Mimicking Mother Nature
by Megan Hall and Steve Moler

Washington State constructed an engineered logjam to help safeguard a vital roadway from chronic flooding and at the same time improved fish habitat.

WSDOT built this engineered logjam on the bank of the Hoh River to help prevent erosion of U.S. Highway 101. The person in the center of this picture provides perspective on the magnitude of the structure. Photo: Herrera Environmental Consultants, Inc.

For the better part of two decades, a remote two-lane stretch of U.S. Highway 101 in western Washington State took a recurring beating from the floodwaters of the Hoh River, which flows to the Pacific Ocean from the glaciers and rainforest of the Olympic Mountains. Major floods in 1981, 1997, 2001, and 2003 inflicted heavy damage on a particularly vulnerable road section where the Hoh takes a 90-degree turn and slams head-on into the highway embankment and then flows along it for about 366 meters (1,200 feet) before turning away. The vulnerable segment, at the highway's Milepost (MP) 174, is about 24 kilometers (15 miles) south of Forks, WA, in Jefferson County.

The Washington State Department of Transportation (WSDOT) spent $2.2 million over a 12-year period on emergency repairs, mostly placing rock groins and riprap revetments extending from the roadway shoulder to the river below. However, significant erosion of the riverbank and shoulder continued.
101 remained in danger of severe undercutting and possible loss of the entire roadway section from catastrophic failure of the unstable slope.

The battered highway, in addition to being one of the State's most scenic routes, is a critical economic lifeline to Washington's northwestern coast, because it is the only route on the Olympic Peninsula capable of carrying commercial truck traffic. A lengthy closure was not feasible.

**Innovation Needed**

The WSDOT engineers urgently needed to find a long-term solution that would not only protect the highway infrastructure, but also would minimize environmental impacts. With the help of the Federal Highway Administration (FHWA), WSDOT was able to implement an innovative strategy consisting of an emerging technology called "engineered logjams" (ELJs).

These manmade logjams mimic those found in nature. In a natural river system, logjams typically form when a large tree falls into the water and becomes embedded in the river bottom, creating a snag that captures additional logs and debris moving downstream. Such logjams are capable of redirecting the channel and slowing the water's destructive forces. As an additional benefit, the logs and debris can create or enhance fish habitat.

Similarly, in the right situations, the construction of ELJs can have beneficial effects on the natural environment by improving fish habitat, while protecting critical transportation infrastructure by stabilizing and taming river channels during flooding. "Despite seeming counterintuitive, placing woody debris in rivers as stable logjams can provide an effective means of managing unstable woody debris that poses a risk to infrastructure," says geomorphologist and leading ELJ expert Tim Abbe of Herrera Environmental Consultants, Inc. WSDOT hired Abbe as a consultant on the Hoh River project.

The project is believed to be the first nationally significant application of ELJs for infrastructure protection, and experts at WSDOT and elsewhere are keeping a watchful, hopeful eye.

(Above) As shown in this aerial shot, the Hoh River takes an abrupt turn and slams head-on into Highway 101 along a quarter-mile
section in the area of MP 174, leaving the highway vulnerable to erosion during the rainy season.

(Above) Floodwaters in March 1997 jumped the highway embankment and took out a portion of the southbound lane of Highway 101 near MP 174, prompting WSDOT to close the highway temporarily and make costly emergency repairs.

"Many methods have been used routinely in the past to prevent erosion--rocks, car bodies, dikes, walls--all of which have had temporary success," says John Hart, the lead WSDOT engineer on the Hoh logjam project. "But ELJs may give us the long-term, environmentally friendly method we've been looking for to protect property and infrastructure."

**Why Use Logjams?**

"Expanding the use of ELJs for infrastructure protection is what separates this project from other logjam projects," says Hart. Prior to the Hoh River solution, most ELJ projects in the past were constructed for habitat enhancement and relatively small-scale bank protection.

**Enhancing Fish Habitat With Logjams**

According to geomorphologist Tim Abbe, woody debris in rivers is a positive and necessary process in many situations. Woody material helps create diverse fish habitat, protect species, enhance water quality, and sustain complex ecosystems. Specifically, currents through the logs scour deep pools where fish, particularly salmon, can rest, find refuge, and reproduce. Logjams also shade the water so that it remains at a cool temperature for spawning, and the decaying logs serve as a source of nutrients for plants and fish.

Studies have shown that fish living around structures of woody debris are healthier than those around rock structures, according to Roger Peters, a fisheries biologist with the U.S. Service. In an April 6, 2005, article in *Environmental Science & Technology Online* titled "Hoh River logjams," Peters wrote: "Rock is just not that good because it does not allc of diverse habitats."

So what prompted WSDOT to try ELJs, something so new and different?
After the 2001 flood inflicted heavy damage on MP 174, WSDOT conducted a reach analysis (a detailed site investigation) of the river along a 13-kilometer (8-mile) section upstream and downstream from MP 174. The reach analysis provided WSDOT with a full understanding of the problem, based on sound science and engineering, and a thorough assessment of long-term solutions for protecting Highway 101 in an environmentally friendly way.

Data from the analysis suggested that the area's relatively unstable glacial geology may have caused large quantities of sediment to be deposited in the water. Over thousands of years, these sediments accumulated in large bars that, over time, caused the river to migrate back and forth across the valley. During the past 50 years, erosion from extensive logging in the valley led to increased sediment deposits. Also, during major floods, the river's accelerated side-to-side movements increased erosion and destructive forces at MP 174 and other problem areas.

The reach analysis found that doing nothing would leave the highway vulnerable to continued flood damage and, possibly, catastrophic failure. Options for action included moving the highway away from the river, which would have involved carving a massive roadcut into a landslide hazard zone, at an estimated cost of $40 million, or constructing a bridge structure at an estimated cost of up to $20 million. Alternatively, the construction of ELJs provided a potentially long-term solution that incorporated habitat-forming elements, at an estimated cost of about $7 million. The study concluded that ELJs were the best option.

After the 2003 flood, during which the river chewed up most of a 214-meter (700-foot)-long riprap revetment and required $500,000 of additional riprap for emergency temporary stabilization, WSDOT asked FHWA for help. After reviewing the reach analysis, design, past history, and cost data, FHWA determined that the site qualified for funding under the Emergency Relief (ER) program and approved $7 million to implement the ELJ alternative. The logjam approach was approved as a "betterment involving added protective features" under the provisions of the ER program.

"Band-aid recurring repairs were no longer considered cost beneficial, and a long-term solution was in order," says Gary Hughes, operations team leader in FHWA's Washington Division. Other regulatory agencies agreed. The U.S. Army Corps of Engineers and the U.S. Fish and Wildlife Service strongly endorsed the project and issued the appropriate emergency approvals.

"When we reviewed WSDOT's proposal, we really liked what we saw," says Dan Mathis, FHWA's division administrator for the State of Washington. "We were impressed with how their solutions dealt so well with balancing both engineering and environmental issues. Instead of the same old solution of rock revetments, they came to us with an innovative plan."

The novel approach to solving chronic flooding problems excited engineers at WSDOT as well. "Everyone involved in this project was ready for something new," says WSDOT hydrologist Jim Park. "This project showed that we can think 'outside the box,' that we're willing and able to develop innovative new approaches and get out of situations where we keep doing the same old things over and over again."

**Engineering the Right Logjam**

The Hoh River ELJ project near MP 174 included construction of four logjam structures in the main channel to divert the river into side channels and help dissipate and redirect the destructive energy. The project also included six bank ELJs extending 15 meters (50 feet) into the channel along the roadbank, plus two smaller bank ELJs, to prevent the river from eroding the highway.
The Inspiration Behind the Engineered Logjam

Before European settlers came to North America, logjams littered rivers and streams in heavily forested areas, helping tame the rivers and creating vast and complex networks of wetlands rich in fish and wildlife. But early pioneers considered logjams and other woody debris a safety hazard and an impediment to river transportation and hence to agricultural and industrial development. Pioneers cleared many rivers and streams of snags, jams, and old-growth trees, and transformed the waterways into simple channels, thereby reducing the wood supplies needed to create natural logjams.

Geomorphologist Tim Abbe conceived the idea of engineering logjams to protect human infrastructure during a hike in 1991. "I came upon a natural logjam and noticed that the logjam was directly influencing the hydraulics and morphology of the stream," Abbe recalls. "Here was this deposit of wood affecting where the stream went and how it behaved."

This observation inspired Abbe to begin considering the idea of building manmade logjams to return rivers to their natural state, to the extent possible for any given situation. In 1995, he supervised construction of what is believed to be the first ELJ project in the United States—and possibly the world—to provide emergency bank protection for private land along the Upper Cowlitz River near Packwood, WA. For this project, Abbe designed three logjam structures using trees found onsite, already fallen over and still retaining their root-balls.
He found that the root-ball is a critical factor in the stability of a river snag, as it acts as both a plow and an anchor. As flow hits the root-ball, it scours the riverbed, and the root-ball sinks further into the substrate to create a snag that can resist even the most formidable floods. This self-strengthening process is what gives natural logjams some of their structural integrity and durability.

When conducting additional research, Abbe found that, in at least one Washington river, natural logjams had lasted for more than 1,000 years. The ELJs constructed on the Cowlitz River withstood a 25-year flood only 6 weeks after being constructed, and the landowner has actually regained some of the previously eroded land, as a result of sedimentation behind the logjams.

Since 1995, more than 50 ELJ projects have been constructed in the Pacific Northwest and 15 in Australia. All are functioning today as intended.

"Reintroducing wood into streams and rivers is not a passing fad," says Abbe. "It's a scientifically recognized component of restoring Pacific Northwest river ecosystems and is also essential to salmon recovery."

Prior to construction of the logjams, a risk assessment was conducted to estimate the maximum scour depths during a 100-year flood. Designing and building for a 100-year flood is the current engineering standard because building for more than that would entail great additional cost. The WSDOT design team calculated contraction scour, abutment scour, and local pier scour to estimate total scour for all the ELJ structures based on an equivalent bridge pier width. It was found that during a 100-year flood, scour could possibly extend 9 meters (30 feet) below the river bottom. Therefore, the WSDOT design team and contractor considered several alternatives to prevent undercutting, such as extending the ELJs deeper, constructing a scour apron of large rock beyond the perimeter of the ELJs, or extending a scour curtain of steel sheet piles beneath the perimeter of the ELJs to create a continuous rigid barrier that would prevent undercutting of the structure. The WSDOT designers chose the sheet pile scour curtain, deciding that it would create the least disturbance and highest level of protection for the cost.

The construction crew installed the scour curtain at each of the four midchannel logjams in the shape of a U, with the open ends downstream. To stabilize the scour curtain, the sheet pile extends below the depth of maximum expected scour and upward into the base of the ELJ structure. The curtain is three-sided and interlocking, so if the river undercut the ELJs to expose the scour curtain, racked logs in the ELJs are expected to settle into the scour hole, thereby providing further protection to the scour curtain.
The design team used one-dimensional (depth- and width-averaged flow) and two-dimensional (depth-averaged flow) numerical models to estimate the hydraulic conditions the ELJs would be subjected to during flood events. The models helped in determining critical design factors such as the location and size of the ELJs, pile size and depth, the size and number of logs, and backfill material. Modeling also was a key tool in evaluating the river's response to the proposed structures, particularly with regard to erosion and flood hazards. The ELJs were ultimately designed to handle flows exceeding a 100-year flood of 2,067 cubic meters (73,000 cubic feet) of water per second. "These logjams were designed to last a long, long time," says Abbe, the geomorphologist. "We engineered them with the same considerations and detail we would apply to designing a bridge with a design life of 75-100 years. They have to be built using sound engineering standards and factors of safety to protect human life and property."

The construction crew stacked and interlaced a 9-meter (30-foot)-high matrix of large logs with the H-pile grid at the core of each...
midchannel ELJ. More than 100 smaller logs were tightly packed into a pile of debris at the upstream end of the structures. Large rocks and river gravel then were backfilled into voids in the log matrix, which further increased the ELJs strength to a safety factor of more than 2, meaning the structures are more than twice as strong as the maximum forces expected to be exerted during a 100-year flood.

The design team conducted an extensive analysis of historical channel migration patterns to predict future changes in the river and the implications for the project. The analyses indicated that the river would continue to shift throughout its channel migration zone, so the ELJ structures were designed to accommodate changes in the river's location, including a 180-degree change in the channel approach. The designers also estimated the sediment transport likely to result from the proposed design, particularly the new diversion channel and its potential downstream effects.

Ensuring minimal backwater impacts was another concern. The design team predicted a maximum change in the backwater level of 0.46 meter (1.5 feet) directly upstream of the midchannel structures, diminishing to zero 305 meters (1,000 feet) upstream of the midchannel ELJs. The localized backwater effect was essential to meet the project goal of redirecting a portion of the river's flow through the diversion channel and away from the highway. The designers expected the diversion channel to enlarge (which it did) after the project was implemented, which in turn diminished the backwater effect. A thorough analysis showed that backwater would not impact developed areas nor change the Federal Emergency Management Agency's floodway delineations.

A Systematic Protocol for Designing and Constructing ELJs

In recent years, scientists and engineers from the Pacific Northwest have developed construction practices for ELJs to ensure that they are built to high standards. To this end, geomorphologist Tim Abbe developed the following logjam design protocol:

1. **Reach Analysis**—attempt to answer such questions as: Why is the road or infrastructure threatened? What are the processes causing the damage? Are things getting worse or better? Should the changes be documented? Historic changes in the river, sediment transport and deposition, materials and stability, hydrology and hydraulics, ecological and biological communities, riparian conditions, and infrastructure constraints. The reach analysis should provide sufficient information to make predictions on the river's future under different scenarios.

2. **Feasibility Study**—evaluate actions that should be considered and assess their feasibility from a cost and constructability perspective. The feasibility study should address such questions as: Can the threatened infrastructure be moved out of harm's way? How much material needs to be moved? What environmental impacts can be minimized in the channel migration zone? Can habitat be restored as part of solving traditional problems, such as bank erosion and flooding? Is there any material available locally? Will partnerships with other stakeholders benefit the project?

3. **Risk Assessment**—evaluate and predict how the project will perform under both adverse and extreme conditions, and evaluate the accuracy of the scientific data to be used in design. The study should also determine the potential effects on changes in flood levels, scour, sedimentation, and bank erosion and should evaluate short- and long-term impacts on humans, infrastructure, and natural habitat. It should include appropriate public outreach and involvement to educate affected groups and individuals and to provide project managers and experts with feedback, insights, and ideas.

4. **Design**—build in "factors of safety" equivalent to those applied to any other civil engineering project. In doing this, engineers should determine the type, size, location, and number of structures needed to withstand maximum forces and achieve the highest level of protection.

5. **Construction**—prepare the site and sequence the construction to include access routes and minimize environmental impacts.
and dewatering, major excavation and grading, careful placement of structures, removal and protection, water quality and erosion control, and revegetation. ELJs can range from relatively simple placement of large woody debris directly into the river to more complex structures, like the Hoh River logjams. Construction can be done in different ways and can have a significant effect on cost, regulatory compliance, and outcome.

6. **Monitoring and Maintenance**—monitor the structures to evaluate structural integrity, accumulation, and ecological effects, and include surveys of fish utilization conducted by the U.S. Fish and Wildlife Service. Periodic maintenance can include repairing any structural damage, and revegetating, as needed.

The engineers selected H-piles with a 1.4 factor of safety to resist bending and overturning, which would compromise the ELJs. According to WSDOT's Hart, the addition of logs, large woody debris, and river sediments increased the strength of the ELJs to a safety factor of about 2—meaning the structures were twice as strong as the maximum forces expected to be exerted on them during a 100-year flood.

In preparing for construction, the construction crew first had to dewater the site by excavating a 610-meter (2,000-foot)-long diversion channel through the floodplain. Next, crews constructed an upstream diversion dam and a downstream backwater dam. Under the supervision of State, Federal, and tribal wildlife experts, as many as 2,000 fish were moved in buckets to the diversion channel. Once the structures were completed, workers slowly reintroduced the river water back into the main channel to minimize disturbing sediments that might redeposit downstream and damage fish habitat.

Each ELJ structure was set up to 18 meters (60 feet) deep into the riverbed and contains a core matrix of 30 or more large spruce trees with the root-balls intact and most large branches cut off. To meet WSDOT's high safety standards, each logjam has a core of 9 to 14 steel H-piles, covered with dozens of racked logs, then backfilled with loose rock and river sediment, and planted with trees.
The construction crews had just 3 months, from July through September 2004, to complete the project prior to the onset of the rainy season, despite the complex design and the need to temporarily divert the river around the site. They succeeded on time and within budget.

**Logjams as a Panacea?**

Initial results of the Hoh River Highway 101 bank protection project have been positive. Although the winter of 2004-2005 was unusually mild for the Olympic Peninsula, there were two peak river flows equivalent to a 2-year flood. Thus far, the ELJs have met or exceeded expectations, successfully diverting the river's erosive power away from Highway 101.

Still, WSDOT and other project stakeholders, including FHWA, are reserving final judgment for the day a major flood puts the ELJs to the test. In a region that routinely receives 508 centimeters (200 inches) of annual rainfall, that day could come at any time. "We're watching this project carefully to see how it works during a major flood event," says FHWA's Mathis. "If it does, I think this type of technology can be applied in appropriate situations elsewhere in the country."

(Above) The H-piles of the midchannel ELJs, such as this one shown under construction, were driven deep into the underlying riverbed. Deep excavation required shoring depicted in the photograph. Steel sheet piling was driven below the lowest log layers on three sides of the structure's core to prevent scour from undercutting the structures. (This piling extends below the logs in the photograph and is not visible.)

Whether logjams prove to be the right answer for MP 174 and similar highways or bridges threatened by flooding rivers, wood removal continues to be part of current river management practice. For example, the Ohio Department of Natural Resources, in its online "Stream Debris and Obstruction Removal Guide," instructs landowners how to remove logjams and other woody debris, noting that, "in-stream debris often gets lodged behind bridge and culvert openings, which can cause higher flood levels and result in additional land inundation and property damage."
Indeed, geomorphologists like Abbe maintain that reintroducing wood is not appropriate for all sites, particularly those where wood accumulations would not have formed naturally, in highly constrained channel segments, or where wood placements would increase risks to public safety or property.

The opportunity exists, however, to improve current river management practices through the reintroduction of wood. The type and size of an ELJ can be adapted to comply with site constraints and achieve the desired factor of safety in most situations.

In the appropriate settings, well-designed ELJs can provide bank protection that emulates the natural character of the river, increases channel complexity, dissipates energy, and creates quality habitat with improved fish passage over a range of flow conditions. Moreover, the use of ELJs is consistent with the principles and practices of context-sensitive design.

Conversely, traditional hardened revetments, like the ones used in previous emergency repairs of Highway 101, are not considered desirable solutions for bank protection on many Pacific Northwest alluvial rivers.

"Rock revetments simplify the morphology and habitat of alluvial rivers by reducing the complexity found along natural banks, disconnecting floodplains, and limiting wood recruitment," says Abbe. According to him, constructing one rock revetment after another has a cumulative effect of concentrating a river's energy, limiting the development of logjams and side channels, and promoting channel incision—all the while reducing the quantity and quality of aquatic and riparian habitat.

Looking forward, only time will tell whether the ELJs are the perfect solution to WSDOT's washout problems along Highway 101. But whatever the case, this project will go a long way to test the waters of this technology, which was originally engineered by Mother Nature.
Megan Hall is an area engineer with FHWA's Washington Division. Her current responsibilities include WSDOT's Olympic Region, the Alaskan Way Viaduct, and the Seawall Replacement Project. She has a degree in civil engineering from the University of Arkansas at Fayetteville and is a member of the Institute of Transportation Engineers. She has been with FHWA for 14 years, including 11 with the Washington Division as an engineer and transportation planner.

Steve Moler is a public affairs specialist at FHWA's Resource Center office in San Francisco, CA. He has been with FHWA for 5 years, providing the agency's field offices and partners with support in media relations, public relations, and public involvement communications.

For more information, contact Steve Moler at 415-744-3103 or steve.moler@fhwa.dot.gov.

Other Articles in this issue:

The Year of the Interstate

Financing Megaprojects

Rule on Work Zone Safety and Mobility

The Older Driver Comes of Age

Mimicking Mother Nature

Improving Freight Transportation

Energy Losses in Storm Drain Access Holes