4:
The material eroded by fast-moving floodwaters is deposited somewhere else, wherever the river slows down and spreads out – in floodplains, in the inside of river bends, in flatter more open valleys far below, or even in people's homes.

Human activity influences how much sediment and debris a stream erodes, carries, and deposits as it travels downhill. Urban areas and other areas with impervious surfaces accelerate run-off into streams and rivers, increasing a river's volume and its erosive power. Dams can trap sediment, but downstream of a dam, a sediment-starved river may also become more erosive.

When people log forests on steep slopes, or excavate ground to build large housing complexes, or leave steep farmland exposed without a cover crop, rain more easily erodes away the exposed soils. When people build roads and add fill, they provide relatively easy-to-mobilize gravels and rocks that a flooded stream can carry away. In New England, where the last great logging era was around the turn of the 20th century, sediments eroded from hillsides during that logging period are still moving through many of the region's river valleys. These are still being mobilized in today's river floods.[18]

Key Insight #5:
Human land-based activities often accelerate the movement of sediments, soils, debris, and even parts of the landscape from hill slope to valley. This effect can last decades or centuries.

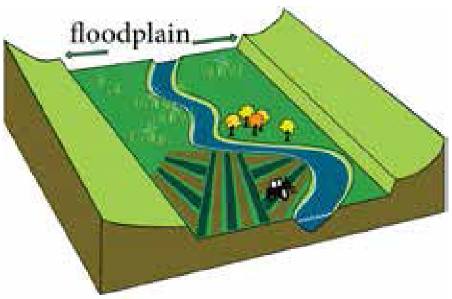
All rivers have variable flows across the days, seasons and years. Because of this, erosion and deposition also vary over time. Rivers and their landscapes can be shaped gradually, eroding their banks during normal high flows, incorporating sediment from small slumps, then dropping it elsewhere in slight rearrangements of the river channel and flow. However, during large river floods rivers can change their landscapes suddenly and on a much larger scale.

Over time, this persistent movement of water, sediment, and debris continually makes and remakes river channels, floodplains, and the riffles, pools and other features of aquatic habitat. The destructive force of river movement and floods is also a creative one on which people and other species depend.

Rivers and Floodplains

A river constantly moves and changes in response to the terrain it crosses, the amount of sediment it carries, and the water flowing through it. If something happens to change these – more water or sediment enters the river, sediment is taken out of the river bed, a dam is built, etc. – the river will shift, flow faster or slower, erode more or deposit more, or even completely leave its channel to form a new one.

A river does this mainly in its floodplain and adjacent lands. A floodplain is the low-lying, flat area where rivers flood and deposit sediment. When rivers flood their floodplains, they renew the soils, providing fertile soil for agriculture as well as for wild plants and animals. They help dissipate volume and energy, reducing the destructiveness of the flood for communities downstream. Even when a river is not in flood, it is often connected through groundwater flow to its floodplain's soils. This helps provide a richly watered environment essential to many important species. Many animal and plant species take advantage of river-floodplain connections to move to new habitats, feeding areas, and communities.



Key Insight #6:
If rivers are allowed to flood, and to spread out to their floodplains when they flood, they contribute important nutrients and ecological benefits. When waters spread out to the floodplain it also lessens the force and damage of the river flood for those downstream.

The interaction between river and floodplain can lead naturally to changes in a river itself. Floodplain sediments, deposited by the river over centuries and millennia, are relatively soft, and made up of small individual particles that are easy for a river to move. Rivers regularly carve meanders through their floodplains (more on meanders below).

Key Insight #7:
It is in the nature of rivers to move their channels and change their landscapes. This is a constant but highly variable process with some predictable patterns.

Also, sometimes a river flood will bring so much sediment from upslope, or move so much floodplain sediment, that it can create a small obstruction for itself. Then, it often breaks through another part of the floodplain soils, carving a new channel, setting off a new process of erosion and deposition.

People impact rivers' processes. When a floodplain is covered with buildings, roads, and railroads, and is separated from its river by flood barriers built to protect these, it loses much of its ability to diffuse the damage from floods. Instead of being reduced in power and force as it spreads out, a river flood continues to be just as destructive as it travels downstream. Flood control dams can greatly reduce floods, and the watering of floodplains. This may help protect human structures and investments built in floodplains, but it comes with significant costs. Dams require the permanent dedication of valley lands to a reservoir – one reason New England chose in the mid-twentieth century not to build as many large flood control dams as other regions.[19] Flood control by large dams also interferes tremendously with the beneficial functions of floodplains, with the rejuvenation of stream gravels, and with the seasonal river flows needed by many important species.

Key Insight #8:
Floodplains are formed by rivers. If a road or structure is on a floodplain then it resides in a place where the river has run or flooded in the past, and is likely to do so again.

Alternatively, sometimes rivers reclaim their floodplains. This may sound romantic (and it can bring long-term benefit) but it can be a destructive process if there are buildings or other investments in the way. When a particularly powerful river flood breaks through one or more of the obstacles blocking its force from spreading out onto the landscape, it often carves easily into the old flood-plain soils underneath. Then, it can quickly erode away foundations under walls, roads and bridges.

> **Key Insight #9:**
> **When people put obstacles in the way of rivers so the rivers cannot access their floodplains, the force of a river flood may break through the obstacles. Alternatively, if the raging river cannot break through, its full force will be retained as it rushes downstream. Either way, the result is often disastrous to human-built structures.**

Predictable Patterns of Channel Change

Within a river channel, moving water and sediment interact with curves and features in the stream bank, and with rocks, boulders and vegetation in the stream. These interactions create complex flows – strong currents, for example, or rapids, or circular eddies. These flows in turn influence the shape of the stream bed or channel or bank – particular portions of the river's flow dig channels downward, extend or move meanders, scour holes or pools, or deposit layers of gravel. These dynamics are too complex to predict precisely in any one location, and indeed, the flow and shape of one point in the channel can change significantly from day to day, season to season, year to year.[20]

> **Key Insight #10:**
> **We cannot know exactly where rivers will move, erode, or deposit sediment or debris, but with an understanding and assessment of specific river processes, patterns and features, we can identify places of high risk.**

There are, however, flow dynamics within rivers that are predictable as general patterns. Assessments of these and other patterns and features can help people evaluate likely risks in specific places (see Recommendation 1). The three general processes discussed below reveal locations where structures, stream beds and stream banks are most at risk in a river flood, and some ways our own land use practices may impact these.

Down-cutting With Ensuing Widening

One of the most common processes of river change in much of New England today, and one of the most destructive, is down-cutting (or incision). Down-cutting is a process in which a river deepens itself dramatically, often with significant consequential stream bank erosion. Down-cutting is often unnoticed in its initial stages, because the changes occur below the surface of the stream.

Down-cutting happens most when rivers are confined in straight channels. When a river is confined – that is, when it has strong rock or cement walls or banks on its two sides – it cannot spread out to dissipate volume and force. When a river is straight, it is steeper than if it is meandering, so it increases its velocity and force.

Some parts of rivers and streams are naturally confined and straight – such as steep mountain streams that run through bedrock and boulders. But frequently rivers are confined and straightened because people have built walls, levees, dikes, berms, or revetments in order to pass water quickly through an area where they have investments–houses, buildings, roads, railroads, infrastructure, or farmland. Unfortunately, the consequence is an even faster, more powerful stream.

Streams are also made more powerful when we cover the landscape with impervious surfaces – things like buildings, asphalt, and cement. These prevent storm water from infiltrating into the ground and instead send it directly as surface runoff into the stream, increasing high flows.

A powerful stream applies enormous force on the stream bed. The erosive capacity of the stream is even greater when we excavate the stream bed to make it deeper, or when we dig out the larger rocks, boulders and gravels, leaving the stream bed with exposed finer-grained sediments and soils. A strong, fast, high-flowing stream erodes easily through finer-grained sediments and soils, causing down-cutting or incision.

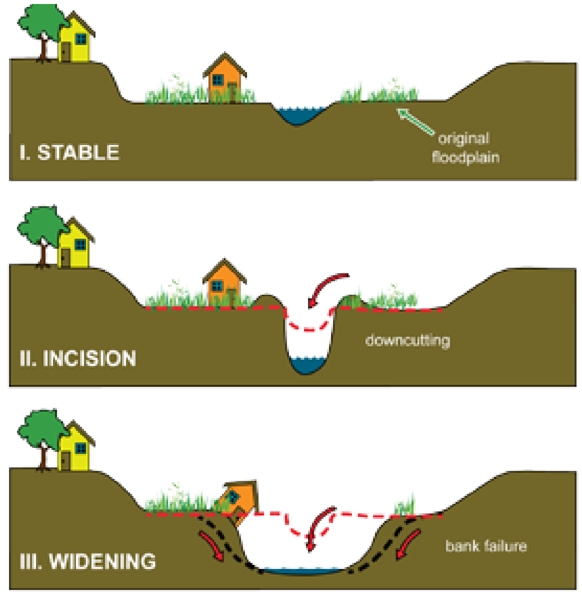
Down-cutting may not initially appear to be a problem for peoples' stream-side investments, which seem protected by bank armor. However, a stream that has down-cut deeply is no longer able to access its floodplain on a regular basis. As a result, high flows that would typically have slowed down and spread out onto the floodplain will now be confined to the small, narrow channel and remain powerful.

Key Insight #11:
Straightened, confined rivers are faster and more powerful.

The stream will eventually dig below the level of the armored channel walls, and erode away the finer sediments until the remaining top layer of the bed has only coarser gravel, rocks and boulders.

This process continues until the bed becomes so resistant to erosion that scientists call it a "pavement" layer. The resistance in the bed becomes greater than the resistance in the bank. Then, the rate of horizontal, outward erosion accelerates, and the river undercuts the armor, levees, or berms, which can collapse catastrophically. Suddenly, the investments that depended on protection from the river are vulnerable. From a stream's point of view, it is re-establishing a floodplain, reclaiming a place to flood and meander. From the point of view of someone who worked hard to protect the human-built stream-side investments, a controlled stream has suddenly become very destructive.

Key Insight #12:
Straightened, confined rivers, especially when they have been excavated, tend to down-cut their beds. A river that has down-cut often then re-widens at a lower elevation. This is likely to be destructive of levees, dikes, berms and other protective structures, as well as the investments they were built to protect.



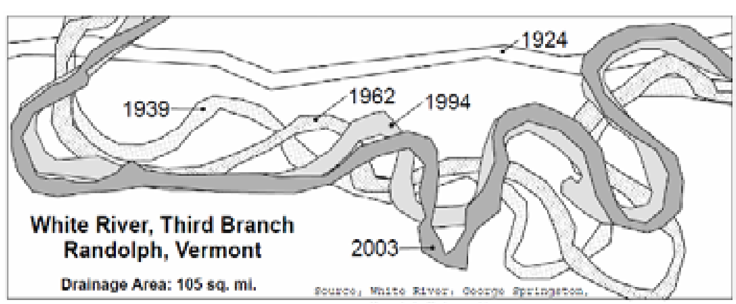
Natural rivers have floodplains where they spread out during high flows (stage I). When we straighten and armor river channels, rivers often undergo down-cutting or incision (stage II). They may widen again at a lower level, as they re-create a new floodplain. This can cause severe damage to streamside built structures (stage III).

Movement of Meanders

A second general pattern is that meanders tend to grow or move over time, causing problems for lands and structures in their way.

Consider why this occurs. For a short stretch, between two meanders, the main flow of the water goes straight. Then, the channel bends. However, the river is not a conscious being; it does not anticipate the bend. The main flow of the water continues straight. It flows into the outside edge of the bend. Only then, when there is no longer anywhere to go forward, will the flow be forced back out and around the bend. But in the meantime, that flow has exerted force on the stream bank. Here, on the

Key Insight #13:
River meanders and braids naturally move over time and space.



Natural rivers move around over time, like this meandering river.

Rivers may also form complex channels like this braided Central American river.

outside edge of the meander bend, if there is erodible sediment, a stream is likely to erode it away, and the meander bend is likely to expand outward.

As the force of the water hits the outer edge of the meander bend, much of it also is pushed down, and so the river will also erode downwards, digging pools at the outer edge of the meander bend and undercutting the riverbank.

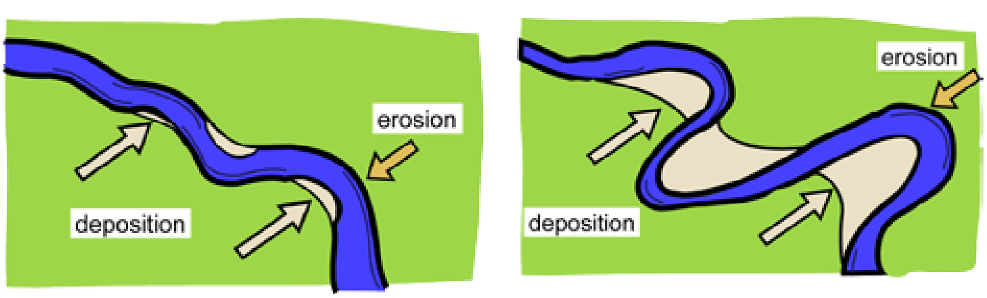
The stream bank above the outer side of the meander bend can become a vertical, backward- moving embankment. Buildings on the vertical sandy embankments above river meander bends may be at particular risk of collapse during river floods.

In steeper, more confined valleys, erosion may be slower, and meanders may not be able to move outward. Instead, erosion is likely to be displaced to the opposite bank, just downstream. In this case, the process of continual erosion and sedimentation may move meanders in a down-valley direction over time. The result of these processes is that over time, meanders tend to get pushed farther and farther outward (in sandy valley bottom settings), and/or down valley (in more mountainous rivers).

Key Insight #14:
Erosion of stream banks is often enhanced at the outside of the meander bend – both outward and downward. Vertical, sandy embankments at meander bends are often evidence of continual undercutting.

In a natural river, these processes may be slow and reduced because meanders decrease a stream's slope and therefore its power. Some erosion and deposition will continue, and over a long or even medium time period, river meanders

Houses at high risk of fluvial hazards, under construction over an eroding bank in Stowe, Vermont.



Over time, river meanders in valley bottoms tend to develop longer, more curved paths.

move around a lot. However, the rough length and slope of the river and its meanders will be fairly stable.[21]

The process of meandering is affected enormously by human activity. If a channel has down-cut and is now widening by undercutting an armored embankment, as described above in the section on down-cutting, it brings to this process the full power of a river in a confined, straightened channel. It is likely to be able to cause considerable erosion very quickly. Even regular daily flows may have the power to amplify a newly forming meander. Upstream activity can also have a significant impact. If the river has been confined and straightened upstream, it will have increased velocity and power coming into a meander. Again, erosion happens much more quickly (see photo from Ch. I of re-claimed meander straight through a road, p. 12).

In contrast, if people have conserved upstream floodplains and provided rivers the room to meander and braid, then the power of the river coming down river will be reduced.

Also, vegetation along river banks and woody debris in and beside the channel can make a big difference to the rate of erosion and channel migration. Strong root systems help protect and hold the soil and stream banks, while tree cover can reduce the force of precipitation. Woody debris in the channel can divert flow away from banks, and capture sediment. However, if people have cleared vegetation from the stream banks or removed all the wood from the channel, the soils are likely to erode more rapidly.[22]

Key Insight #15:
Vegetation and woody debris in the channel and on stream banks can slow river erosion.

Scour Holes Around Fixed Infrastructure

The third predictable pattern of channel change involves the creation of scours. When the flow of a river encounters an immovable object in its path, the force of the water is often diverted down, or sometimes to the side. This causes scour – that is, the intense erosion of sediments in a particular place that creates sudden deeper spots, or holes. Bridge abutments, large boulders, trees, culverts – any of these that are directly within the path of a river's flow are likely to create scour. Scour is often the secondary, unanticipated negative effect of our efforts to secure the location of a structure without regard to river patterns. It is often damaging because it can undermine the structures we have built, and because it can cause abrupt changes in depth of the channel that aquatic organisms may not be able to navigate.

Key Insight #16:
When we place fixed objects and structures in a river's path, we may create scour and damaging erosion either beside or underneath. This can undermine buildings and infrastructure, as well as habitat connections for aquatic organisms.

Toward River-Smart River and Land Management

These sixteen key insights about river flood hazards that come from the science of fluvial geomorphology lead to some principles for river-smart river and land management.[23]

The most fundamental management principle is: **We cannot stop river floods, but by managing rivers and riverside lands differently, accommodating their dynamic movements and interactions with the landscape, we can reduce their destructive force and keep our communities safe.**

The most important lesson for on-the-ground management is that we need to allow rivers to move.[24] We need to accept that when rivers flood, they move fast and with considerable force, and with large volumes of water, sediment and debris. First, as much as possible, we need to allow rivers to flood onto their floodplains. This allows flooding rivers to dissipate the energy and volume, reduce their velocity, and deposit nutrient-rich sediments.[25] Second, rivers need to meander and braid. This reduces their slope and therefore their velocity and destructive force. It also allows sediment and woody debris to be deposited along meanders and braids, where these deposits maintain rivers and renew habitat, rather than in giant accumulations that can damage lands, bridges and roads.

To give rivers room to move, we should keep our buildings, roads, structures and other investments out of their way wherever possible. We should remove berms and levees where we can, and restrict development on floodplain lands and river meander corridors, or what Vermont calls “river corridors” (see Example 13, p. 58). We can use a wide range of management tools, including outreach, planning, funding support, incentives, ordinances, conservation, easements, and buy-outs (see Recommendations, Chapter IV).

If budgets allow, there can be more active design work in streams, rivers and riverside landscapes.[26] However, giving rivers the time and space to produce their own restored channels and landscapes is often the simplest and least expensive option, and thus is the emphasis for this report.

In some cases, we have to protect and armor narrow straightened channels – many New England towns were built right up against rivers, and in the region's steep valleys it may be financially impractical to move roads. When we protect and armor river channels, however, we should do so with caution and forethought, for we will be displacing force, volume, and sediment – whether to the side, to the stream bed, or downstream. We need to think at watershed scale, realizing that what we do in one location in a river system affects the risk of hazard faced in another, and what we do in many locations can dramatically increase or decrease damage in the next river flood. In rivers and watersheds where numerous sites must be armored, it may be important to find other, upstream places in the watershed where the river can be given room to spread out, to lessen impacts on vulnerable areas downstream.

Important Science and Management Lessons for River-Smart New England Communities

There are three key science and management lessons to take from this chapter about how to help New England communities become river-smart.

New England community officials, staff, landowners and residents, as well as the people working in and around New England communities, should:

1. **Understand and apply the science of river dynamics and its key insights on river floods**– both in general, and in relation to specific locations of concern and opportunity.
2. **As much as possible, find ways to give rivers room to move**– to carry and deposit water, sediment and debris, to flood floodplains, and to meander and braid.
3. **When armoring stream banks or deepening channels is unavoidable, mitigate this** so as to reduce unintended consequences of erosion and deposition that will be displaced elsewhere.