WSDOT Fish Passage Program

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ABSTRACT

Since 1991, the Washington State Department of Transportation (WSDOT) has partnered with the Washington Department of Fish & Wildlife (WDFW) to help sustain and restore aquatic ecosystems by improving fish passage and natural stream functions at road crossings through a statewide program for the Washington highway system. This program was the recipient of an Exemplary Ecosystem Initiatives award in 2010 from the U. S. Department of Transportation – Federal Highway Administration.

The health of salmonid populations is one of the indicators of ecosystem health and integrity and a major natural resource concern in the Pacific Northwest. Adult salmon, steelhead, sea-run cutthroat, and anadromous bull trout migrate from the sea to freshwater to access their natal streams. Juvenile salmon rear in fresh water streams, sometimes for a year or more, moving up and/or downstream seeking food and cover, before outmigrating to the sea. Resident salmonids also migrate to spawning and rearing habitat.

Culverts can impede fish movement when flow velocity is too high, water depth is too shallow or sharp changes in gradient are too steep for fish to navigate. These impediments to fish passage result from improper culvert installation, culvert deterioration, changes in basin flow conditions over time, and because human understanding of fish passage needs has evolved over time.

WSDOT funds staff at WDFW to inventory fish barriers, assess habitat, and help WSDOT prioritize barriers for correction. The two agencies work together and with other stakeholder groups at the project level, to scope, design and implement corrections. The program is based on the best available science, and has evolved as knowledge has developed over time about habitat utilization and stream crossing design effectiveness.


Barrier corrections are prioritized at a statewide level for the greatest habitat gain and potential benefit to fish. At the watershed scale, WSDOT works with WDFW to select the best alternative for correcting fish passage problems. Historically, culverts have been designed for hydraulic capacity, but through this program, WSDOT and WDFW, now utilize the “stream simulation” design approach to correct a culvert barrier where feasible. This design method mimics the natural conditions that occur in the streambed adjacent to the road crossing. A stream simulation crossing structure is designed to imitate the natural streambed, spans wider than the existing stream channel width and has a similar gradient as the existing natural stream. This provides many other improvements for ecological functions in addition to fish passage by allowing for more natural stream processes of sediment and nutrient transport as well as connectivity for small and medium sized animals.
As part of this effort, over 6,000 stream crossings statewide have been physically evaluated for passability. Barriers are prioritized for the greatest habitat gain and potential benefit to fish. WSDOT funds design and construction, for retrofit and replacement of culverts for fish passage on a standalone basis, through a dedicated Environmental Retrofit Program. This is in addition to corrections that are completed as part of typical highway projects. The combined result to date is 245 corrections improving access to over 1322.8 lineal kilometers (822 mi) of potential upstream habitat gain.

INVENTORY

The initial inventory was conducted by driving WSDOT highways and evaluating culverts at salmon streams. Over the years, the inventory evolved from using professional judgment to evaluate whether salmon could pass through culverts, to developing a protocol for all species of fish considering hydraulic drop, depth, and velocity to assess culverts in all fish-bearing streams across Washington State.

On December 5, 1991, WSDOT and the Washington Department of Fisheries (WDF), since merged with the Department of Wildlife, entered into an agreement to inventory and correct fish passage barriers identified on WSDOT rights-of-way. The field crew, consisting of fish biologists and/or scientific technicians, would use their professional judgment when determining whether salmon could get through the culvert, considering hydraulic drop, culvert slope, water depth and velocity, however no specific assessment criteria existed. The field crew members would confer with one another when making fish passage barrier calls and determining the severity of barriers (i.e. total barrier or partial barrier). A WDFW study (Powers et al 1997) initiated in 1994 by engineers Pat Powers and Ken Bates, and fisheries biologist Tom Burns, tested the swimming and jumping abilities of different salmon species, which later contributed to the refinement of fish passage methods and barrier correction criteria.

Prior to the merger of Washington Departments of Fisheries and Wildlife in 1994, the WSDOT culvert inventory was salmon-centric; fish passage barrier assessments were conducted up to 7% stream gradient, which marked the presumed upper limit of salmon habitat. Stream crossings located upstream of the point where the stream gradient exceeded the 7% gradient were not inventoried. Subsequent to the merger, fish passage barrier inventories were expanded to include higher gradient steelhead trout habitat. The first gradient changes were implemented in July 1995. Following these changes, all culvert evaluations and physical habitat surveys were done for WSDOT stream crossings up to a 12% gradient.

In 1998, WDFW modified the gradient criteria for fish habitat from 12% to 20% to include and to adhere to the current forest practice rules which were modified as new research showed salmonids utilizing streams with gradients up to 20%. Under the new criteria, all fish bearing stream crossings were to be assessed. These criteria changes related to gradient occurred about midway in the comprehensive inventory of all state highway stream crossings.

In 1998 a reinventory of the state highway system was initiated that encompassed the change in the gradient criterion and the development of an assessment protocol. During the reinventory, field crews (consisting of 2 people) located culverts by driving slowly along the shoulder of the main highway or on/off ramp, or sometimes by walking along the highway if traffic conditions were unsafe to drive or there was no shoulder. All WSDOT highways (including all on/off ramps) were inventoried documenting all crossings encountered, regardless of fish use.

WDFW first published the Fish Passage Barrier and Surface Water Diversion Screening Assessment and Prioritization Manual (WDFW 1998; updated in 2000 & 2009), to provide a standardized methodology for evaluating fish passage at road crossings. This manual was updated in 2009 to include evaluation of additional instream features, including road crossings, dams, fishways, natural barriers, and surface water diversions. The manual also includes methods for habitat assessment and prioritization of fish passage and diversion screening features for correction.

The recently completed road based inventory was conducted with one person driving while another person looked for white hash marks indicating culvert crossings and also referring to a detailed map in order to anticipate where the next crossing was located. The crew would stop at every crossing encountered and collect basic information for each crossing. For every potentially fish-bearing stream crossing, a Level A (and Level B when necessary) assessment was conducted and the data is entered into the WDFW Fish Passage and Diversion Screening Inventory (FPDSI) database. The Level A and Level B are the two methods found in the Manual that are used for evaluating fish passage at culverts. The Level A assessment is the initial culvert assessment tool for fish passage, with culvert slope and hydraulic drop criteria leading to a barrier call. The Level B method is a hydraulic analysis which roughly calculates the maximum velocity and corresponding depth in the culvert at the high fish passage design flow and compares the values to the criteria in state law for adult trout. Limited information is collected on non-fish-bearing streams; these are not evaluated for fish passage. Cross-drains are not included in the database; however they are noted in the inventory log.
The new barrier assessment protocol eliminated the use of professional judgment in most cases, except in less common situations where the Level A and Level B protocol was not practical (i.e. tidally influenced streams, culverts with tide gates or flood gates, baffled culverts and fishways). In cases where the Level A and Level B could not be used, professional judgment may still be used in evaluating fish passage for culverts.

Some field indicators for fish passage barriers include:

- Bedload deposition at upstream end of culvert, sometimes creating an abrupt drop into culvert, indicates culvert may be undersized.
- Flow-line or rust-line in culvert indicates the culvert may be undersized, resulting in high velocities through culvert.
- Multiple culverts with only one culvert conveying most of the flow may indicate culvert is undersized.
- High water marks above culvert at upstream end and evidence of “over-topping” may indicate culvert is undersized.
- Plunge pool size large in relation to normal stream features (pools and riffles measured outside of the hydraulic influence of the culvert) indicates high energy/scouring activities; culvert may be undersized.
- Low flow sheeting, common in box culverts with flat/sheer culvert bottoms.
- Slope or internal grade break appears to exceed 1% (estimated only when accurate slope measurement cannot be made).
- Measured velocity through culvert is > 1.2 m/sec (4 ft/sec) at or below the fish passage design flow.
- Physical blockage within the culvert.

The reinventory was completed in 2007 to include a comprehensive inventory of all road crossings at fish bearing streams on the entire state highway system of 11,335.45 kilometers (7,043.52 miles). During the WSDOT inventory, a total of 6,478 crossings in natural drainages were inspected. Of the 6,478 crossings inspected, WDFW identified 3,175 as crossings in fish-bearing streams. Approximately 60% of the fish-bearing crossings were determined to be fish passage barriers.

Modern technology has improved the inventory process over the years, including the use of:

- Nitestar mileage meter used to get more accurate road milepost locations.
- Geographical Information System (GIS) to generate better maps used when locating stream crossings.
- Global Positioning System (GPS) to document the geographical location of inventoried features.
- Digital cameras to photograph each feature inventoried.

HABITAT ASSESSMENT & PRIORITIZATION

As a basis for prioritization of fish passage restoration projects, a habitat assessment is conducted for all identified WSDOT fish passage barriers.

Since 1991, WDFW has conducted habitat surveys for more than 2,000 WSDOT stream crossings, surveying more than 510 kilometers (315 miles) of fish-bearing stream habitat upstream of WSDOT fish passage barriers. WDFW continues to conduct habitat assessments and prioritize fish passage barrier correction for the WSDOT Fish Passage Program.

Stand-alone fish passage barrier projects are prioritized by WDFW to target sequential correction of barriers that have the largest gains in fish habitat and the greatest production benefits for fish. A numeric indicator called the Priority Index (PI) is assigned to each barrier culvert and factors in such things as expected passage improvement, production potential of the blocked stream, fish stock health, fish species present, and project cost.

PROJECT SCOPING

Each fish passage barrier correction project undergoes a multi-phased pre-scoping process. The first step in this process is a biological scoping by WDFW biologists involving verification of inventory and habitat assessment data for WSDOT and all other barriers within the watershed. A crucial element of the biological scoping is verifying that the habitat conditions and species expected to benefit are correctly reflected in the PI value for each barrier. In addition to the PI, the biologists consider other factors for project selection, such as the number and location of additional barriers in the watershed, project feasibility, likelihood for success, other restoration efforts in the watershed, and project costs.
All the information gathered during the biological scoping process is summarized in a biological scoping report and a map is generated illustrating the location of additional human made barriers downstream and upstream of the WSDOT barrier. If the PI value drops below the current scoping threshold as a result of changes the biologist makes, the project is deferred until higher priority projects are completed. Projects that require correction of other fish passage barriers or that require correction of habitat deficiencies in the watershed prior to development of a correction strategy may be placed on hold.

Once biological scoping is complete, projects that successfully meet the verification process have a WDFW scoping engineer assigned to develop conceptual designs for barrier correction. When the WDFW scoping engineer has identified all reasonable conceptual design options, a pre-scoping meeting is held. WDFW participants in this meeting are, at a minimum, the scoping biologist, scoping engineer and area habitat biologist (AHB). WSDOT participants include the regional scoping engineer and representatives of the Environmental Services Office, Regional Program Management, Regional Environmental Office, and Regional Project Development Office. The outcome of this meeting is a consensus decision about which conceptual design option will be pursued.

A stakeholder concurrence form is generated that documents the outcome of the meeting and includes the cost estimate for the selected design option. Once each participant present at the meeting reviews and concurs with the information on the concurrence form, pre-project scoping is complete and the project is eligible to be placed on a Ten Year Plan for correction.

FISH PASSAGE DESIGN

When a fish passage barrier is identified and scheduled for correction, WSDOT works with WDFW to pick the best alternative for correcting the fish passage problem. Crossing structure designs are based on the latest edition of WDFW’s Design of Road Culverts for Fish Passage manual that can be found on the web at http://wdfw.wa.gov/publications/00049/wdfw00049.pdf. This manual provides a variety of culvert correction options. The three methods for culvert design are hydraulic, no slope and stream simulation. A bridge should be considered if the stream width exceeds 6.1 m (20’), the stream slope is greater than 6% or the movement of large debris is present in the stream system.

The goal is to select a design that maximizes fish passage for the species present and can be constructed successfully at a particular site. The WSDOT and WDFW, where feasible, prefer to use a type of culvert design called “stream simulation” to correct a fish passage barrier. The premise for stream simulation (Figure 1) is that if fish can migrate through a natural channel, they can also migrate through a man-made culvert that simulates a natural channel.

![Figure 1: A 0.7 m (2.2’) round culvert was replaced with stream simulation designed 3.6 m (11.8’) span x 1.8 m (6’) rise bottomless concrete box at an Unnamed Tributary to Squamish Harbor on SR 104 at milepost 12.30 near the Hood Canal Bridge.](image-url)
Stream simulation crossing structures are designed to imitate the natural streambed and are constructed wider than the existing stream channel width and sloped at a similar gradient as the existing stream. This design method best mimics the natural conditions that previously occurred in the streambed location prior to the existing culvert being placed. These culverts are filled with a sediment mix that emulates the natural channel, erodes and deforms similar to the natural channel, and is unlikely to change grade unless specifically designed to do so. This fill material is placed in the culvert to mimic a stream channel and is allowed to adjust in minor ways to changing conditions.

The most basic stream simulation culvert is a bottomless culvert placed over a natural streambed. The larger stream width with the stream simulation design allows for sediment transport and woody debris passage through the structure during high flow events. An additional benefit with stream simulation designed crossing structures is that small and medium sized animals are able to travel through the crossing structure because a portion of the streambed is usually dry along the margins (Figure 2).

**Figure 2:** An undersized 1.2 m (4') round culvert was replaced with stream simulation designed 4.9 m (16') span x 2.9 m (9.5') rise bottomless concrete box culvert at Mosquito Creek on US 101 southeast of Aberdeen, WA. This culvert provides habitat connectivity for deer and other animals as well as 3.5 km (2.2 miles) of upstream habitat for fish.

**FISH PASSAGE & WILDLIFE**

WSDOT is developing an innovative combination fish passage and wildlife connectivity project (Figure 3) on U.S. 97 near Goldendale, WA. A culvert that is undersized relative to modern standards is located at Butler Creek at milepost 21.3 and has been identified as a fish passage barrier due to slope and excessive water velocities. The creek provides habitat for steelhead and resident trout and there is 16 km (10 miles) of upstream habitat available. To the north and south of this culvert is a 12.8 km (8 miles) stretch of highway between mileposts 15 to 23 that has seen an increasing number of deer-vehicle collisions: 300 deer carcasses were removed in a five-year period from 2004 to 2008. This stretch is one of the top ten worst deer-vehicle collision areas in Eastern Washington.

**Figure 3:** This undersized 3.2 m (10.5') round culvert in Klickitat County will be replaced with a 19.8 m (65') bridge with a 3 m (10') wildlife bench incorporated into the channel design.
WSDOT is designing a 19.8 m (65') bridge span that will have new stream channel underneath with a 3 m (10') wildlife passage bench and at least 2.74 m (9') of vertical clearance for wildlife, including deer. Wildlife fencing that is 2.43 m (8') tall and escape ramps will be constructed between natural barriers to encourage the animals to cross under the new bridge. This creative project will likely solve an aquatic and wildlife connectivity problem with a single action.

**FISHWAYS**

In addition to culverts, WSDOT owns & maintains 160 fishways (Figure 4) statewide. During the 1990’s, many WSDOT fish passage barriers were retrofitted with fishways, as an interim fish passage repair. Fishways, commonly called fish ladders, are human-made structures built to facilitate passage of fish through, over, or around an instream barrier. Most fishways enable fish to pass around the barriers by swimming and leaping up a series of relatively low steps into the waters on the other side.

Fishways are considered a low-cost solution to fish passage barrier correction, compared to the cost of culvert replacements and bridge installation. However, the high costs associated with regular inspection and maintenance of the structure over time, and the potential for these structures to fail and become fish passage barriers, have made fishways a less-desirable option for fish passage barrier correction. A real limitation with fishways is they don’t always provide passage for all life stages of fish.

![Figure 4](image_url)

**Figure 4:** A steel culvert was assessed as a barrier due to slope & water velocity was retrofitted with a pool-and-chute fishway at milepost 8.8 at Cement Creek on SR 401 in the southwest corner of WA. The advantage of a pool-and-chute fishway is the wide range of stream flows through which they operate effectively.

Regular inspections and maintenance are essential in the continued successful operation of fishways. Maintenance of the fishways includes removal of organic debris and sediments, repairing broken or missing baffles and other similar activities ensuring fish passage.

For some fishways, maintenance alone can no longer provide unimpeded fish passage indefinitely. Eventually, baffles, log and concrete controls deteriorate, or the structures associated with fishways need to be replaced. When the fishways were originally designed, it was recognized that they were intended to provide relatively short-term, inexpensive fish passage solution. Over the years, fishways provided uninterrupted fish passage, particularly in situations where culvert replacement with a larger culvert or a bridge would have been very difficult or prohibitively expensive. When the fishways reach their lifespan and can no longer provide fish passage, they are put on the barrier list to be evaluated by biologists and engineers for a repair solution. WSDOT is moving towards replacement of fish passage barriers rather than designing and building engineered fishways.
EVALUATION

WDFW evaluates all culvert correction projects one year following construction to ensure they are functioning properly. If the culvert is performing as anticipated, it is assumed that fish of all life stages can pass. Adult spawner surveys (Figure 5) are a way to determine species presence or absence above a completed fish passage project or to evaluate fish use prior to correction.

![Figure 5: Adult coho salmon returning to spawn several weeks after a bridge construction project at Tibbets Creek at milepost 15.48 on Interstate 90 near Issaquah, WA. These fish appeared in the fall of 2007 after three round 1.2 m (4') barrier culverts were replaced with two 15 m (49') long bridges.](image)

Three such surveys are conducted per year for each project. Typically, the surveys are conducted 500 meters below and above the road crossing, or to the confluence with a larger body of water downstream, or to a natural barrier upstream. If there is no spawning habitat within 500 meters upstream or downstream of the fish passage project, the survey may be relocated according to where fish are likely to spawn. If salmonids are not detected upstream of the fish passage project in the first year after construction, surveys may be performed in subsequent years.

SUMMARY

WSDOT has partnered with WDFW since 1991 to identify and remove high priority fish passage barriers that have the most benefit to fish. The combined result to date is 245 corrections improving access to over 1322.8 lineal kilometers (822 mi) of potential upstream habitat gain.

Completing a comprehensive fish passage inventory and habitat assessment are important steps in developing salmonid recovery projects. WSDOT and WDFW acknowledge that correcting fish passage barriers using a jurisdictional approach is not as successful as taking a watershed approach to fish passage barrier correction. In a watershed-based inventory, all human-made fish passage barriers are assessed and prioritized for correction within the watershed. At the watershed scale, WSDOT works with WDFW to pick the best alternative for correcting fish passage problems. Historically, culverts have been designed for hydraulic capacity, but through this program, WSDOT and WDFW, now utilize the “stream simulation” design approach to correct a culvert barrier whenever possible. This design method mimics the natural conditions that occur in the streambed adjacent to the road crossing.

ACKNOWLEDGMENTS

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BIOGRAPHICAL SKETCHES

Jon Peterson is the Fish Passage Coordinator for the Washington State Department of Transportation since 2002 with 26 years of experience working for the state of Washington. Jon has a Master of Public Administration from the Evergreen State College and a Bachelor of Science in Forest Resources from the University of Washington.

Mike Barber is the Stream Restoration Program Manager for the Washington State Department of Transportation. Mike has a Master of Science Degree in Biology from Eastern Washington University and 26 years’ experience as a fish biologist and 16 years of experience working on fish passage.

Susan Cierebiej is a biologist with 18 years’ experience working for the state of Washington. She has worked in the field of fish passage and habitat restoration for the Washington Department of Fish and Wildlife since 1996. Susan holds a Bachelor of Science in Environmental Science from the Evergreen State College.

Eva Barber has worked as a fish and wildlife biologist for the Washington Department of Fish and Wildlife for 14 years. She holds Bachelor of Science in Molecular Biology from Western Washington University. Eva has been working on fish passage since 2002.

REFERENCES

For additional information about WDFW’s fish passage efforts refer to the Fish Passage website at http://wdfw.wa.gov/conservation/habitat/fish_passage/

For additional information about WSDOT’s fish passage efforts refer to the Fish Passage Program website at http://www.wsdot.wa.gov/Environment/Biology/FP/fishpassage.htm


CRITICAL LINKAGES: ASSESSING CONNECTIVITY RESTORATION POTENTIAL FOR
CULVERT REPLACEMENT, DAM REMOVAL AND CONSTRUCTION OF
WILDLIFE PASSAGE STRUCTURES IN MASSACHUSETTS

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ABSTRACT

The University of Massachusetts Amherst, working in partnership with The Nature Conservancy and state agencies, has
integrated data related to landscape connectivity and human development and completed a comprehensive analysis of
areas in Massachusetts where connections must be restored to support biodiversity and minimize vehicle-wildlife
collisions. The Critical Linkages project has been developing spatially explicit tools, including maps and scenario-testing
software, to mitigate impacts of roads on the environment and help inform the design of new roads. The project built on
the existing Conservation Assessment and Prioritization System (CAPS), a computer model developed by UMass that
incorporates biophysical and anthropogenic data to develop an index of ecological integrity. Within the framework of
CAPS the connectedness and aquatic connectedness metrics were used to model various scenarios and quantify the
differences among them. Using this approach we conducted a comprehensive statewide assessment of restoration
potential for 1) dam removals, 2) culvert replacements and 3) construction of wildlife passage structures on roads and
highways. A baseline assessment of connectedness and aquatic connectedness provided a statewide base scenario for
comparison of restoration options. Scenario-testing software was developed to efficiently assess restoration potential
for large numbers of possible restoration projects and then applied statewide to identify road segments, road-stream
crossings and dams that currently obstruct aquatic and terrestrial wildlife movement and that offer the greatest
opportunity for restoration of landscape connectivity in Massachusetts.

INTRODUCTION

The disruption of landscape connectivity by human land use activities is considered a principal cause of the decline in
biodiversity and is increasingly of concern to conservation scientists (Chetkiewicz et al. 2006, Crooks and Sanjayan
2006, Hilf et al. 2006, Beier et al. 2008). In addition, connectivity is considered a vital attribute of a landscape (Taylor
et al. 1993) and deemed critical to the adaptive capacity (sensu Elmqvist et al. 2003) of a landscape in the face of
climate change (Czucz et al. 2011). There is perhaps no more ubiquitous and insidious anthropogenic influence on
landscape connectivity than roads. Roads have both direct (e.g., animal mortality) and indirect (loss of landscape
permeability resulting in fragmentation) effects on terrestrial and aquatic ecosystems (Forman et al. 2003). To a large
degree, the placement and construction of roads in large measure determines how permeable the landscape is to the
movement of organisms, energy, and matter.

In light of the above and in the face of continued human development and climate change, minimizing the influence of
roadways on landscape connectivity is of paramount concern among conservationists and planners. Consequently, the
aim of this study was to develop a modern methodology to assess and prioritize where to use mitigation techniques to
best facilitate wildlife passage and reduce the risk of animal-vehicle collisions along roadways. Our specific objective was
to evaluate and prioritize locations for potential wildlife passage structures and culvert upgrades in Massachusetts,
although we extended this to include dam removals as well, even though dams are frequently not associated with
roadways – dams are otherwise analogous to culverts in impeding movement of aquatic organisms in riverine networks.

In addition, our objective was to employ a "coarse-filter" approach in our assessment of connectivity; i.e., one that did not
involve any particular focal species or process but instead holistically considered ecological systems or settings. While
there have been many other efforts to develop methods and software tools for similar purposes (e.g., Fuller and Sarkar
2006, Theobald et al. 2006, Roberts et al. 2010) and many proposed measures of connectivity available for use in this
case (e.g., Clabrese and Fagan 2004, Fagan and Calabrese 2006, Saura and Pascual-Hortal 2007, Estrada and Bodin
2008, Kindlmann and Burel 2008, Theobald et al. 2011), none of the available approaches make use of resistant kernels
(Compton et al. 2007), which we believe provide the most synoptic perspective on landscape connectivity.
Resistant kernels combine two familiar methods: 1) standard kernel density estimation, and 2) least cost path analysis based on resistant surfaces, into a hybrid approach that allows for nonlinear ecological distance relationships and accounts for connectivity between every location to every other location (as opposed to between a single designated source and destination location). Resistant kernels are described in more detail in the methods section. Consequently, we developed a new approach based on resistant kernels and applied it to potential road crossings, culvert upgrades and dam removals across Massachusetts.

The Concept of Landscape Connectivity

The concept of landscape connectivity (Merriam 1984) provides the broad conceptual underpinning for this study and our approach, and thus it is important to clarify and define the concept as we use it here given the diverse and often confusing uses of the concept in the literature. The concept of landscape connectivity has been defined as the “degree to which the landscape facilitates or impedes movement among resource patches” (Taylor et al. 1993) or as “the functional relationship among habitat patches, owing to the spatial contagion of habitat and the movement responses of organisms to landscape structure” (With et al. 1997). Both of these definitions highlight the functional nature of connectivity, by emphasizing the dependence of movement on landscape structure. Furthermore, while these and other definitions emphasize the movement of organisms, the concept of landscape connectivity can be extended to consider more generally the movement of energy, matter, or information (gene flow) across the landscape. Regardless of which currency is used, the greater the degree of movement or flow across the landscape, the greater the overall connectivity of the landscape.

While the above definitions emphasize the functional nature of connectivity, ecologists often distinguish between functional connectivity (or what is generally referred to as simply “connectivity”) and structural connectivity (or what is sometimes referred to as “continuity”) (Crooks and Sanjayan 2006). Structural connectivity measures the spatial arrangement of landscape elements (e.g., habitat types or ecological systems) without reference to the likelihood of movement of particular organisms (or energy, matter or information for that matter) through the landscape. In contrast, functional connectivity incorporates at least some aspects of the behavioral response of individuals, species, or ecological processes to the physical structure of the landscape (Crooks and Sanjayan 2006). Thus, functional connectivity reflects the interaction of ecological flows (e.g., movement of organisms) with the physical landscape structure (i.e., the composition and spatial configuration of the landscape).

What constitutes functional connectivity clearly depends on the organism or process of interest; for example, patches that are connected for bird dispersal might not be connected for salamander dispersal. Thus, functional connectivity is affected by the structural connectivity of the landscape, but the magnitude and nature of the effect depends on how the organism or process scales and perceives the landscape. A central question in landscape management for the conservation of biodiversity and ecological integrity is, “as the physical continuity of the landscape is disrupted (through development), at what point does landscape connectivity become impaired and adversely impact ecological processes?” In other words, at what point do structural disconnections impact the functional connectivity of the landscape.

In this study, we evaluate functional connectivity, not just continuity per se, but we do so in a generalized manner because we do not have a single focal organism or process. Instead, we are concerned with how myriad organisms and processes collectively respond to the physical continuity of environments. This approach is implemented in our “resistant kernel estimator” methodology that combines the physical distribution of land cover types and ecological settings (i.e., continuity) with the concept of permeability or ecological resistance, whereby each location confers a varying degree of resistance to ecological flows (i.e., connectivity).

Functional connectivity can be subdivided further into potential connectivity, which uses some basic, indirect knowledge of the potential for movement, and actual connectivity, which directly quantifies movement rates based on actual observations (Fagan and Calabrese 2006). The primary difference between potential and actual connectivity lies in the amount of information available on the response of the organism or process to landscape structure. Although assessing the actual connectivity of the landscape might be the goal, we usually do not have sufficient empirical information on how landscape structure influences movement behaviour or other ecological flows across the landscape to permit this level of assessment. Thus, most analyses of landscape connectivity are of the potential connectivity of the landscape. In this study, we evaluate potential connectivity, as we do not have empirical data on movement, nor do we have a single species or process on which to focus estimates of movement rates.

There are myriad ways to measure the functional connectivity of a landscape or of a particular landscape unit (e.g., grid cell) within a landscape. In the context of our approach, the functional connectivity of a landscape unit can be assessed from three different perspectives.
We refer to the connectivity of a focal cell to its ecological neighborhood (i.e., its landscape context) when it is viewed as a target as connectedness; in other words, to what extent are ecological flows (e.g., dispersal) to that cell impeded or facilitated by the surrounding landscape. Connectedness is a function of both the similarity of the neighboring cells to the focal cell (i.e., the more similar the more connected) and any impediments to movement from the neighboring cells to the focal cell (i.e., the more impediments the less connected).

The outflow from a focal cell, for example when it is viewed as a source, we refer to as dispersion. Dispersion is a function solely of impediments to movement from the focal cell outward to all neighboring cells; it does not take into account whether or not the destination cells are similar to the focal cell, only whether stuff can get there.

Lastly, we refer to the rate of flow through a focal cell (i.e. when it is viewed as a conduit) as conductance. Conductance refers to how much stuff moves through a focal cell when all neighboring cells are treated as sources, and it is a function of the focal cell's permeability (or resistance) to ecological flows as well as its strategic position in the landscape between other cells. For example, a wildlife passage structure on an expressway may be quite permeable to wildlife crossings, but if it is not located along an important movement route between sites A and B, it will not function to promote the linkage of A and B. Thus, conductance deals with the role of each location in conferring connectivity to the broader landscape.

From a conceptual standpoint, all three components of connectivity (i.e., connectedness, dispersion and conductance) are relevant to this study. However, after preliminary examination of the results we limited our final results to the use of connectedness. Thus, in this study, we are principally concerned with the effect of roads, culverts and dams on the connectedness of the surrounding landscape.

What ultimately influences the functional connectivity of the landscape is the scale and pattern of movement relative to the physical structure of the landscape (With 1999). Thus, functional connectivity is a scale-dependent concept and there is no one right scale for assessing it. In the context of this study, because we are dealing with biodiversity in its broadest sense (i.e. approaching it using a coarse filter), it is impossible to define a single scale for assessing connectivity that will be meaningful for all organisms and processes of concern. Yet at the same time it is impractical to examine connectivity at every relevant scale. As a practical compromise, we distinguish two important scales for assessing connectivity, which we refer to as local and regional scales.

The distinction between these two scales is best illustrated from the perspective of movement of organisms (rather than energy or matter). In this context, local connectivity refers to the spatial scale at which the dominant organisms interact directly with the landscape via demographic processes such as dispersal and home range movements. This is the landscape context that an individual organism might experience during their lifetime.

Regional connectivity refers to the spatial scale exceeding that in which organisms directly interact with the landscape. This is the scale at which long-term ecological processes such as range expansion/contraction and gene flow occur. At this scale, individuals generally do not interact with the landscape, but their offspring or their genes might over multiple generations. Consequently, there is no real upper limit on the regional scale; the longer the time frame, the larger the regional scale at which the landscape context matters.

In the first phase of this study reported in this paper, we are concerned with local connectivity; regional connectivity will be addressed in the next phase of this study. Of course, even this does not constrain the range of suitable scales for assessing connectivity, since even the dominant organisms in a community may have ecological neighborhoods that vary in scale by orders of magnitude. Thus, in choosing the spatial scale(s) for the local connectivity assessment (using the resistant kernel estimator), we incorporated two important considerations. First, we focussed on vertebrates, largely because their life history and habitat use patterns are better understood than many plants and invertebrates and because they are more often the focus of conservation concerns. Second, we focussed on the average maximum movement distances of a suite of organisms; in other words, we did not use the maximum movement distance of a single “indicator” species nor did we choose to bias the result towards the most or least vagile organism.

In summary, connectivity is a complex and multi-faceted concept with many different constructs depending on the application. In this study, we are interested in evaluating and prioritizing locations for potential wildlife passage structures, culvert upgrades and dam removals based on an assessment of how these mitigation measures influence functional, potential, local connectivity as measured from the perspective of connectedness.
The Critical Linkages Project

The University of Massachusetts (UMass) in collaboration with The Nature Conservancy (TNC) integrated data related to landscape connectivity and human development, and developed a comprehensive analysis of areas in Massachusetts where connections must be protected or restored to support biodiversity and minimize vehicle-wildlife collisions. The Critical Linkages project built on the existing Conservation Assessment and Prioritization System (CAPS) through a statewide landscape connectivity study. Phase 1 of the project involved scenario analysis using CAPS to assess the potential for restoring functional connectivity via dam removal, culvert/bridge replacement and use of wildlife passage structures on roads and highways.

METHODS

The Conservation Assessment and Prioritization System (CAPS) is an ecosystem-based (coarse-filter) approach for assessing the ecological integrity of lands and waters and subsequently identifying and prioritizing land for habitat and biodiversity conservation. CAPS is a computer software program and an approach to prioritizing land for conservation based on the assessment of ecological integrity for various ecological communities (e.g., forest, shrub swamp, headwater stream) within an area.

The first step in the CAPS approach is the characterization of both the developed and undeveloped elements of the landscape. Developed land uses are grouped into categories such as various classes of roads and highways, e.g., high-intensity urban, low-density residential, agricultural land, and other elements of the human dominated landscape. Undeveloped (“natural”) land is mapped based on ecological community classification (e.g., swamp, marsh, bog, pond). With a computer base map depicting various classes of developed and undeveloped land, we then evaluate a variety of landscape-based variables (“metrics”) for every point in the landscape. A metric may, for example, take into account the microclimatic alterations associated with “edge effects,” intensity of road traffic in the vicinity, nutrient loading in aquatic ecosystems, or the effects of human development on landscape connectivity. Two of the these metrics measure the connectedness of each undeveloped cell; i.e., the degree to which a focal cell is surrounded by ecologically similar cells and the degree of impedance of ecological flows from similar neighboring cells to the focal cell. One (connectedness) applies to both terrestrial and aquatic cells and the other (aquatic connectedness) applies only to aquatic cells, as described below.

Because CAPS provides a quantitative assessment for each metric it can be used for comparing various scenarios. In essence, scenario analysis involves running CAPS separately for each scenario, and comparing results to determine the loss (or gain) in specific metric units. This scenario testing capability can be used to evaluate and compare the impacts of development projects on habitat conditions as well as the potential benefits of habitat management or environmental restoration.

In Phase 1 of the Critical Linkages project we used the scenario testing capabilities of CAPS to assess the change in either the connectedness or aquatic connectedness metrics for three types of ecological restoration to promote connectivity: dam removal, culvert/bridge replacement, and the use of wildlife crossing structures on roads and highways (for technical reasons, railroads have not yet been included in the analysis).

Connectedness

The connectedness metric is a measure of the degree to which a focal cell is interconnected with other cells in the landscape that can be a source of individuals or materials that contribute to the long-term ecological integrity of the focal cell. Connectedness uses a resistant kernel (Compton et al. 2007) to assess the local connectivity around a focal cell. The resistance of each cell is based on the ecological distance to the focal cell in ecological settings space, defined by a number of ecological settings variables (Table 1) that define ecological community characteristics. It measures the multivariate distance across all ecological setting variables between the focal cell and those of neighboring cells. See Figure 1 for an example of a resistant kernel.

Connectedness is the sum of resistant kernels built for each cell in the neighborhood of the focal cell (fig. 2) weighted by ecological distance to the focal cell. Underlying this metric is the assumption that dispersion of ecological flows from similar ecological communities is more important to long-term integrity than those from dissimilar communities. The connectedness metric applies to all ecological communities including aquatic communities (e.g., lakes, rivers, streams). In order to characterize the ecological distances and ultimately the resistant surface for developed land classes we included anthropogenic elements among these gradients. These included aquatic barriers, terrestrial barriers, traffic rate, imperviousness, and developed.
<table>
<thead>
<tr>
<th>Biophysical attribute</th>
<th>Biophysical variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Growing season degree-days</td>
<td>Degree-days is calculated by taking the sum of daily temperatures above a threshold ($10^\circ$C). Temperatures above an upper threshold of $30^\circ$C are excluded.</td>
</tr>
<tr>
<td></td>
<td>Minimum winter temperature</td>
<td>The minimum temperature ($^\circ$C) reached in the winter</td>
</tr>
<tr>
<td>Solar energy</td>
<td>Incident solar radiation</td>
<td>Solar radiation based on slope, aspect, and topographical shading.</td>
</tr>
<tr>
<td>Chemical &amp; physical substrate</td>
<td>Soil pH</td>
<td>Soil pH</td>
</tr>
<tr>
<td></td>
<td>Soil depth</td>
<td>Soil depth (cm)</td>
</tr>
<tr>
<td></td>
<td>Soil texture</td>
<td>Soil texture based on USDA-NRCS classification</td>
</tr>
<tr>
<td></td>
<td>Water salinity</td>
<td>Salinity (ppt) in coastal settings in three broad classes: fresh, brackish, and saltwater</td>
</tr>
<tr>
<td></td>
<td>Substrate mobility</td>
<td>The <em>realized</em> mobility of the physical substrate, due to both substrate composition (i.e., sand) and exposure to forces (wind and water) that transport material</td>
</tr>
<tr>
<td></td>
<td>CaCO$_3$ content</td>
<td>Calcium carbonate content based on the composition of the soil and underlying bedrock</td>
</tr>
<tr>
<td>Physical disturbance</td>
<td>Wind exposure</td>
<td>Wind exposure based on the mean sustained wind speeds at 30 m above ground level using a 200 m resolution model</td>
</tr>
<tr>
<td></td>
<td>Wave exposure</td>
<td>Direct exposure to ocean waves</td>
</tr>
<tr>
<td></td>
<td>Steep slopes</td>
<td>The propensity for gravity-induced physical disturbance</td>
</tr>
<tr>
<td>Moisture</td>
<td>Wetness</td>
<td>Soil moisture (in a gradient from xeric to hydric) based on a topographic wetness index</td>
</tr>
<tr>
<td>Hydrology</td>
<td>Flow gradient</td>
<td>Gradient (percent slope) of a stream approximated by categories such as step-pool, riffle, run, cascade and flat water</td>
</tr>
<tr>
<td></td>
<td>Flow volume (watershed size)</td>
<td>The absolute size of a stream or river</td>
</tr>
<tr>
<td></td>
<td>Tidal regime</td>
<td>In coastal areas, degree of tidal influence</td>
</tr>
<tr>
<td>Vegetation</td>
<td>Vegetative structure</td>
<td>Coarse vegetative structure, from unvegetated through shrubland through closed canopy forest</td>
</tr>
<tr>
<td>Development</td>
<td>Developed</td>
<td>Whether a cell can be considered largely developed or undeveloped</td>
</tr>
<tr>
<td></td>
<td>Traffic rate</td>
<td>A scaled measure of traffic volume on roads and highways</td>
</tr>
<tr>
<td></td>
<td>Impervious</td>
<td>Percent of impervious surfaces</td>
</tr>
<tr>
<td></td>
<td>Terrestrial barriers</td>
<td>Degree to which a cell constitutes a barrier to terrestrial organisms</td>
</tr>
<tr>
<td></td>
<td>Aquatic barriers</td>
<td>Degree to which a cell constitutes a barrier to aquatic organisms</td>
</tr>
</tbody>
</table>
Dams generally have traffic rates of zero. However, dams that have a road that runs along their surfaces will have non-zero traffic rates. Dams have a terrestrial barrier score of zero unless a road goes over the dam, in which case it gets the road’s terrestrial barrier score. The aquatic barrier scores are a function of dam height.

Aquatic barrier scores for road-stream crossings are based on an assessment protocol and scoring system developed by the River and Stream Continuity Partnership (2010, [www.streamcontinuity.org](http://www.streamcontinuity.org)). The protocols were developed for implementation by trained volunteers or technicians and rely on information that can be readily collected in the field without surveying equipment or extensive site work. The Partnership also created an algorithm for scoring crossing
structures according to the degree of obstruction they pose to aquatic organisms. Data and crossing scores from over 1,000 crossings were used to create a model to predict aquatic barrier scores for those crossings that had not been assessed in the field.

To assign terrestrial barrier scores for road-stream crossings we created a scoring algorithm using data collected by the River and Stream Continuity protocols. The following variables were included in the scoring algorithm: height, width, openness (cross-sectional area divided by structure length), substrate and span (an approximation of constriction ratio). As with aquatic barriers a model was developed to predict terrestrial barrier scores for crossings that had not been assessed in the field.

The road-stream crossing models for both aquatic barrier and terrestrial barrier produced noisy results ($R^2$≈0.4). Therefore, we calculated 60% confidence intervals for both scores to allow modeling both a “best estimate” scenario (based on the predicted score) and a reasonable “best case” scenario (described below). To calculate 60% confidence intervals on the scores we broke the data into three equal sized strata for predicted scores. For each stratum we then calculated a 60% confidence interval from the distribution of the residuals in the predictions. The lower bound of the confidence interval was the prediction minus the 20th quantile of the residuals for all observations in the stratum while the upper confidence interval was based on the 80th quantile of the residuals in the stratum. We smoothed the transitions between strata to force the confidence intervals to increase monotonically with predicted score (fig. 3).

Terrestrial barrier scores for road segments were parameterized based on road class and professional judgment by an expert team. Traffic rates for roads are assigned from MA Department of Transportation (MassDOT) interpolated road traffic data, using the ADT (average daily traffic) field. We modified traffic rates somewhat to correct errors; for example, when traffic rates were zero due to missing data, or where traffic was overestimated for unpaved roads running through state forests. Traffic rates were converted to a probability of roadkill using a mechanistic model presented by Hels and Buchwald (2001) and Gibbs and Shriver (2002), as illustrated in Figure 4.
Aquatic Connectedness

Ecological flows modeled for connectedness are allowed to flow overland and diagonally from cell to cell. As a result, resistant kernels can wrap around highly resistant cells or patches of cells. This makes sense for organisms that move terrestrially (flows can easily go around a building, parking lot or subdivision). However, for aquatic organism passage this is a problem because what would otherwise be considered severe barriers (dams, bad culverts) are easily circumvented. We created aquatic connectedness to get around this problem. Aquatic connectedness functions much like connectedness but is constrained to move only along the centerlines of streams, rivers, water bodies and wetlands. Aquatic connectedness includes one settings variable not used by connectedness (aquatic barriers) and ignores four settings variables used by connectedness (terrestrial barriers, traffic, imperviousness, and developed). This allows aquatic connectedness to respond to the effects of culverts, bridges, and dams on aquatic passability, rather than the effects of roads that may pass overhead.

Scenario Analysis

Within the framework of CAPS the connectedness and aquatic connectedness metrics are used to model various scenarios and quantify the differences among them. Using this approach we conducted a comprehensive statewide assessment of restoration potential for 1) dam removals, 2) culvert/bridge replacements and 3) construction of wildlife passage structures on roads and highways. A baseline assessment of connectedness and aquatic connectedness provided statewide base scenarios for comparison of restoration options.

In calculating the change in connectedness and aquatic connectedness we used the modeled aquatic barrier and terrestrial barrier scores for road stream crossings to produce a “best estimate” delta score. In an effort to bracket these results and as a hedge against the uncertainty of the modeled scores we also used values associated with the 60 percent confidence intervals to produce what we called a reasonable “best case” value for the change in either connectedness or aquatic connectedness. Where terrestrial barrier and aquatic barrier scores based on field assessments were available these were used instead of modeled scores.

When conducting dam removal scenarios the “best estimate” analysis used the modeled aquatic barriers scores for road-stream crossings with potential to affect aquatic connectedness in the vicinity of dams. For the “best case” analysis road-stream crossings in the vicinity of dams were scored at the 60% confidence interval above their estimated score.

For culvert/bridge replacement scenarios the “best estimate” analysis was based on the modeled scores for aquatic barriers. “Best case” analyses set the target crossing score at the 60% confidence interval below the estimated score with all other crossings scored at the 60% confidence interval above their estimated score.
When evaluating wildlife passage structures for “best estimate” analyses we used the modeled terrestrial barrier scores for road-stream crossings with potential to affect connectedness associated with road/highway segments. For the “best case” analysis road-stream crossings in the vicinity of dams were scored at the 60% confidence interval below their estimated terrestrial barrier score. For wildlife passage structures the scaled traffic rate, impervious, and terrestrial barriers settings variables were reduced by 90 percent.

RESULTS

Dams

A total of 2,467 dams were included in the dam removal scenario analysis. Results from a portion of the state are shown in Figure 5. A cumulative histogram of the dams arranged by change in aquatic connectedness (fig. 6) suggests that much improvement in aquatic connectivity could be achieved with the removal of a relatively small number of dams.

Road-Stream Crossings

Culvert/bridge replacement scenarios were conducted for 26,582 road-stream crossings throughout Massachusetts. A sample of the results is shown in Figure 7. Figure 8 is a cumulative histogram of the road-stream crossings arranged by change in aquatic connectedness. These results suggest that selective replacement of a small proportion of culverts/bridges would yield disproportionate benefits in terms of aquatic connectivity.

Road and Highway Segments

A total of 48,859 miles of roads and highways were included in the scenario analysis for wildlife passage structures. Results of this analysis for a portion of the state are shown in Figure 9. For technical reasons railroads have not been included in this analysis.

Availability of Results

Complete results of these analyses are available from our web site: www.masscaps.org.

Figure 5. Results of dam removal scenario analyses for a portion of Massachusetts. Size of the circles is proportional to the change in “aquatic connectedness” that would be achieved by dam removal. Red circles are “best estimate” and yellow circles “best case” results.
Figure 6. Cumulative histogram of dams arranged by change in “aquatic connectedness.”

Figure 7. Results of culvert/bridge replacement scenario analyses for a portion of Massachusetts. Size of the circles is proportional to the change in “aquatic connectedness” that would be achieved by crossing replacement. The larger the circles the greater the improvement in “aquatic connectedness.”
Figure 8. Cumulative histogram of road-stream crossings arranged by change in “aquatic connectedness.”

Figure 9. Results of wildlife passage structure scenario analyses for a portion of Massachusetts. The color of the lines is proportional to the change in “connectedness” that would be achieved by the construction of a wildlife passage structure. The darker the color the greater the benefit of using a passage structure.
DISCUSSION

Scenario-testing software was developed to efficiently assess restoration potential for large numbers of possible restoration projects and then applied statewide to identify road segments, road-stream crossings and dams that currently obstruct aquatic and terrestrial wildlife movement and that offer the greatest opportunity for restoration of landscape connectivity in Massachusetts. Cumulative histograms of dams and road-stream crossings arranged by change in aquatic connectedness (fig. 5 and 7) indicate that a relatively small proportion of dams and crossings accounts for much of the restoration potential statewide. These histograms suggest that there is much to be gained from prioritizing restoration efforts.

CAPS Scenario analysis provides an efficient method for comprehensive assessment and prioritization of movement barriers. It is, however, important to remember the limitations of a modeling exercise such as the Critical Linkages analysis.

Data gaps and errors inherent in the source data used in CAPS are likely to affect the accuracy and usefulness of the analysis. Examples include:

- Unmapped dams
- Unmapped natural barriers to aquatic organism passage (e.g., waterfalls)
- Phantom road-stream crossings erroneously generated by the intersection of roads and streams data in GIS
- Lack of information on the passability of dams (e.g., fish passage structures)
- Lack of information about passability for most road-stream crossings (only about ten percent had been assessed in the field)
- Lack of information about the location of wildlife movement barriers associated with roads (Jersey barriers, fencing)

Another limitation of this analysis is that it only included single structure (dam, culvert) restoration scenarios. This focus on single structures can mask benefits of restoration potential for multi-structure projects. As part of our comprehensive state-wide analysis it was not feasible to evaluate all possible combinations of structure scenarios. However, we are developing separate software to be used with CAPS allowing users to define custom scenarios that can include multiple structures and combinations of different types of structures (e.g., culverts and dams).

The CAPS coarse filter, community based approach is an efficient means for integrating needs of a variety of organisms as well as ecological processes (flow of energy, materials and information). However, scale is important for community-based analyses. Phase 1 of the Critical Linkages project presented here is based on analyses at the local scale. The results of these analyses may be less appropriate for highly vagile species such as birds, bats, and some anadromous fish. The next phase of the Critical Linkages project will focus on regional scale assessment of connectivity. Results from this next phase of analysis are likely to be more relevant for these highly vagile species.

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MAINTAINING HYDROLOGIC CONNECTIVITY ACROSS I-90 EAST OF SNOQUALMIE PASS

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ABSTRACT

Improving ecological connectivity is a primary goal of the Washington State Department of Transportation (WSDOT) I-90 Snoqualmie Pass East Project. The I-90 Project is located in a section of the Central Cascade range that contains many delicate ecosystems, and bisects key north-south migration corridors for wildlife. The project therefore includes many ecological connectivity objectives, including improving hydrologic connectivity - the natural flow paths that transmit water, sediment, and nutrients through watersheds, aquifers, and streams. To meet the project’s hydrological connectivity objectives, WSDOT and the U.S. Forest Service (USFS) have been conducting research for the past five years to develop innovative stream crossing, subsurface drainage, and roadfill designs.

WSDOT and the USFS began their research by mapping Hydrologic Connectivity Zones (HCZs) where the highway corridor intersects wetlands, seepage zones, stream corridors, alluvial fans, and other important hydrologic features. WSDOT and USFS then installed a network of monitoring wells on each side of the highway to characterize subsurface conditions and flow paths near each HCZ. The research team analyzed two years of data at each site in combination with rainfall, snow depth, and temperature data to characterize seasonal behavior and potential impacts of the highway on natural flow paths.

Much of the highway corridor runs along the bases of hillslopes where streams and seepage zones emerge to feed wetlands and aquifers on terraces that line the margin of the Yakima River Valley. Observed data show that fall storms and spring snowmelt are critical periods for groundwater recharge and flow. Groundwater levels are lowest during the late summer, and in mid-winter when soils and seepage zones freeze.

The highway cuts into slopes and intercepts seepage that is currently diverted into ditches and culverts. At these locations the research team determined that WSDOT could maintain hydrologic connectivity by redirecting seepage flow into subsurface drains or permeable fill that would allow water to flow through the roadbed and disperse on downslope terraces. In other locations the highway crosses wetlands where connectivity of both subsurface and surface flow is important. The team found that WSDOT could use bridges or multiple oversized drainage culverts at these locations to provide both hydrologic connectivity and wildlife passage. At stream crossings the project will use bridges and larger culverts to provide fish passage and accommodate floodplain processes such as channel migration.

WSDOT and USFS’ hydrological research and studies in the project area have provided the I-90 Project team with a baseline understanding of flow paths at each HCZ. This data enabled the project engineering team to overcome challenges in the design of the funded Phase 1 of the project. These include constructing a major interstate on areas of porous roadbed, solving maintenance concerns for subsurface drainage systems, and resolving the interaction between hydrologic connectivity measures and stormwater treatment systems. Engineers have also used this data to advance preliminary designs for HCZs in the unfunded Phase 2 portion of the project.

INTRODUCTION

The I-90 Snoqualmie Pass East Project is being developed by the Washington State Department of Transportation (WSDOT) and the Federal Highways Administration (FHWA) to improve safety, reduce congestion, and improve ecological connectivity (Figure 1). The Snoqualmie Pass area is a critical link for the north-south movement of wildlife, and the I-90 corridor crosses the narrowest width of public land in Washington’s Cascade Mountains (WSDOT and FHWA, 2006). Maintaining and improving ecological connectivity is therefore an integral part of the project.
WSDOT and its partners recognized early in project planning that hydrologic processes are central to ecological connectivity. The project passes through U.S. Forest Service (USFS) land, and must comply with USFS Aquatic Conservation Strategy and riparian reserve management programs that require consideration of hydrologic connectivity. The project crosses numerous streams, and often sits on glacial and alluvial terraces with unconfined aquifers that feed the Yakima River (Figure 2). Seepage and shallow groundwater from the hillslopes above I-90 deliver cool water and nutrients to streams and wetlands (Figure 3), and are important sources of water for aquatic habitats during dry periods (Meyer et al. 2003; USDA 2003; Poole and Berman 2001). I-90 also bisects numerous wetland complexes that provide important habitat on the Yakima River valley floor (Null and McQueary 2004). The project therefore includes measures that are designed to improve hydrologic connectivity, which we have defined as “maintaining natural flow paths that transmit water, sediment, and nutrients to and through watersheds, aquifers, and streams” (WSDOT and FHWA, 2006).
The project will construct bridges and larger culverts to improve the movement of water, sediment, woody debris, and aquatic species at stream crossings. It will also include unique and innovative drainage features to accommodate sheet flow and subsurface flow at wetlands and seepage zones. This paper describes monitoring and research conducted in
partnership with the USFS to better understand how the highway influences hydrologic connectivity, and how highway drainage systems can be designed to replicate natural flow paths.

**HYDROLOGIC CONNECTIVITY AT STREAM CROSSINGS**

Road crossings of streams in Washington State are required by law to provide fish passage. In most cases this is best accomplished with culverts or bridges that meet the Washington State Department of Fish and Wildlife’s (WDFW) stream simulation criteria (WDFW, 2003). This involves a structure long enough to span the top-of-bank width plus an additional 20 percent. The bed is constructed with a slope, substrate, and configuration similar to upstream and downstream reaches. For confined streams this method creates a crossing structure that allows natural movement of water, sediment, and wood, and fish passage under a wide range of conditions. Wolfe Creek, located on the slopes above Keechelus Lake, is an example of this type of stream, where a 2-meter (6-foot) culvert will be replaced with a bridge that spans a 6.1-meter (20-foot) stream simulation width (Figure 4).

Unconfined streams have important floodplain interactions that require larger structures to maintain hydrologic connectivity. In these cases WSDOT has designed bridges that substantially span the floodplain and channel migration zone of the stream. This allows the stream to migrate across its floodplain to create important wetland and off-channel habitat and recharge floodplain aquifers. It also provides important corridors for wildlife migration to the lower valleys. Gold Creek is the most extreme example of this type of crossing, where WSDOT is replacing a 42-meter (138-foot) bridge with a 335-meter (1100-foot) bridge to span floodplains and wetlands in the delta where Gold Creek meets Keechelus Lake (Figure 5).

![Figure 4. Proposed Wolfe Creek culvert for fish passage and hydrologic connectivity.](image)
HYDROLOGIC CONNECTIVITY AT SEEPAKE ZONES AND WETLANDS

The I-90 project has unique objectives for hydrologic connectivity that go beyond the typical highway project focus on stream crossings. WSDOT has therefore conducted monitoring and research to help design the non-conventional drainage systems and roadfill configurations that will be required to meet these objectives.

Monitoring Program

WSDOT monitored shallow groundwater at six Hydrologic Connectivity Zones (HCZs) for two water years beginning in the fall of 2004 (Figure 2). The objectives of the monitoring program were to (1) characterize how seasonal conditions influence water levels and flow paths, and (2) identify how the highway influences subsurface flow at each site. This information was then used to develop preliminary design recommendations for surface and subsurface drainage systems.

WSDOT and the USFS delineated HCZs at locations where the highway bisects the following landscape features:

- Hillslope seepage zones
- Alluvial fans where groundwater and shallow surface flow recharge wetlands
- Floodplain fringes on unconfined streams, adjacent slopes, and terraces
- Major wetland complexes

Seepage zones and alluvial fans were identified from reconnaissance field surveys, surficial geology maps, soils maps, and well logs (Washington State Department of Ecology, 2004). Wetlands were identified in the field using standard wetland delineation methods (Null and McQueary, 2004).

Wells were installed in transects at each HCZ to measure unconfined groundwater levels upslope and downslope of I-90. Wells upslope of I-90 were typically shallow and drilled in gravelly hillslope colluvial deposits. Wells downslope of I-90 were typically less than 6.1 meters (20 feet) deep and were drilled in silty sands and gravels derived from glacial deposits and coarse alluvium. Water levels were recorded at six-hour intervals over the entire monitoring period.

Seasonal Behavior of Measured Groundwater Levels

The project corridor experiences wet and cold winters followed by spring snowmelt and dry, warm summers. The wet season typically begins in early October with a series of fall rainstorms that can create significant runoff. By late December the area is usually covered by snow, with a peak snow pack of about 1.3 meters (52 inches) in February/March. Most of the snow on the Yakima River valley floor melts by mid May, but the streams and aquifers in the corridor are also influenced by snowmelt from higher elevations where the snowpack may persist well into June (U.S. Department of Agriculture, 2007). The first year of our monitoring program was warmer and drier than normal,
with a series of warm spells in late January that melted much of the snowpack. The second year was much wetter with a substantial snowpack that persisted through early May.

Figures 6 shows how groundwater levels responded to seasonal conditions. Groundwater levels dropped to a minimum at the end of each summer dry season, but rose rapidly in response to fall rainstorms. In the fall of 2005 rainstorms were scattered, and groundwater levels fell soon after each individual rainstorm. In the fall of 2006 rainstorms were closely spaced, and water levels remained elevated through November.

Cold weather and the initial development of the snow pack caused declines in winter groundwater levels. This reflects a loss of groundwater recharge as the ground freezes. Minimum winter water levels were similar to the water levels seen at the end of the summer dry season. Groundwater levels rose again in late February and snowmelt continued to recharge groundwater through late spring. This is the period when seepage zones and shallow subsurface flow were most active. After snowmelt ended water levels dropped continuously throughout the dry season, and most seepage zones were dry at the surface by late August.

Wells on lowland terraces and floodplains were drilled in deeper deposits, and generally showed a wider range of water levels. In 2006 several wells on the Yakima River valley floor showed a distinct second peak in late spring water levels, after the lowland snow pack had melted. This peak correlates strongly to periods of high storage in Keechelus Lake, when water may seep through porous glacial deposits under the dam and recharge aquifers on the Yakima River valley floor. This second water level peak may also be related to groundwater recharge by late-season snowmelt from higher elevations.

Monitoring Results and Implications for Highway Design

Our monitoring found three general types of flow at the HCZs, each with unique objectives and challenges for maintaining hydrologic connectivity:

Hillslope Seepage Zones

At the Milepost 61.1 and Hudson HCZ’s the highway cuts into hillslopes underlain by bedrock and thin colluvial deposits. Under natural conditions this shallow groundwater would have continued to flow downslope onto glacial and
alluvial terraces, perhaps emerging as seepage at the toe of the slope. This water would have recharged aquifers in the terrace deposits, and likely supported small pockets of wetlands and moist microhabitats on the terrace surface. Monitoring wells just upslope of the highway show water levels in these areas higher than the roadside ditches. The ditches intercept the shallow groundwater and seepage that emerges from roadcuts and redirects it into cross culverts that are typically spaced several hundred feet apart. These cross culverts discharge into rills and eroded gullies that artificially concentrate flow and reduce groundwater recharge on the downslope terraces.

At these locations the primary design objectives for hydrologic connectivity are to (1) minimize interception of seepage in road cuts and ditches, and (2) transmit shallow subsurface flow through the road prism in a manner that replicates subsurface natural flow paths. Figures 7 and 8 illustrate two concepts for drainage designs that could achieve these objectives. In the first, subsurface collection systems are placed in the roadside ditches to convey any intercepted water into multiple small pipes that carry water across the highway. This is similar to subsurface drainage systems used for foundation drainage. The pipes would be closely-spaced to minimize flow concentration, and would discharge through energy dissipaters to spread the water onto the surface of the downslope terrace. This is similar to how seepage often emerges at the toes of natural hillslopes, and would allow the water to form micro wetland habitats and eventually infiltrate into the ground to recharge the terrace aquifers.

Figure 7. Hydrologic connectivity at seepage zones using subsurface drains.
The second concept uses coarse roadfill material to create a permeable road prism (Figure 8). Conventional highway design typically involves well-graded fill that is compacted to provide a stable roadbed. In this case WSDOT would use coarse fill that would maintain permeability while still providing a stable foundation for road construction. The top and bottom elevations of this permeable layer would be designed based on the anticipated water levels upslope and downslope of the highway.

Other highway infrastructure and maintenance needs will pose significant challenges to the designs of these nonconventional drainage systems. In particular, the design of the subsurface collection systems will need to be closely coordinated with the design of highway runoff conveyance and treatment systems. Highway runoff contains fine sediment that could clog subsurface collection systems, as well as pollutants that could contaminate aquifers and aquatic habitats. The stormwater treatment and subsurface drainage systems will therefore need to be designed to avoid discharge of untreated highway runoff onto the downslope terrace.

This stretch of I-90 is located in a harsh subalpine environment that requires continual maintenance of the road surface and adjacent ditches. Roadside maintenance plans will need to include measures to avoid compaction and damage of subsurface drainage systems during ditch maintenance and snow clearing activities. Traction sand frequently builds up in roadside ditches, and will require careful management to prevent clogging of the subsurface collection system.

Section View

Figure 8. Hydrologic connectivity at seepage zones using permeable roadfill.

Wetland subsurface and sheet flow

At Bonnie Creek, Swamp Creek, and the Stampede Pass Interchange the highway bisects low-gradient wetlands on old glacial channels and terraces in the Swamp Creek valley. Bonnie Creek once flowed diffusely through these wetlands into the Yakima River and Swamp Creek floodplains. The original highway construction placed fill across the original wetland flow path, and concentrated the creek into an incised channel that runs along the western edge of these wetlands. Monitoring data on the upslope side of the highway shows water near the surface through much of the spring and early summer, supporting extensive wetlands behind a berm just above the highway. Wetlands no longer exist on the downslope side of the highway, where groundwater levels are typically 3 meters (10 feet) below the ground surface. Similar patterns can be seen in the data for transects in the Swamp Creek floodplain and at the Stampede Pass Interchange.

Hydrologic connectivity objectives for these types of sites include (1) minimizing interception of upslope wetland flow by highway ditches, and (2) providing conveyance structures that accommodate diffuse wetland sheet and subsurface flow towards former wetlands and terraces on the downslope side of I-90.

WSDOT has selected bridges for high-priority sites where hydrologic connectivity objectives dovetail with key wildlife crossing and habitat connectivity objectives. For example, Bonnie Creek is also an important location for connectivity of mature forest habitat. Hydrologic connectivity at this location will be provided through a 183-meter (600-foot) bridge that will allow continuous wetland flow under the highway. The existing ditches and drainage channels will be filled, converting Bonnie Creek from a concentrated single channel into a braided and meandering wetland swale.

Lower cost alternatives were selected at other sites with lower wildlife connectivity values. At these locations wetland flow will be restored by providing multiple over-sized culverts under the highway (Figure 9). The pipes will be located to

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spread water out and mimic low-gradient wetland flow. The inlets of the pipes will be set at the overtopping elevation for wetlands on the upslope side of the highway. The beds of the culverts will be buried with coarse material that will slow water and reduce flow energy. Culverts may also be strategically enlarged to provide wildlife passage for target species. The outlets will disperse water and encourage infiltration onto the terraces downslope of I-90.

Figure 9. Hydrologic connectivity at wetlands using oversized culverts.

Restoring hydrologic connectivity at these former wetland crossing sites will improve groundwater recharge and allow former wetlands to re-develop on the downslope side of the highway. In some locations it could also lower wetland levels upslope of the highway, where roadfill has blocked historic drainage paths and created artificial ponding. Restoring historic drainage paths at these sites therefore poses unique regulatory challenges to balance protection of existing wetland resources against the long-term benefits of restoring natural processes.
Subsurface and surface flow across alluvial fans

At the Price Creek Sno-Park the highway and associated rest areas sit at the base of an alluvial fan that formed at the transition from a steep hillslope onto a glacial terrace. Water from multiple small channels and shallow groundwater flows down this fan and emerges onto parking lots where it is captured by the highway drainage system and conveyed to creeks and gullies downslope of I-90. Prior to highway construction this flow fed wetlands and other forested habitats on terraces.

Groundwater monitoring data show water levels within 1 meter (3 feet) of the surface of the alluvial fan from mid fall through late spring. Water levels drop to about seven feet below ground by the end of the summer, at which time seepage into the Sno-Park is probably minimal. Groundwater levels under the rest area on the downslope side of the highway followed similar patterns, indicating that groundwater is able to flow beneath the highway prism to the downslope terrace.

WSDOT plans to remove the Sno-Park and restore natural flow paths and wetlands on both sides of the highway. The Sno-Park on the upslope side of the highway sits on a terrace where the ground and water levels are significantly higher than levels on the downslope side of I-90. Wetlands in these areas will therefore be created as two separate systems, connected across the highway by multiple oversized culverts similar to those shown in Figure 9. The culverts will be strategically located to serve the multiple flow paths that typically occur on the alluvial fan, and will be set at elevations that allow water to spill from the upslope wetlands to restored wetlands on the downslope side of I-90.

NEXT STEPS

Construction of the first phase of the project began in 2009 along Keechelus Lake. This phase includes hydrologic connectivity structures at stream crossings for Gold Creek, Wolfe Creek, Rocky Run, Resort Creek, and Townsend Creek. It also includes several segments of permeable roadfill to convey seepage intercepted from rock faces to Keechelus Lake. Later phases of the project are in the planning and design stages, and will include many of the innovative subsurface flow and wetland connectivity measures described in this paper. WSDOT will continue research and monitoring to refine the designs of these measures.

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BIOGRAPHICAL SKETCHES

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REAL-TIME DATA ACQUISITION FOR THE MONITORING OF RIVER WATER QUALITY DURING MOTORWAY CONSTRUCTION IN IRELAND

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ABSTRACT

The construction of road scheme river crossings can significantly impact aquatic ecosystems containing protected species, particularly those that are sensitive to the input of sediment. The potential of motorway construction activity to impact freshwater ecosystems has been well documented. The proposed paper will describe a pilot-scale water quality data acquisition system that was developed specifically to provide real-time water quality data during the construction of the recently opened M3 motorway that traverses a Special Area of Conservation (SAC) in Ireland.

A water quality monitoring station was established that enabled the following water quality parameters to be monitored in real-time: Temperature, Turbidity, pH, Dissolved Oxygen. The water quality sensors were powered by a solar panel and the data recorded was instantaneously transmitted via a mobile phone link to a dedicated web site. The primary concern in this instance was the input of excessive sediment. Relationships were established for the rivers in question to enable the on-line turbidity measurements to be converted to SS concentrations. Alarms could also be set on the data acquisition system to signal that a parameter has exceeded water quality limits.

River water quality was recorded continuously at 10-minute intervals both during road construction and for a significant period of time post construction. Data recorded during the motorway construction indicated that the dry-weather SS concentrations were well-within permissible limits. However, during storm events, SS concentrations were dramatically elevated on the rising limit of the flood hydrograph due to sediment transport from earthworks activities associated with the motorway construction. A significant decrease in SS concentrations was recorded for both dry and wet weather flows following re-vegetation of the top-soiled surfaces adjacent to the watercourses traversed by the motorway.

This pilot study demonstrates how cost-effective, state-of-the-art technology can be deployed to continuously monitor in real-time water quality impacts of motorway construction through ecologically sensitive watercourses. Traditional grab sampling is unlikely to provide data at sufficient frequency in water bodies with marked temporal variability. The monitoring protocols developed in this pilot-scale study have already been incorporated into the proposed environmental management of other motorway construction schemes in Ireland, for example, the Environmental Impact Study for the M20 motorway which will cross over rivers containing the endangered pearl mussel, an aquatic species which is highly sensitive to SS. A real-time monitoring system will enable any potential elevation in solids levels due to construction activities to be rapidly detected and corrective action to be taken in a timely fashion to prevent any detrimental effects on the pearl mussel.

INTRODUCTION

The potential for motorway construction activities to impact water quality has been well documented and many studies have identified the degradation in water quality due to elevated levels of sediment (Vice et al. 1969, Beschta 1978, Extence 1978, Duck et al. 1985, Luce and Black 1999, Cerdà 2007). During the construction of river crossings, the disturbance of soil associated with earthworks can result in sediment transport into adjacent watercourses (Barton 1977, Cline et al. 1983, Barrett 1995, Lane and Sheridan 2002). Protected rivers in Special Areas of Conservation (SAC) in Europe or other conservation areas globally are of particular concern as they frequently contain protected species which may be sensitive to elevated sediment concentrations. In road construction it is crucial to mitigate, as far as practicable, the aquatic impacts at the planning, design and construction stages and to monitor water quality once construction commences.

Exposed areas of soil due to excavation, vegetation removal or soil stockpiling are the main sources of sediment from motorway construction activities (Barrett et al. 1995, Wheeler et al. 2005). This sediment has the potential to be mobilized and transported into a watercourse during rainfall events. Elevated concentrations of suspended sediment (SS) and deposited sediment can affect the quality of the water and the stream bed habitat (Forman et al. 2003) which can have detrimental effects on aquatic biota. In fish, elevated SS can clog gills, reduce their growth rates, increase
physiological stress and/or reduce feeding efficiencies (Bisson and Bilby 1982, Waters 1995, Shaw and Richardson 2001). In addition, elevated levels of deposited sediment in spawning gravels can also reduce fish egg survival (Greig et al. 2005). Increases in both suspended and deposited sediment can alter macroinvertebrate communities by increasing drift, reducing their density and richness and/or cause burial (Jones et al. 2011).

Water Quality Regulations such as the Freshwater Fish Directive (2006/44/EC) have designated all freshwaters in Ireland, capable of supporting salmon, trout, char and whitefish, as salmonid waters. Permissible limits for water quality parameters such as SS, amongst other parameters, are specified in these regulations. In the European context, the Water Framework Directive (WFD 2000/60/EC) encompasses all waters including those designated as salmonid waters. The WFD requires these waters to achieve “good” quality status by 2015 with no degradation in water quality. In respect of these regulations, it is important to understand the potential impact of motorway construction on the aquatic environment, especially in ecologically sensitive catchments. Using a small-scale pilot study, this paper evaluates real-time data loggers for monitoring water quality at motorway construction sites with a focus on a special area of conservation.

REAL-TIME MONITORING VERSUS TRADITIONAL GRAB SAMPLING

Continuous monitoring using in-situ sensors has been shown to be a superior sampling methodology compared with manual spot or grab sampling (Glasgow et al. 2004, O’Flynn et al. 2010). To date, however, it would appear that this approach has not been adopted to monitor the effects of motorway construction on adjacent watercourses in Ireland. It is widely recognised that traditional grab sampling may not be sufficient to capture episodic pollutant inputs and such events can be missed due to temporal and spatial variability (Allan et al. 2006, Vrana et al. 2005, Glasgow et al. 2004). In particular, rainfall events can contribute significant quantities of sediment to watercourses during motorway construction (Lane and Sheridan 2002) and, unless repeated grab sampling is employed during these events, the peak inputs of sediment can be missed. In contrast, real-time data acquisition systems can provide continuous, long-term data on water quality. Such data can be relayed to a website giving direct access to the current status of water quality. Alarms can also be set if parametric limits are exceeded. This easily accessible water quality data can then be used to help better manage construction activities and aid the timely deployment of appropriate mitigation measures.

TURBIDITY AND SUSPENDED SOLIDS

Turbidity is a measure of water clarity, measured by the degree of light scattering by SS in the water, while SS is an absolute measure of the concentration of suspended particles in the water (Jastram et al. 2010). SS must be measured by laboratory determination and frequent sampling of water quality is required to establish temporal trends in SS (Gippel 1995). In contrast, turbidity can be measured on site with portable probes making it a suitable parameter for real-time monitoring. Many regulations concerned with the protection of fish, report permissible limits either in terms of turbidity or SS, but generally not both. For example, in Ireland, the Freshwater Fish Directive (2006/44/EC) stipulates that the annual average for salmonid waters should be ≤25 mg/l SS, whereas, in the U.S. sediment limits are mainly reported as turbidity standards for the protection of fish and wildlife habitats (Table 1). The Canadian water quality guidelines for the protection of aquatic life specify both turbidity and SS, and limits vary according to the duration of input (CCME 2002).

Many studies have tried to establish relationships between the SS and turbidity. Some have established relationships for particular watercourses (Gippel 1995, Suk et al. 1998, Packman 1999, Minella et al. 2008). Other studies, however, advise that such relationships should be used with caution since factors such as particle size, shape and distribution and even season can influence the relationship (Sutherland et al. 2000, Bash et al. 2001, Holiday et al. 2003, Robertson et al. 2007, Bilotta and Brazier 2008).
Table 1. Freshwater turbidity standards for protection of fish and wildlife habitats in U.S. states arising from anthropogenic activities (Bash et al. 2001).

<table>
<thead>
<tr>
<th>U.S State</th>
<th>Turbidity (NTU)</th>
</tr>
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<tbody>
<tr>
<td>Alaska</td>
<td>25 units above natural</td>
</tr>
<tr>
<td>California</td>
<td>20% above natural, not to exceed 10 units above natural</td>
</tr>
<tr>
<td>Idaho</td>
<td>5 units above natural</td>
</tr>
<tr>
<td>Minnesota</td>
<td>10 units</td>
</tr>
<tr>
<td>Montana</td>
<td>10 units (5 units above natural)</td>
</tr>
<tr>
<td>Oregon</td>
<td>10% above natural</td>
</tr>
<tr>
<td>Washington</td>
<td>5 units above natural for ‘excellent’ waters and 10 units above natural for ‘good’ waters</td>
</tr>
<tr>
<td>Wyoming</td>
<td>10 units above natural</td>
</tr>
</tbody>
</table>

PILOT STUDY

Study Area

This study was undertaken in the east of Ireland. The recently constructed M3 motorway was chosen for the pilot study since the scheme traverses rivers protected as Special Areas of Conservation (Fig. 1). Construction of the 60km scheme began in April 2007 and was completed in June 2010.

The Boyne River is classed as an SAC, the Boyne itself and its tributaries (Skane and Lismullin rivers) contain important salmonid populations and spawning habitats. To facilitate the M3 motorway, two culverts were constructed across the River Skane and eight across the River Lismullin. A real-time data acquisition system was established during the construction period for the purpose of monitoring water quality. The monitoring site was located at the confluence of the Skane and Lismullin rivers, downstream of the culverts constructed on both tributaries (Fig. 2).

Figure 1. Location of the M3 construction scheme and River Boyne watercourses.
Culvert construction was completed by the time the real-time system was deployed (February 2010) but large areas of un-vegetated soil, arising from earthworks activities, were still exposed along the banks of the two rivers (Fig. 3). This sediment had the potential to be mobilized during rainfall events and to be transported directly into the adjacent watercourses. Hydroseeding on exposed earthworks was carried out in late April 2010 and trees were planted but it took a several months for vegetation to become established.

Methods

The real-time data acquisition system deployed in this study recorded depth (mm), turbidity (FTU), temperature (° C) and dissolved oxygen (ppm) at 10 minute intervals. Solar panels powered the system and all the data was transmitted to a website (http://89.124.67.3/ucd/). Wipers were also installed on the sensors to prevent biofouling. For the purpose of this paper, turbidity is the primary focus and the main parameter discussed. A sample of the real-time data recorded is presented in Figure 4.
The turbidity of the watercourses adjacent to the motorway construction was examined during dry weather and rainfall events when the banks were exposed and later when the banks had re-vegetated. Rainfall data obtained from the closest meteorological station (Dublin Airport) and water depth readings were used to identify rainfall events.

To determine a turbidity/SS relationship for the Lismullin river, water samples were taken from the river. The bed of the river was ‘kicked’ and the plume of sediment generated was sampled and analysed in the laboratory. Turbidity was measured using a Hach 2100n IS turbidity metre and SS were measured using the standard methods in Greenberg et al. (1998). To test if turbidity can be used to predict SS a linear regression was carried out using SPSS statistical package.

RESULTS

A significant relationship was found between turbidity and SS for the Lismullin river samples, as illustrated in Fig. 5 ($r^2=0.806 \ p<0.001$). From this relationship, SS can be predicted from the recorded turbidity values. For example, 5.5NTU would be the equivalent of 25mg/l SS (Fig.5).
Examination of rainfall events, before and after the exposed banks had re-vegetated, revealed that, in April 2010 when banks were exposed, the water depth reached a level of 861 mm with a peak turbidity in the region 100 NTU (Fig. 6a). In November 2010, when banks had begun to re-vegetate the river rose to a depth of 734 mm but turbidity levels remained below 5 NTU (Fig. 6b).

Figure 5. SS and turbidity relationship for the sediment plume from Lismullin river.
Equation of the line $y = 4.39(x) + 0.78$, $r^2 = 0.806$, $p < 0.001$.

Figure 6a. Turbidity (FTU) and depth readings (mm) in April 2010, banks exposed.
Figure 6b. Turbidity (FTU) and water depth (mm) in November 2010, banks re-vegetated
During motorway earthworks, when soil was exposed there were numerous spikes in the turbidity
readings, with values sometimes exceeding 100 NTU. Once the banks began to re-vegetate by
early October, the turbidity values significantly declined and generally remained below 5 NTU.

**DISCUSSION**

The real-time data presented in Figures 4 and 6 shows a number of interesting features:

(a) In Figure 4, a diurnal variation in dissolved oxygen (D.O) levels clearly mirrors the photo-voltaic charging by the
solar panel. D.O. levels increase during daylight, as a result of increased algal photosynthesis and decrease in
darkness, but remain above the minimum D.O. level of 50% ≥ 9mg/l recommended for Irish salmonid waters;
(b) A diurnal variation in water temperature is evident and this is clearly a further factor that influences D.O. levels;
(c) Figure 6(a) shows a short-term turbidity (and by corollary suspended solids) levels of the water dramatically
increase (>100NTU) following the rapid increase in water depth during the storm event,
(d) Following the recession of the flood event, the turbidity of the water returned to its background levels;
(e) The establishment of vegetation on the soil surface dramatically reduces the peak water turbidity on the rising
limb of the flood hydrograph (Fig.6(b)).

The real-time data presented above clearly illustrates that a rapid increase in water depth due to rainfall events
resulted in a short-term elevation in water turbidity during motorway construction. However, it is unknown what impact,
if any, these elevated sediment events may have had on the salmonids in the Skane and Lismullin. There are numerous
aboratory studies detailing the impacts of elevated sediment concentrations on fish. Robertson et al. (2000)
demonstrated that juvenile Atlantic salmon exposed to 260-460mg/l of SS for 2.5 hours exhibited a decrease in
foraging and avoidance behaviour. Avoidance behaviour was also demonstrated in juvenile coho salmon when they
were exposed to turbidity >70 NTU (Bisson and Bilby 1982) for 30 minutes. Shrimpton et al. (2007) exposed juvenile
coho salmon to 8 hour pulses of 200mg/l SS and observed lower enzyme activities compared to control fish. Sigler et
al. (1984) found that a turbidity of 25 NTU significantly reduced the growth of juvenile steelhead trout and coho
salmon. Some studies, however, suggest that if fish are impacted, recovery can occur once the source of the sediment
is eliminated (Barton 1977, Taylor and Roff 2003). However, elevated levels of SS have the potential to deposit on the
geriver bed and pose a longer-term threat to aquatic biota including infiltration of spawning gravel (Greig et al. 2005,
Jensen et al. 2009). It is, therefore, important to detect and minimise even short duration inputs of sediment.

With the exception of Robertson et al. (2007), most studies conducted on the impact of sediment on fish either report
SS or turbidity (but not both) and it is difficult to make comparisons across studies. Reporting both SS and turbidity
values would provide a more comprehensive dataset for regulatory agencies in determining permissible limits for the
protection of aquatic species. If real-time data on water quality was made available during construction work to relevant personnel, this would enable appropriate measures to be initiated to minimise further inputs of sediment. Research on the performance of mitigation measures on exposed soils such as slope coverings, matting, wood mulches or temporary vegetation has shown that these measures can significantly reduce the input of sediment during motorway construction (Cline and Forest 1983, Barrett et al. 1995, Faucette et al. 2007).

In light of this pilot study, the following comments are relevant to monitoring and controlling road construction generated SS impacts on adjacent watercourses:

- SS concentrations can only be monitored continuously by real-time turbidity measurements, which must then be converted using an established turbidity/SS correlation to SS. As noted above, there are many confounding factors associated with the establishment of such relationships.
- In the European context, the Freshwater Fish Directive (2006/44/EC) applies to salmonid waters. The SS guide limit of 25mg/l in the Directive is specified as an annual average guide value (not a maximum permissible limit). The term ‘average’ suggests that short term exceedances (either natural or anthropogenic) may not necessarily be in breach of the water quality regulations, provided the annual average SS does not exceed 25mg/l. Hence, in the context of earthworks construction and its impact on the aquatic environment, compliance with the SS parametric limits in the Directive is somewhat ambiguous.
- Biofouling of the lens of the turbidity sensor in a natural aquatic environment may result in erroneous turbidity (and hence SS) values unless provision is made for the sensor lens to be automatically cleaned.

One of the merits of the real-time data acquisition system deployed in this study is that it is relatively portable and can be moved from one location to another during the course of the motorway construction scheme, as required. As a result of this pilot study, the use of a real-time data acquisition system has been proposed in the EIS on another motorway scheme in Ireland which will cross rivers containing the protected and endangered freshwater pearl mussel (Margitifera margitifera L.).

CONCLUSIONS

Dry weather turbidity and SS values were low during the construction of the M3 motorway but short-term elevated values were recorded during storm events. A marked decrease in the turbidity and SS was seen following the re-vegetation of exposed earthbanks. This research clearly highlights the critical role of a relatively low-cost, state-of-the-art, real-time water quality data logging system in monitoring and ultimately guiding effective control of sediment inputs from construction activities, particularly in ecologically sensitive catchments.

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REFERENCES


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