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Flood Effects on Road-Stream Crossing Infrastructure: Economic and Ecological Benefits of Stream Simulation Designs

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Flood Effects on Road–Stream Crossing Infrastructure: Economic and Ecological Benefits of Stream Simulation Designs

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ABSTRACT: Stream simulation design is a geomorphic, engineering, and ecologically based approach to designing road–stream crossings that creates a natural and dynamic channel through the crossing structure similar in dimensions and characteristics to the adjacent natural channel, allowing for unimpeded passage of aquatic organisms, debris, and water during various flow conditions, including floods. A retrospective case

Efecto de las inundaciones en la infraestructura de pasadizos fluviales: beneficios económicos y ecológicos de los diseños de simulación de arroyos

RESUMEN: el diseño de simulación de arroyos es un enfoque geomórfico, de ingeniería y con consideraciones ecosistémicas en el que se crean pasadizos erigiendo un canal natural y dinámico entre arroyos a través de estructuras de paso similares en dimensiones y características al canal natural adyacente, permitiendo así el paso irrestricto de organismos acuáticos, debris y agua durante distintas condiciones de flujo, incluyendo inundaciones. Se llevó a cabo un caso de estudio retrospectivo acerca de los éxitos y fracasos de la construcción de pasadizos entre arroyos en la parte alta de la cuenca del Río Blanco y el parque Nacional Montaña Verde, en Vermont, justo después de las inundaciones sucedidas tras el paso de la tormenta tropical Irene, en agosto de 2011. El daño fue en gran parte evitado en dos pasadizos donde se implementó el diseño de simulación de arroyos, no así en distintos pasadizos que fueron construidos mediante el diseño hidráulico tradicional, en los que el daño fue extensivo. El análisis de costos sugiere que incrementos relativamente pequeños en la inversión inicial, destinados a implementar un diseño de simulación de arroyos, dan como resultado considerables beneficios sociales y económicos. Se presentan recomendaciones que podrán ayudar tanto a las agencias como los participantes genuinamente interesados en el tema, a mejorar los pasadizos fluviales mediante un incremento en la coordinación que promueva las metodologías del diseño de simulación de arroyos, aumento de los fondos y la flexibilidad de las agencias y participantes para actualizar aquellos pasadizos cuya resiliencia a las inundaciones haya fallado y expandir los talleres de capacitación dirigidos a participantes federales, estatales y locales.

study of the survival and failure of road–stream crossings was conducted in the upper White River watershed and the Green Mountain National Forest in Vermont following record flooding from Tropical Storm Irene in August 2011. Damage was largely avoided at two road–stream crossings where stream simulation design was implemented and extensive at multiple road–stream crossings constructed using traditional undersized hydraulic designs. Cost analyses suggest that relatively modest increases in initial investment to implement stream simulation designs yield substantial societal and economic benefits. Recommendations

are presented to help agencies and stakeholders improve road-stream crossings, including increasing coordination to adopt stream simulation design methodology, increasing funding and flexibility for agencies and partners to upgrade failed crossings for flood resiliency, and expanding training workshops targeting federal, state, and local stakeholders.

BACKGROUND

Hundreds of thousands of road-stream crossings exist in the United States (Coffman et al. 2005), and fragmentation of aquatic habitat from road-stream crossings has a well-documented impact on salmonids and aquatic diversity (Rieman et al. 1997; Hudy et al. 2005), including eastern Brook Trout (*Salvelinus fontinalis*). In the past decade, the U.S. Department of Agriculture Forest Service (USFS) surveys of national forests in Virginia, Washington, Oregon, and Alaska indicated that half to two-thirds of road-stream crossings were barriers to fish passage at some life stage (Coffman 2005; Heller 2007). Research in the Northeast (Nislow et al. 2011) demonstrated that stream sections located above impassable culverts had fewer than half the number of fish species and less than half the total fish abundance compared to stream sections above and below passable culverts.

During storm events, road-stream crossings may fail catastrophically when floodwaters exceed the hydraulic capacity of a culvert and/or sediment and debris plug the culvert. The

subsequent damage to road infrastructure and adjacent property can deliver large pulses of sediment to stream channels (Furniss et al. 1997; Nelson et al. 2012). In many forest environments, the dominant failure mechanisms for road-stream crossings are wood and sediment accumulation at the inlet, typically initiated by small woody debris (e.g., twigs, sticks, and branches) not much longer than the culvert diameter and often not exceeding the width of the channel (Cafferata et al. 2004; Flanagan 2004). Researchers have linked observed increases in flood frequencies and intensities in the Northeast to anthropogenic climate change and have cautioned that current infrastructure requirements will need to be reevaluated based on new flood-risk information (Spierre and Wake 2010). Culvert failure probability during flood events can be reduced through appropriate sizing and configuration (Furniss et al. 1997; Flanagan et al. 1998), particularly when replacing undersized structures with appropriately designed culverts and bridges (Furniss et al. 1998).

In addition to causing severe impacts to human safety, property, and infrastructure, large flood events have profound effects on wild trout and aquatic biota due to higher water velocities and increased sedimentation (Trombulak and Frissell 2000; Angermeier et al. 2004). Numerous studies have linked abundance of age-0 trout to the timing and magnitude of flood events (e.g., Seegrist and Gard 1972; Carline and McCullough 2003; Warren et al. 2009). Though young fish are often more susceptible to loss during flood events, high mortality of adult trout has been documented as well (Carline and McCullough 2003). In



Figure 1. Road failure at a 3-m culvert placed within a 6-m bankfull width stream, Green Mountain National Forest. Photo credit: Dan McKinley, Green Mountain National Forest.

the absence of barriers, however, habitat is recolonized in several years by individual fish from metapopulations (e.g., Dolloff et al. 1994; Letcher et al. 2007; Nislow et al. 2011). Studies of several wild Brook Trout populations by the Vermont Fish and Wildlife Department (VFWD) in the White River, Mad River, and Dog River watersheds found that flooding from Tropical Storm Irene reduced total trout populations to 33%–58% of pre-flood levels (Kirn 2012). Barring anthropogenic alteration of in-stream habitat with heavy machinery, Brook Trout populations would be expected to return to pre-flood population structure within 2–3 years (Kirn 2012). Studies by Dolloff et al. (1994) in North Carolina and Carline and McCullough (2003) in West Virginia indicate that though individual habitat units changed, overall habitat composition and complexity persisted and in some cases improved after floods.

The upper White River watershed was selected as a case study for this article because of the extensive flood damage experienced in five valley towns during Tropical Storm Irene (Irene) on August 27–28, 2011, a portion of which was related to failure of undersized hydraulic design road–stream crossings and associated road damage incurred by communities beyond the structure replacement costs (Figure 1). The extensive damage to culverts on town lands adjacent to the Green Mountain National Forest (GMNF) allowed for comparison of crossing failures and associated impacts between older traditional hydraulic designs and newer stream simulation designs (Stream Simulation Working Group [SSWG] 2008). Before Irene struck, two stream simulation designs had just been completed in the watershed adjacent to the upper White River and in a nearby watershed within the Connecticut River basin that sustained similar precipitation levels and flood damage. An additional crossing that approached stream simulation design standards within the upper White River watershed on the GMNF avoided damage as well. Survival of these three GMNF road–stream crossings designed for aquatic passage highlights the broader benefits of ecologically beneficial stream crossing designs, including reduced rates of crossing failure and storm damage to roads and property, reduced costs of road maintenance, and reduced likelihood of adverse impact to communities and businesses caused by flood damage. The U.S. Fish and Wildlife Service (USFWS), which has been active across the watershed in post-storm response with local partners such as the White River Partnership (WRP), has used fish passage as its primary objective when partnering on upgrading road–stream crossings. It employs a range of ecologically beneficial approaches to achieve aquatic organism passage and improved flood resiliency, including the stream simulation design method (J. Rowan, USFWS, personal communication).

ROAD–STREAM CROSSING DESIGN APPROACHES

Aquatic organism passage (AOP) at road–stream crossings has been the subject of engineering, fisheries, hydrology, and wildlife specialists' concern for many decades, beginning with federal and state agencies involved in fish management and road and highway construction in Alaska, California, Oregon, Idaho,

and Washington (Orsborn et al. 2002; Clarkin et al. 2005). Prior to the 1970s, a hydraulic design approach to road–stream crossings focused on efficiently conveying flood flows with minimal or no concern for the movement and habitat needs of fish (Figure 2a). In the 1970s and 1980s, hydraulic design structures were modified to create hydraulic conditions that allowed for passage of adult fish including fishways, baffles, and weirs (Figure 2b; Cenderelli et al. 2011). Structures substantially narrower than the width of the adjacent natural channel, however, were only partially successful in allowing passage for the targeted adult fish species, and they did not address the passage needs of multiple species occupying the stream corridor at different life stages and flow conditions. Into the 1990s, hydraulic engineers continued to study and provide design advice to agency fisheries biologists. As Endangered Species Act listings for Pacific Coast salmonids increased in the 1990s and understanding of river and stream geomorphology among agency staff improved, inventories of road system crossings and design improvements to provide passage of all aquatic species, not just adult salmon and trout, increased. Recognizing the limitations of hydraulic design approaches for meeting the passage needs of multiple species occupying the stream corridor at different life stages and flow conditions, a stream simulation design approach was developed (Figures 2c–2e).

Gradually, federal agencies such as the USFS, USFWS, Natural Resources Conservation Service, Bureau of Land Management, and National Oceanic and Atmospheric Administration developed or recognized fish passage programs specific to road–stream crossings. In recognition of the pervasive problem of undersized culverts inhibiting the passage of aquatic organisms, wood, sediment, and debris across the country's vast road network, especially on public lands, the USFS and other agency technical specialists convened a cadre of hydrologists, watershed scientists, geomorphologists, road engineers, and fisheries biologists who further developed and refined the concept of stream simulation design in the 1990s (SSWG 2008; Cenderelli et al. 2011). In 2008, the USFS identified stream simulation design as its preferred approach for all national forest road–stream crossings on fish-bearing streams and integral to meeting the intent of the Clean Water Act (to restore and maintain the chemical, physical, and biological integrity of the nation's waters; 33 U.S.C. § 1251(a)) and the Endangered Species Act (to provide a means whereby the ecosystems upon which endangered species and threatened species depend may be conserved 16 U.S.C. § 1531(b)) (USFS 2008).

STREAM SIMULATION DESIGN

Stream simulation designs are recognized as more effective in facilitating juvenile and adult fish and other AOP than traditional culvert designs (House et al. 2005; Cenderelli et al. 2011) or low-water fords (Bouska and Paukert 2011). The premise of stream simulation design is that by creating channel dimensions and characteristics through a road–stream crossing that are similar to those in the natural channel, fish and other aquatic organisms will experience no greater difficulty moving through the

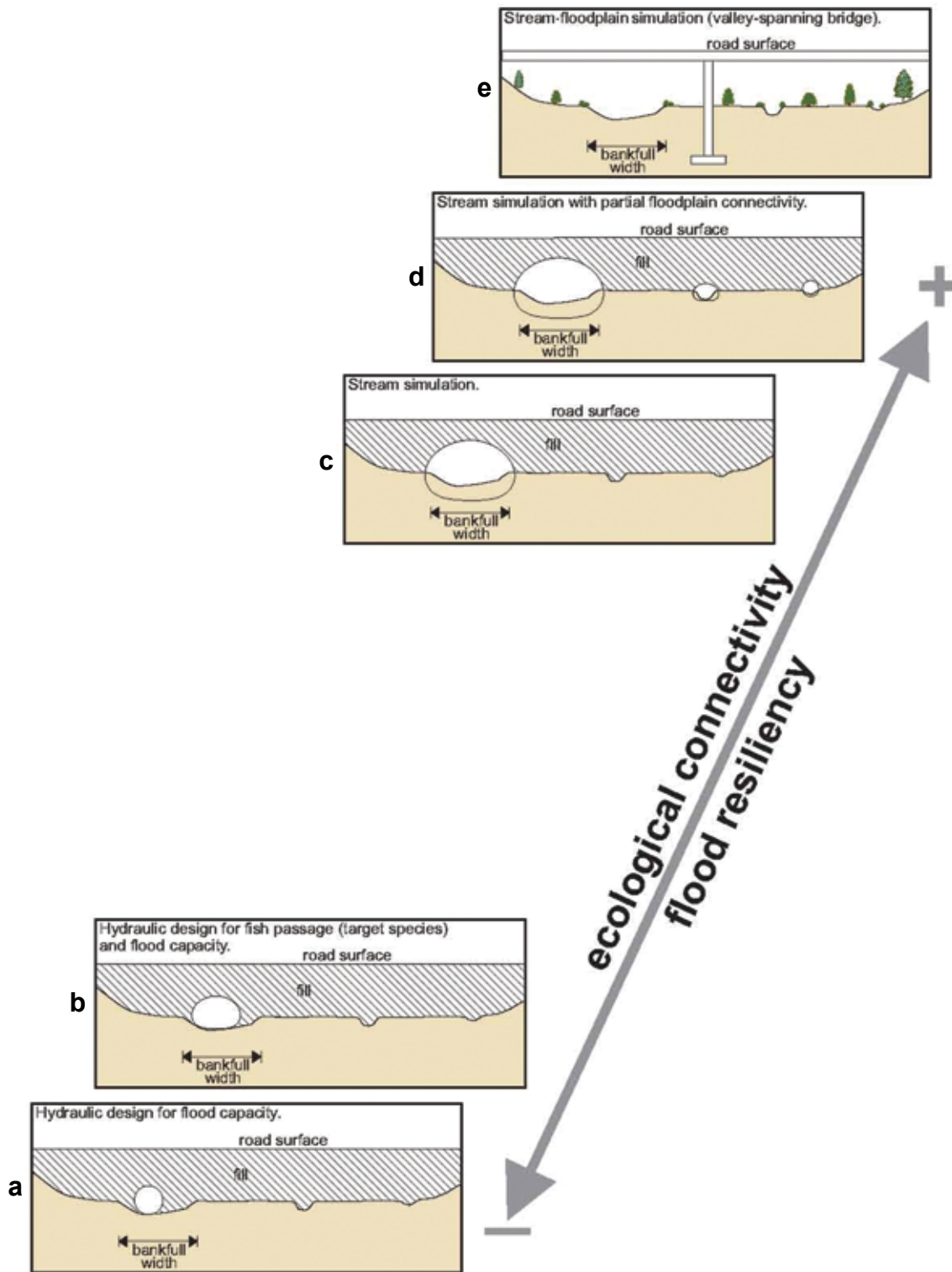


Figure 2. An ecological connectivity and flood resilience continuum for different design approaches at road-stream crossings (adapted from SSWG, 2008). The stream-floodplain simulation design (top graphic) provides passage for all aquatic and terrestrial species all at flow levels and minimal interference of stream and floodplain processes, resulting in greater ecological connectivity and flood resiliency. The stream simulation design (middle graphic) provides for fully functioning floodplain processes, passing floodwater, sediment and woody debris and all aquatic species for a broad range of flows. The hydraulic design for flood capacity (bottom graphic) only provides for partial functioning of stream processes, impedes passage of some floodwaters, sediment, and woody debris during high flows, and impedes passage of most aquatic species for most flows, consequently providing low ecological connectivity and flood resiliency.

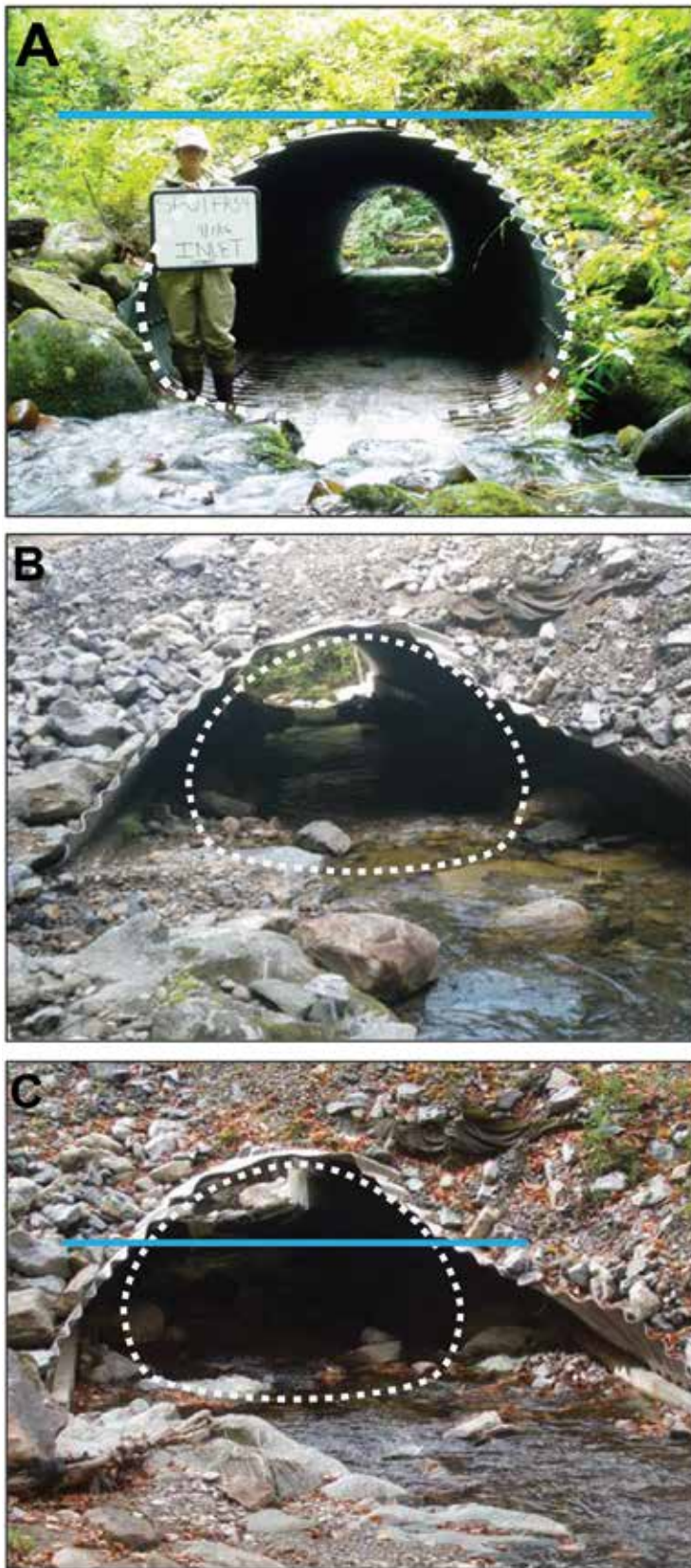


Figure 3. Sparks Brook road-stream crossing located on the Green Mountain National Forest, showing (a) original hydraulic design pipe-arch built in late 1960's, with a 2.5 m span and 1.9 m rise; (b) stream simulation design open-bottom arch structure built in 2010 with 4.5 m span, 1.62 m rise and footers extending 2.7 m below channel bed; (c) replacement structure after Irene flood. The blue line illustrates the actual peak flood water-surface elevation as well as the estimated peak flood elevation if the original culvert had been in place. Photo credit: Dan McKinley, Green Mountain National Forest.

structure than if the crossing did not exist (SSWG 2008). Stream simulation crossings are designed to maintain geomorphic and hydrologic continuity with the adjacent natural channel by building a “design channel” through a road-stream crossing structure with gradients, cross-sectional widths and shapes, bed forms, flow depths, and sediment size characteristics that are similar to those of a stable, nearby reference channel (SSWG 2008). The stream simulation design approach is applicable on any channel type or gradient and in most environmental settings (Cenderelli et al. 2011). To avoid constricting flood flows, the width of a stream simulation design structure is equivalent to or exceeds the bankfull width of the natural channel. For channels with wide, adjacent floodplains, the stream simulation approach recommends installing floodplain relief culverts to facilitate partial floodplain flow continuity through the road fill and reduce the concentration of water through the main crossing structure during floods greater than bankfull flow. The replacement structure type and size, which can include a bridge or variety of culvert configurations, are determined by the stream simulation channel dimensions as well as any projected vertical and lateral adjustments of the stream over the service life of the structure. The mobility of the constructed channel bed material as well as the stability of key particles used to build grade controls in the bed of the road-stream crossing structure are analyzed to ensure that they have properties (mobility and stability) similar to those in the natural reference channel (Cenderelli et al. 2011).

The proposed design structure is also evaluated to provide sufficient hydraulic capacity and passage of debris during the 100-year recurrence interval design flood. Stream simulation structures are required to have headwater-to-depth ratios less than 0.8, meaning that adequate space exists between the 100-year flood elevation and the top of the road-stream crossing structure (Figures 3 and 4). This clearance provides room for debris transport and reduces the likelihood of ponding or backwatering on the upstream side of the crossing, which can create pressurized flow within the structure during large-magnitude floods. Observations and analyses of stream simulation structures show that the headwater-to-depth ratio for the 100-year design flood discharge is typically between 0.5 and 0.7. In other words, stream simulation structures typically have the ability to convey water and debris through the structure for flows well in excess of the 100-year flood. A road-stream crossing sized using the stream simulation method reduces or eliminates backwatering or ponding at the inlet during floods and makes those areas less prone to sediment and debris accumulation. Like a natural channel, a stream simulation channel is able to adjust its dimensions in response to a wide range of floods and sediment or wood inputs without compromising the movement needs of aquatic organisms or the hydraulic capacity of the structure (Gubernick and Bates 2003; Cenderelli et al. 2011).



Figure 4. Typical hydraulic design double culvert over Jenny Coolidge Brook, May 2010. Green Mountain National Forest showing estimated height of 100-flood design discharge in red. Photo credit: Brian Austin, Green Mountain National Forest.

The hydraulic capacity design method differs from the stream simulation design method in fundamental ways (Figure 5). Stream simulation design determines the size of the structure based on the physical dimensions of the natural channel first and foremost and evaluates hydraulic capacity as a secondary check to ensure sufficient conveyance of the 100-year flood with additional clearance for debris transport. In contrast, traditional hydraulic design methods give no consideration of the actual physical dimensions of the natural channel when sizing the road–stream crossing structure. Hydraulic design structures are sized to pass a design flood (e.g., Q10 flood, Q25 flood, Q100 flood) with headwater-to-depth ratios typically at 1.0 or greater (Hotchkiss and Frei 2007). Design flood discharge estimates are usually determined using regional regression equations that typically have standard error estimates greater than 40%. Additionally, regional regression equations used to predict design discharge were typically developed for larger drainages and are not necessarily applicable to small drainages, which add to the uncertainty of the discharge estimates. Recent analyses and predictions under a changing climate suggest that the set of return interval floods underlying hydraulic capacity designs are no longer valid. In New England, trends in measures of precipitation intensity (Huntington et al. 2009) and frequency of larger precipitation events increased by 85% since 1948 (Madsen and Wilcox 2012), and the recent record-breaking storm events such as Tropical Storms Irene, Lee, and Sandy (Douglas and Fairbank 2011) and the projected increases in total annual precipitation (Intergovernmental Panel on Climate Change 2007) and rain on snow events (Douglas and Fairbank 2011) strongly suggest the need for changing flood discharge estimates.

COST COMPARISON OF TRADITIONAL HYDRAULIC VS. STREAM SIMULATION DESIGNS

There continue to be significant challenges to designing and installing road–stream crossings for aquatic organism passage and flood resilience. The choice of a suitable design method to replace a failed road–stream crossing is almost always influenced by budgetary constraints, but the true cost of a crossing failure is rarely considered. The cost of a failure includes not only the cost to replace the structure itself but also the cost to replace other affected infrastructure and property (e.g., roads, houses) and delay costs from disruption in commerce and travel. These delay costs are often not considered in the replacement cost because they are experienced by traffic users, homeowners, and businesses and are not a direct expense to an agency's budget (Perrin and Jhaveri 2004). Failures during a major flood can be particularly problematic for towns because emergency replacement costs are generally higher than planned replacement costs. The loss of a road–stream crossing or associated damage to road infrastructure also threatens human health and safety by creating hazards and disrupting access by emergency services. Lastly, widespread road closures and detours can be detrimental to the tourism industry by creating the perception that the area is not “open for business,” as was the case across much of Vermont during the fall foliage season following Irene (Lunderville 2011).

Stream simulation design options typically have higher up-front installation costs than traditional hydraulic designs,



Figure 5. Stream simulation design culvert at Jenny Coolidge Brook, installed in June 2010, showing height of 100-year design discharge in red and height of Tropical Storm Irene flood level in blue. Photo credit: Brian Austin, Green Mountain National Forest.

making them appear less economical, particularly for highway and road maintenance departments facing chronic budget shortfalls. The installation cost of a structure (e.g., bottomless arch culvert) designed using the stream simulation approach varies with the type and size of the crossing selected and project site characteristics. Data from across the northwest United States suggest that a 50% increase in structure width results in a 20%–33% increase in total project cost (Gubernick 2011). A review of 2008 GMNF cost comparisons (Table 1) for the traditional and stream simulation designs on the GMNF found that stream simulation designs increased construction costs between 9% and 22%. Though a \$20,788 cost increase is significant, as was the case for the Bingo Road crossing, this increase quickly becomes more economical when compared to costs exceeding \$100,000 on road repairs after a flood (Tables 2–4).

Long-term maintenance and replacement costs should also be considered. Hydraulic designs (Figures 2a and 3) that constrict the stream channel can incur a yearly maintenance cost from debris removal and pose a greater risk of unexpected replacement costs from failure during large magnitude floods (Furniss et al. 1997). In contrast, stream simulation designs that span the bankfull channel (Figures 2c–2e and 4) have demonstrated minimal or no annual maintenance costs and are flood resilient and are likely to last longer than their projected service life (Long 2010). Galvanized steel culverts installed using the stream simulation design method have an anticipated service life of 50 to 75 years because the constructed stream channel

bed and margins protect the structure from abrasion as bed load moves through the crossing. By comparison, traditional galvanized steel culverts installed using the hydraulic design method typically last 25 to 50 years depending on the gauge of steel, water chemistry, and rate of abrasion by bed load movement (State of Idaho 1965). An agency or landowner should weigh the higher installation cost of using a stream simulation design method with the long-term costs of likely repeated replacement and repair of undersized culverts (Long 2010).

TROPICAL STORM IRENE CASE STUDY

On August 27–28, 2011, Tropical Storm Irene brought significant rainfall to much of New England and eastern New York, with many areas receiving over 16 cm of rain (Vermont Agency of Natural Resources 2011) that caused considerable damage throughout the Northeast United States. Over the 42-hour period across New England, total rainfall reached over 30 cm in many locations, inundating entire watersheds and drainage basins simultaneously. Record river levels were reached at 37 stream gages in New York, eight stream gages in Vermont and western Massachusetts, five stream gages in New Hampshire, and at least one stream gage in Connecticut and Maine. Flow magnitudes exceeded predicted 100-year discharge in many catchments. For example, the gage on the Ayers Brook at Randolph, Vermont, with a 79-km² drainage area and flow record of 71 years, recorded a peak discharge that greatly exceeded the 500-year flood flow estimate (Lunderville 2011).

Table 1. Cost comparison of traditional hydraulic design vs. AOP stream simulation design in the Green Mountain National Forest.

Estimated costs from damage survey reports					
Road no./name	Traditional culvert/replace in kind (\$)	Betterment/AOP stream simulation replacement (\$)	Anticipated % cost increase for AOP stream simulation design	Actual construction cost (\$)	Actual % cost increase for AOP stream simulation design
FR42.05.0 over Bingo Road	92,950.00	142,050.00	53	113,738.00	22
FR42B.00.0 over Bingo Brook	112,175.00	156,775.00	40	Never constructed, road decommissioned	NA
FR49.00.5 over Boyden Brook	93,800.00	140,700.00	50	Never constructed, Irene damaged site access road	NA
FR92.00.0 Over Goshen Brook	106,635.00	172,200.00	61	119,835.00	12
FR92A.00.0 over Hale Brook	104,700.00	130,250.00	24	113,725.00	9

Table 2. Costs to repair damages to National Forest System roads resulting from stream crossing failures in the upper Whiter River Watershed, Vermont, during Tropical Storm Irene, 2011.

Forest road no.	Road name	Stream name	Drainage area (km ²)	Bankfull width (m) based on regional curves	Failed structure type and size	Ratio of structure to bankfull width	Approximate repair cost due to crossing failure (\$)	Approximate total road repair cost (\$)
FR394	Townsend Brook	Townsend Brook	1.3	3.0	Native stringer bridge with approximately 1.5-m opening	0.50	81,000	104,000
FR226	Corporation Brook	Corporation Brook	4.4	5.0	2.0-m culvert	0.40	10,000	105,000
FR45	Chittenden Brook	Chittenden Brook	14.8	8.6	Bridge 11.6 m	1.35	175,000	190,000
FR35	Upper Michigan	Michigan Brook	19.9	9.8	3.7-m culvert	0.38	247,000	247,000
FR39	Texas Falls	Texas Falls Brook	NA	NA	Numerous 46- to 60-cm cross-drain culverts	n/a	82,000	82,000
						Totals	595,000	728,000

Source: Dan McKinley (GMNF, personal communication).

Table 3. Summary of town road infrastructure damages from Tropical Storm Irene, 2012.

Town	Total culvert inventory	Total number of failed culverts	Estimated cost of culvert repairs (\$)	Town minimum culvert standard	Typical culvert type
Granville	Town has no records	18	60,000 (pipes) and 39,000 (additional damages)	18-in. minimum diameter for town roads, Q25 hydraulic design for state roads	Spiral arch or pipe
Hancock	Town has no records	4	1.1 million (Churchville Rd.)	Same as above	Steel pipe
Pittsfield	237	25	114,000 (pipes and labor)	Same as above	Plastic pipe
Rochester	Town has no records	31	197,000 (four priority culverts)	Same as above	Steel pipe
Stockbridge	Town has no records	5	No records	Same as above	Varies

Table 4. Churchville Road culvert failure estimated costs to the Hancock community.

Example of costs incurred to the town of Rochester at Churchville Road from debris plugging and failure of a single undersized culvert	
Structure	Estimated cost (\$)
Culvert	0 (no damage to culvert)
Churchville Rd.	1.1 million
Unmaintained road improvement	84,000
Traffic delay costs (gas, lost work time, etc.)	To be determined
Total cost	1,184,000+

Commercial, residential, and transportation infrastructure across the region was significantly damaged from high water, debris, and erosion. Flood damage was the most severe along tributaries to Lake Champlain in Vermont and the Adirondacks of northeastern New York, as well as in the Connecticut River Valley in western Massachusetts, New Hampshire, and Vermont. Thirteen towns in Vermont became isolated from bridge and culvert washouts (Lunderville 2011). The state of Vermont incurred damage to over 200 state road segments and 200 state bridges, and towns reported over 2,000 road segments, 277 bridges, and nearly 1,000 culverts damaged or destroyed by flooding from Irene. Vermont went into disaster mode and state and federal emergency management agencies began responding to 225 of Vermont's 251 municipalities (Lunderville 2011). Across the state, there were multiple instances where undersized culverts failed. This type of widespread infrastructure damage from large flood events and the persistence of undersized road-stream crossings is not unique and has occurred across the country in Maine, New York, Massachusetts, Pennsylvania, both South and North Dakota, and Alaska (J. Rowan, USFWS, personal communication).

DAMAGES IN THE UPPER WHITE RIVER WATERSHED

The White River is Vermont's fourth largest subbasin, draining an area of 1,839 km² within the Connecticut River Basin (Figure 6). Elevation ranges from 1,067 m along the spine of the Green Mountains at the western edge of the watershed to approximately 183 m at the confluence with the Connecticut River on the eastern edge of the watershed (Ruddell et al. 2007). As the longest undammed tributary to the Connecticut River, the White River has been very important to state and federal efforts aimed at revitalizing Atlantic Salmon (*Salmo salar*) populations (WRP 2012). The White River watershed was designated as a Special Focus Area of the USFWS Silvio O. Conte National Fish and Wildlife Refuge in part because the watershed provides nursery and rearing habitat for juvenile Atlantic Salmon and potential spawning habitat for adults (WRP 2012). Eastern Brook Trout are the dominant species in the headwater tributaries and are a focus of USFWS and USFS aquatic connectivity and habitat restoration efforts.

The upper White River main stem comprises approximately 38.6 km of stream extending from the headwaters of the White River in Ripton to the confluence with the Tweed River in Stockbridge (Ruddell et al. 2007). The five valley towns of Stockbridge, Rochester, Hancock, Pittsfield, and Granville are located along the upper White River and bordered to the west by the GMNF. Each town has its own independent government and town populations range from 298 to 1,139 (U.S. Census Bureau 2010). The GMNF includes 40% of the upper White River watershed north of Stockbridge. Development occupies approximately 5% of the watershed and has occurred mostly along the river corridor and has negatively impacted water quality and aquatic habitat (WRP 2012).

Between 2004 and 2007, the VFWD inventoried 1,501 road-stream crossings statewide on streams greater than 2.4 m bankfull width. It found that that only 5.3% provided full passage of aquatic organisms, and nearly 91% significantly constricted the natural channel width (structure width to bankfull width ratio less than 0.75). A subset of the inventory is located in the upper White River subbasin. Of the 43 culverts surveyed, 15 failed during Tropical Storm Irene, provided either reduced or no AOP, and had culvert width to bankfull width ratios ranging from 0.27 to 0.90, with an average of 0.54. Based partially on the inventory data, in 2009 the VFWD produced AOP guidelines for the state that identified stream simulation design as its preferred approach for road-stream crossings (VFWD 2012).

On the entire GMNF, Irene damaged 40 km of transportation infrastructure at an estimated repair cost of \$6.4 million. In the upper White River watershed, the GMNF suffered \$728,000 in road damage, with an estimated 70% due to debris plugging at road-stream crossings (Table 2). Three of four road-stream crossings that failed were hydraulic designs with crossing width to bankfull width ratios less than 0.52. These undersized hydraulic culverts were also identified aquatic organism passage barriers. The fourth crossing, a bridge over Chittenden Brook located on an alluvial fan (a natural depositional zone), was constructed in 2010 with a span greater than bankfull width for increased flood capacity and AOP. During Irene, large bank failures upstream delivered a tremendous amount of woody debris downstream, which settled on the alluvial fan and plugged the bridge, causing the stream to overtop the bridge and wash out the bridge approach—the design failure point—leaving the bridge undamaged. The Chittenden Brook example underscores how no road-stream crossing design can guarantee avoidance of damages during large floods but that site location and adopting an ecological approach with flood resiliency as a primary objective can reduce infrastructure damage considerably.

The towns of Rochester, Hancock, Pittsfield, and Granville suffered damage to or complete loss of 70 road-stream crossings. These communities were left isolated without power and water for three days due to road damage and road-stream crossing washouts. Following a presidential disaster declaration, the towns were eligible to apply for financial assistance through the Federal Emergency Management Agency's (FEMA) Public Assistance Grant Program for the repair or restoration of infrastructure and facilities to predisaster condition (Lunderville 2011). Coauthor Campbell met with either the road foreman or town administrator for each of these towns during April 2012 to obtain flood impact information (Table 3). Where possible, they provided Irene-induced crossing failure information, such as culvert size and location, cost data from FEMA project worksheets, and descriptions of major failures.

The towns of Rochester and Hancock provided several specific examples of extensive impacts from the failure of a single road-stream crossing. The failure of a 3.4-m-diameter culvert at Nason Brook in Rochester resulted in an estimated \$1 million in damages to Woodlawn Cemetery. During Irene, the culvert became plugged with debris and then redirected a large volume

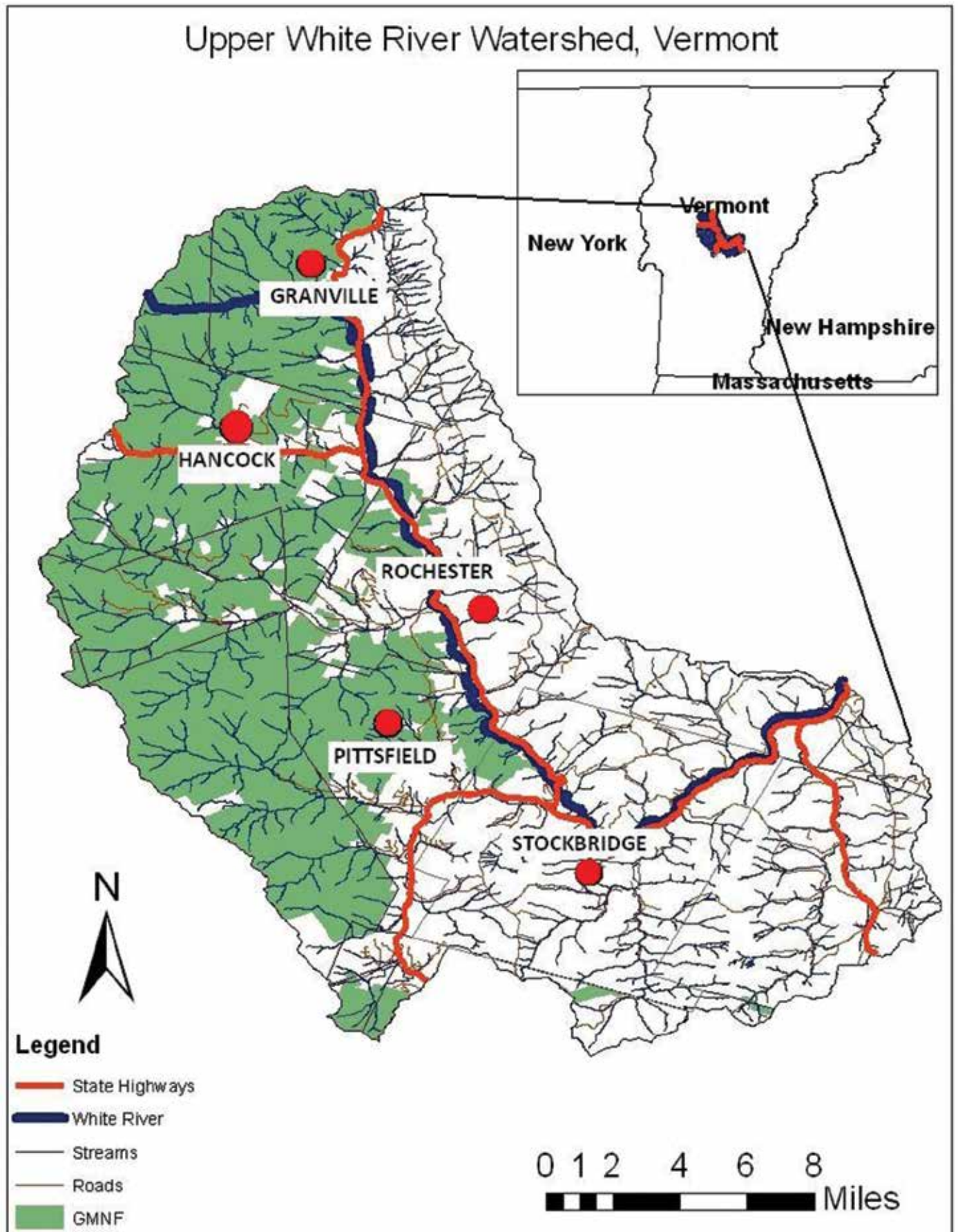


Figure 6. Upper White River watershed study area.

of water onto the cemetery grounds, unearthing 50 caskets and strewing their remains throughout downtown Rochester (Davis 2011). The USFWS and the WRP are currently working with FEMA and Rochester to replace the failed culvert. The cost for this culvert to be upgraded to a flood resilient 9.7-m bridge is approximately \$50,000, which the USFWS was able to obtain specific to this site at a lower than average cost.

In Hancock, on Churchville Road, a 3.6-m-diameter steel pipe, originally designed to pass a 25-year recurrence interval flood, failed and resulted in long-term travel disruption and major damage costs. Though the culvert itself remained intact, the floodwaters overtopped it and washed out more than 350 m of Churchville Road, which was not replaced until August 2012, with a repair cost of approximately \$1 million. A nearby unmaintained road had to be upgraded in order for residents to regain access to the main highway, at a cost of approximately \$84,000, with residents bearing the cost of driving an additional 2 miles each way to reach Vermont Route 100. The total cost of the culvert failure and associated damage is at least \$1,184,000, excluding traffic and delay costs (Table 4). In both examples, had the culverts been appropriately sized, it is unlikely that these damages would have been as disruptive and costly.

THE LINK BETWEEN AQUATIC ORGANISM PASSAGE AND FLOOD RESILIENCE

In contrast to the extensive damage experienced by towns in the Vermont case study, two stream simulation design culverts that were installed on the GMNF before Irene not only survived the storm but incurred no maintenance or replacement costs. USFS fisheries and engineering staff had targeted the upgrade of these two hydraulically designed pipes on Forest Service roads for replacement in 2010 and 2011 because they were barriers to the upstream movement of eastern Brook Trout and other aquatic organisms and because they were identified as a risk for debris plugging and failure in large storm events. These two crossings located on Sparks Brook (Figure 3), immediately adjacent to the upper White River watershed, and on Jenny Coolidge Brook (Figures 4 and 5), also in the Connecticut River Basin, were designed to span the bankfull dimensions of the natural channel, resulting in structures with sufficient hydraulic capacity to convey flows in excess of the Q100 peak flow while providing additional headwater clearance for debris transport. Preliminary hydraulic analysis of Jenny Coolidge Brook estimates peak storm discharges during Irene exceeded the 500 year recurrence interval (R. Gubernick, USFS, personal communication). In addition, on Joe Smith Brook in the upper White River watershed, a hydraulic design culvert was recently replaced with a Q100 bottomless arch to provide greater flood capacity and a natural bottom for AOP. Though this road–stream crossing upgrade was not strictly a stream simulation design with regard to gradient, channel banks, and substrate size, the structure still spanned the bankfull dimensions of the natural channel and it also survived Irene undamaged. Three additional stream simulation crossings located on GMNF listed in Table 1 were still in the early stages of construction when Irene hit and were not included in the flood resiliency analysis but will allow

for a more robust comparative analysis with traditional culvert designs during future floods.

Though additional monitoring is needed, other examples demonstrate the flood resilience of road–stream crossings designed for aquatic organism passage across the region impacted by Irene. In Worthington, Massachusetts, a double 3-m box culvert, which prevented Brook Trout and resident darter passage on a 9-m bankfull section of Bronson Brook, a tributary of the Westfield River, catastrophically failed in an August 2003 storm. A 12-m arch culvert replacement has since survived several major storms, including Tropical Storm Irene, without damage to the structure, road or adjacent stream banks (A. Singler, American Rivers, personal communication). In Hancock, New York, between 1996 and 2005 three flood events caused damage to an undersized and perched pipe culvert on Big Hollow Creek, which was a barrier to trout movement. In those 9 years, Delaware County spent over \$70,000 to repair damages to the culvert as well as the road and adjacent ditches. In addition, the detour length associated with closure of the road for repairs was 18 miles. Late in 2005, with hazard mitigation funding assistance from FEMA, the county installed a more ecologically beneficial three-sided concrete box culvert with a natural bottom, designed to convey a 100-year storm and provide fish passage at all flow levels, for a cost of \$143,000. The improved crossing has survived seven federally declared flood disasters, including Irene, without significant damage since its replacement in 2005 (W. Reynolds, Delaware County Department of Public Works, personal communication).

The flood resilience of stream simulation designs has been documented during significant flow events elsewhere. On the Siuslaw National Forest on the Oregon coast, eight stream simulation design crossings installed in 2003 have weathered floods up to a 20- and 25-year recurrence interval range. Though adjustment of the streambed constructed beneath the road crossing ranged from negligible to significant, all eight crossings have maintained AOP, successfully passed sediment and debris, and avoided any infrastructural damage (B. Ellis-Sugai, USFS, personal communication). In southeast Alaska, the Tongass National Forest installed 93 stream simulation design crossings since 1998 (94% installed between 2000 and 2005) that have survived flood events in the estimated 25- to 50-year recurrence interval range without major failure and have maintained fish passage to state standards at 98% of locations (J. McDonell, USFS, personal communication).

BARRIERS TO IMPLEMENTING ECOLOGICALLY BENEFICIAL ROAD–STREAM CROSSINGS

Extreme events such as Tropical Storm Irene can create a window of opportunity for increased investment in disaster mitigation; however, for the towns in the White River Valley, existing regulations and funding mechanisms hindered the replacement of damaged road–stream crossings to increase aquatic organism passage and flood resilience. Under the Public Assistance Program, FEMA funds between 75% and 90%

of the estimated cost for a culvert replacement if it passes the “50% rule” (a structure is eligible for replacement if the repair cost exceeds 50% of the replacement cost). Otherwise, FEMA provides financial assistance at the 75%–90% rate to repair the original structure but not necessarily the costs to repair roads or other structures damaged by the culvert failure. In some cases, the culvert itself may remain in place while the road fails, but because the culvert is technically undamaged it will not pass the 50% rule. For example, Hancock was ineligible to receive public assistance funds to replace the Churchville Road culvert because the structure survived the flood but was eligible to receive public assistance funds to repair the road damaged by the plugged culvert. When a culvert is eligible for replacement, FEMA only provides financial assistance to rebuild the structure to its predisaster condition or up to passing the Q25 with 0.3-m clear space and 0.61-m embedment. If a town chooses to upgrade a failed culvert and does not have specific guidance from a state natural resources agency, FEMA reimburses the estimated cost of repairing or replacing the original culvert and the town must bear the cost difference for the upgrade. Towns face difficulties meeting these rules and simultaneously funding the additional costs to upgrade to stream simulation designs in the midst of expensive disaster recovery efforts.

Towns and counties may apply for funding to replace or upgrade road–stream crossings through FEMA’s Hazard Mitigation Grant Program (HMGP), but this grant money is not available until 6 months after the disaster declaration, and total funding made available is not determined until a full year after the disaster. The amount of money available through this program is based upon the total amount paid out under emergency assistance in the months following the declared disaster. More important, the state prioritizes use of the funds and may not necessarily include road–stream crossing upgrades among eligible projects. Applying for HMGP funding requires a cost–benefit analysis and a demonstration of three historic losses at the site (Munroe and Crosby 2012). In order to meet this requirement, towns need to maintain detailed records of previous failures. FEMA does not maintain an accessible database of this information. In addition, FEMA only requires that project worksheets be kept by an applicant for three years from the date the state closes a grant (FEMA 2011), decreasing the likelihood that towns have the necessary information for HMGP eligibility if previous failures occurred before that time period.

Based on the information we observed, local governments face significant barriers to upgrading undersized road–stream crossings that obstruct aquatic organism passage and present chronic failure risks. These impediments include inconsistent and poorly defined crossing standards and limitations on FEMA assistance for structure upgrades and replacements. For example, three separate hydraulic standards apply to the towns in the upper White River watershed. The 1998 Vermont Department of Transportation *Hydraulics Manual* (VTrans 2001) requires state highway crossings to have a minimum design capacity of Q50 and town highway and local road crossings to have a minimum

of Q25. The Vermont Department of Transportation revised the Town Road and Bridge Standards in 2011 to recommend that towns adopt a 45.7-cm-diameter and a Q25 conveyance as their minimum requirement for new road–stream crossings, allowing for structures to span less than half of bankfull width. For a stream alteration general permit, the Vermont Agency of Natural Resources requires crossings to be at least 1.2 times bankfull width, although applicants can apply for an individual permit to include a smaller crossing. Following Tropical Storm Irene, FEMA allowed a minor increase in culvert size of 0.3 m for debris and 0.61 m for embedment and replaced to the lowest standard adopted by an individual town. Because Pittsfield had recently changed the town culvert standard to 46 cm, it was eligible to upgrade eighteen 38-cm diameter culverts to 46-cm-diameter pipes under FEMA’s Public Assistance funding. Granville did not upgrade its town culvert standard and was only eligible to replace 13 of 18 destroyed culverts with in-kind replacements funded through FEMA’s Public Assistance program. The observation that all documented failed crossings in the study area had crossing width–to–bankfull width ratios of less than one and that these crossings met state minimum criteria underscores the need for a revised approach to achieve greater flood resiliency.

Economic justification for traditional hydraulic design has focused on short-term costs and not long-term persistence. The economic, societal, and natural resource costs of these failed road–stream crossings and the adjacent infrastructure are not included in up-front cost calculations. At the federal, state, and municipal levels, the increased benefits of building ecologically beneficial crossings for AOP and greater flood resiliency are not calculated. Time constraints and pressures to reopen failed roads and return emergency services to communities generally drive quick repair of infrastructure to a working condition rather than long-term flood resiliency.

Other cultural and political factors impede a systematic approach to replacing culverts and road crossings to ecologically beneficial standards. In Vermont and across New England, independent town governance and highway departments discourage application of uniform techniques and the effective transfer of skills and training in river dynamics, engineering, hydraulics, and aquatic ecology needed to design and build flood resilient road–stream crossings. In addition, the misperception that “fish-friendly” crossings have no economic or societal benefit outside of natural resource protection is commonly heard in New England following flood events.

RECOMMENDATIONS

Based on the upper White River watershed case study, the following recommendations are presented to federal and state agencies, communities, and nongovernmental organizations in order to better integrate ecological objectives into road–stream crossing design and provide more effective flood resiliency across the country.

Prioritization

- Target “repeat offenders”: Before the next major storm, replace undersized culverts that have caused extensive road and property damage and/or failed more than once. This will require better record-keeping by communities.
- Identify priority sites at a watershed scale for aquatic health or critical populations and road–stream crossings that have high social significance; for example, high-volume traffic, major commuting delays, provision of critical emergency services, etc. In southeastern Massachusetts, The Nature Conservancy and a regional planning agency collaborated to identify key locations in the transportation network where both river continuity and public welfare were impacted by existing structures; these were included in the Regional Transportation Plan as priorities for improvement (South-eastern Massachusetts Metropolitan Planning Organization 2012).

Regulatory

- Work with FEMA and affected agencies to address regulatory road blocks to restoring infrastructure that would be more resilient to flood events in future years.
- Coordinate among federal and state agencies, including FEMA, the Natural Resources Conservation Service, state emergency management, departments of transportation, and environmental agencies to adopt as a standard the latest technologies that incorporate multidisciplinary, ecologically beneficial approaches to road–stream crossing such as stream simulation design.
- Change regulatory preference for in-kind emergency repair to upgrading road-crossing structures based on flood resiliency through strong guidance on interpreting FEMA Sections 404 and 406 funding, particularly the definition of what constitutes a road–stream crossing failure. It is currently common practice to reuse clearly undersized culverts that have been washed out by a flood and simply rebuild the road with new materials.
- Consider changes to language in U.S. Army Corps of Engineers 404 Nationwide Permit process to provide more prescription for ecologically beneficial road–stream crossing criteria consistent with the intent of the Clean Water Act, which requires the protection and restoration of the physical, chemical, and biological integrity of the nation’s waters.
- Adopt consistent state and town standards for road–stream crossings that incorporate AOP concerns and increased flood resiliency. FEMA replaces structures to the lowest standard adopted by the local government.

Funding

- Adopt an incident command structure for flood-affected areas modeled after the National Incident Management System approach to wildfires and other disasters impacting communities and/or regions. Place high priority on deployment of an interagency flood response “Strike Team”

composed of fluvial restoration, engineering, and fisheries experts to flood-affected regions immediately (see Sidebar).

- Allow other federal agencies to contribute to the state and town cost shares of 12.5% typically required by FEMA for projects that serve a role in providing multiple benefits and flood resilience. Higher upfront project costs are an impediment to towns when they are forced to replace many structures at once.
- Increase Hazard Mitigation Grant Program share beyond the current 10%–15% of total cost of disaster reimbursement monies.
- Use a collaborative whole watershed approach similar to the USFWS’s Irene recovery effort when prioritizing road–stream crossing upgrades in order to leverage resources, focus efforts, and address impacts at the watershed scale (see Sidebar).

Education and Future Research

- Expand interagency workshops to increase understanding of ecologically beneficial approaches to road–stream crossing design, true life cycle costs analysis, and river dynamic principles modeled after the highly successful USFS stream simulation design and USFWS fish-friendly crossing workshops. Target state and county transportation, engineering staff, and heavy equipment operators who are routinely contracted for postflood remediation work. Consider development of an interagency-approved certification program for such workshop attendees for ecologically beneficial approaches to designing and constructing road–stream crossings.
- Conduct further research of life cycle cost analysis for federal and state reimbursement criteria for failed structures to include likelihood of failure based on crossing width : bankfull width ratio.
- Track crossing failures and crossing : bankfull width ratios nationally to help agencies better understand failure causes and identify trends of failure associated with this metric (Perrin and Jhaveri 2004).

In summary, this article makes the case that adoption of the stream simulation design approach provides multiple benefits to communities, state, and federal governments, particularly as extreme weather events become a more common occurrence. Road–stream crossing infrastructure represents large investments that are currently susceptible to catastrophic failure during large flood events, resulting in significant economic and societal costs to communities. This case study suggests that investing in stream simulation designs with flood resiliency as a primary objective has the potential to reduce these economic and societal costs through reduced failure rates and lower maintenance costs while maintaining important ecological values. Increased interagency coordination and prioritization of geomorphic, engineering, and ecologically based designs for road–stream crossings are needed across federal, state, county, and municipal scales to help prevent a recurrence of this kind of extreme damage and disruption experienced by Vermont and much of New England following Tropical Storm Irene.


USFWS AND MOBILIZATION OF A PILOT “STRIKE TEAM”

In September 2011, the USFWS Northeast Region mobilized various technical field staff for immediate post-emergency engineering and technical support for fish passage and stream restoration recovery needs following Tropical Storm Irene in Vermont and New York. The USFWS dedicated roughly \$132,600 to the upper White River watershed response, including \$32,584 for staff time through the month of October 2011 and \$100,000 in project funding to the local grassroots organization the White River Partnership (WRP) that focused on the town of Rochester through an agreement funded by the National Fish Passage Program. Based on previous surveys to prioritize aquatic organism passage needs for Atlantic Salmon and eastern Brook Trout in collaboration with the WRP, the USFWS staff provided review of nine road–stream crossing sites, restoration of two sites, data collection on four other sites, and a technical review of all projects. The USFWS has already developed design plans to restore fish passage at five additional sites in Rochester. The upgrades involve replacing traditional hydraulic designs with bottomless arch culverts that exceed measured bankfull width, as well as the diameter of the standard Q25 hydraulic design width by a range of 1.3 to 2.4 times and the flow area of the Q25 hydraulic design by 2.4 times on average. In all cases the USFWS provided towns with design plans to improve both fish passage and flood resilience in conjunction with repair and cost estimates from FEMA.

In the case of the upper White River watershed, the USFWS response to local communities was enhanced through partnership with the USFS GMNF, which provided additional technical expertise and project funding. Identification, organization, and deployment of interagency as well as intra-agency strike teams in collaboration with local and state governments and non-government organizations has the potential to increase response capability in terms of speed and duration, provide for comprehensive support across broader geographic areas, and establish continuity from the federal government to local governments. Yet efforts to address a larger storm or respond to a wider area of damage would have exhausted agency capacity to deliver critical services, underscoring the need for coordinated interagency deployment of technical experts to respond to flood-damaged communities.

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The efforts of the United States in reference to the introduction of useful food fishes should not be limited to the salmonidae already mentioned (to which the various species of trout, salmon, white-fish and smelts belong) and to the shad, as many other kinds yet remain for consideration. The land-locked salmon, the European char and the smelt, will be available for all ponds or lakes of a certain extent and temperature. In these they will pass the greater part of their time, running up into the tributaries or outlets to spawn. The great Danube salmon, which sometimes reaches the weight of 100 pounds, would find a perfectly suitable residence in the Mississippi river and its tributaries, feeding on the worthless chubs, suckers and cat fish so abundant therein. The alewife can be propagated to a much greater extent than at present. The sterlet, a kind of small sturgeon found in the Volga and in Russia, is esteemed far beyond the turbot, will thrive in the Mississippi valley and in the lakes. The gourami, an East India fish, can be placed to great advantage in the mill-dams, ponds, etc., of the south, thriving as it does in very warm water and feeding entirely on vegetable matter. It attains a weight of twenty pounds or more, grows with great rapidity, and is unsurpassed in the excellence of its flesh.

Spencer F. Baird (1873): National Fish Culture, Transactions of the American Fisheries Society, 2:1, 25–32.