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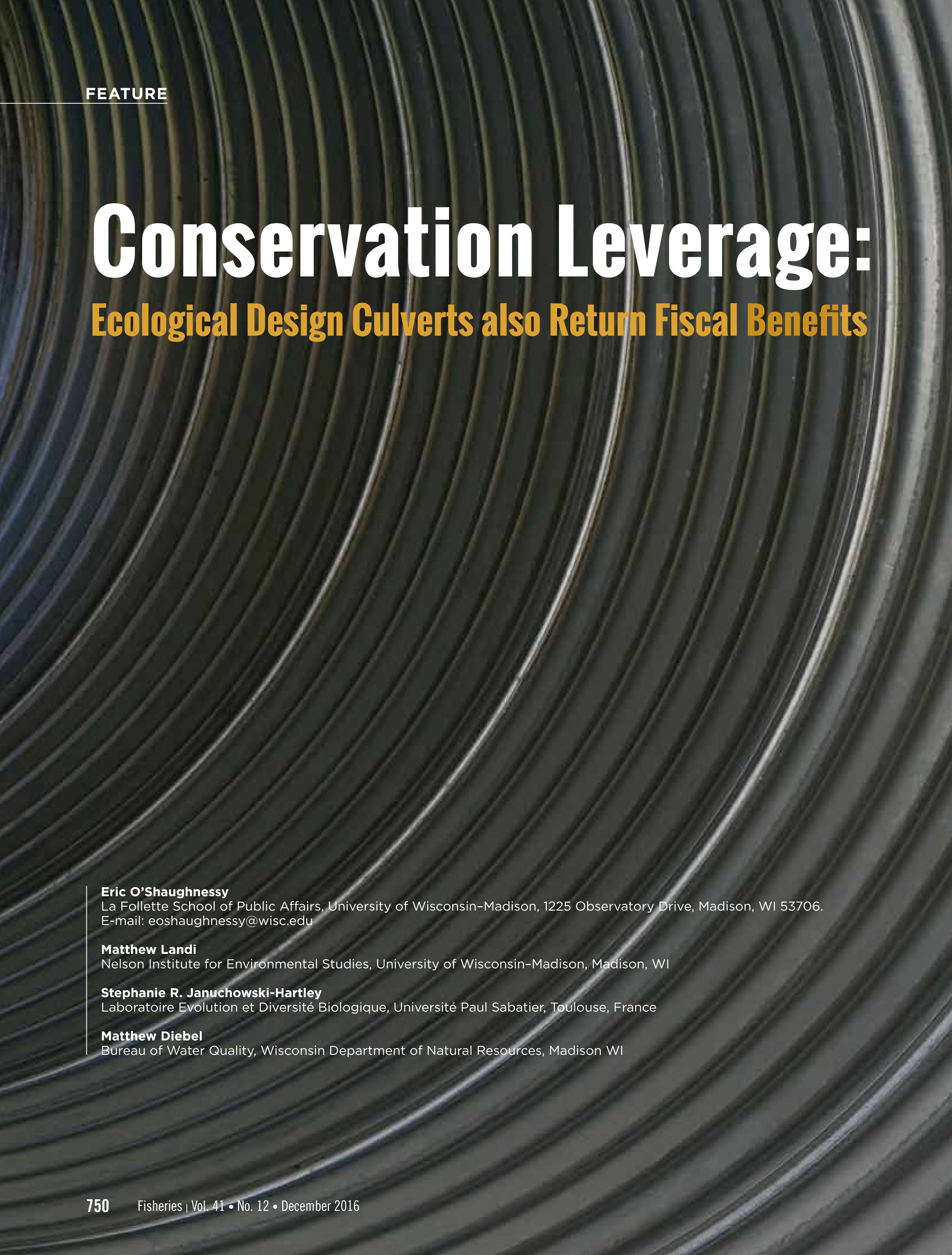

FEATURE

Conservation Leverage:

Ecological Design Culverts also Return Fiscal Benefits

Eric O'Shaughnessy
La Follette School of Public Affairs, University of Wisconsin–Madison, 1225 Observatory Drive, Madison, WI 53706.
E-mail: eoshaughnessy@wisc.edu

Matthew Landi
Nelson Institute for Environmental Studies, University of Wisconsin–Madison, Madison, WI

Stephanie R. Januchowski-Hartley
Laboratoire Evolution et Diversité Biologique, Université Paul Sabatier, Toulouse, France

Matthew Diebel
Bureau of Water Quality, Wisconsin Department of Natural Resources, Madison WI

Traditional hydraulically designed culverts impede ecological connectivity and degrade aquatic ecosystems. This problem is compounded by their ubiquity in the built environment. To overcome these limitations, alternative designs have been created to facilitate natural conditions and restore ecological connectivity. However, these "ecological design" culverts have perceived fiscal limitations that have prevented widespread implementation and consequently hampered conservation and remediation of stream ecosystems important for myriad fish species and aquatic organisms. We addressed these perceived fiscal limitations using cost–benefit analysis to estimate the lifetime fiscal net benefits of ecological design culverts over hydraulic culverts. We found that in nearly half of all cases remediation with ecological design culverts was more cost effective than maintaining hydraulic culverts and that it is most cost effective on small streams compared to larger ones. We also found that higher upfront replacement costs for ecological design culverts are overcome by their lifetime fiscal benefits. This is because of longer life span, reduced maintenance, and improved flood event resiliency of ecological design culverts. Our findings suggest that cost–benefit analysis could help conservation decision makers overcome higher construction costs and guide more cost-effective and sustainable solutions for aquatic conservation and ecological connectivity.

Conservación con ventaja: diseño de alcantarillas ecológicas ofrecen beneficios fiscales

El diseño hidráulico tradicional de alcantarillas impide la conectividad y degrada los ecosistemas acuáticos. Este problema se ve agravado por su ubicuidad en los ambientes afectados. Para superar tales limitaciones, se han creado diseños alternativos que facilitan condiciones naturales y sirven para restaurar la conectividad. No obstante, estas alcantarillas de diseño ecológico han sido sujetas a limitaciones en el terreno fiscal que previenen su implementación en gran escala, lo que en consecuencia ha obstaculizado la conservación y remediación de ecosistemas fluviales que son clave para una miríada de especies de peces y organismos acuáticos. Aquí se abordan estas limitaciones fiscales mediante análisis costo-beneficio para estimar los beneficios fiscales netos de largo plazo de usar alcantarillas ecológicas en vez de alcantarillas hidráulicas. Se encontró que en casi de la mitad de los casos, la remediación utilizando alcantarillas ecológicas, en comparación a las hidráulicas, era más efectiva en términos de costos; y lo mismo aplica a cauces pequeños versus cauces grandes. También se encontró que los beneficios fiscales a lo largo de la vida útil de las alcantarillas ecológicas, sobrepasan sus costos de reemplazo. Esto se debe a que las alcantarillas de diseño ecológico duran más, demandan poco mantenimiento y tienen mayor resiliencia en eventos de inundación. Estos resultados sugieren que un análisis costo-beneficio pudiera ayudar a los tomadores de decisiones a enfrentar los altos gastos de construcción, guiándolos a soluciones sostenibles y más efectivas para la conservación y conectividad ecológica.

Effet de levier de la conservation : Les ponceaux de conception écologique procurent aussi des avantages fiscaux

Les ponceaux traditionnels conçus de manière hydraulique empêchent la connectivité écologique et dégradent les écosystèmes aquatiques. Ce problème est aggravé par leur omniprésence dans l'environnement bâti. Pour surmonter ces limitations, des conceptions alternatives ont été créées pour faciliter les conditions naturelles et restaurer la connectivité écologique. Cependant, ces ponceaux de « conception écologique » se sont heurtés aux limitations fiscales, ce qui a empêché leur mise en œuvre généralisée, ce qui a par conséquent entravé la conservation et la restauration des flux d'écosystèmes importants pour les espèces de poissons innombrables et les organismes aquatiques. Nous avons abordé ces limitations fiscales perçues, en utilisant une analyse coûts-avantages pour estimer la durée de vie des avantages fiscaux nets des ponceaux de conception écologiques par rapport aux ponceaux hydrauliques. Nous avons constaté que, dans près de la moitié de tous les cas, la réhabilitation des ponceaux de conception écologique était plus rentable que le maintien des ponceaux hydrauliques, et qu'ils sont plus rentables sur les petits cours d'eau par rapport aux plus grands. Nous avons également constaté que la hausse des coûts initiaux de remplacement des ponceaux de conception écologique est surmontée par la durée de vie des avantages fiscaux associés. Ceci est dû à une plus grande longévité, une maintenance réduite, et l'amélioration de la résilience des événements d'inondation des ponceaux de conception écologique. Nos résultats suggèrent que l'analyse coûts-avantages pourrait aider les décideurs de la conservation à surmonter les coûts de construction plus élevés et à proposer des solutions plus rentables et durables pour la conservation aquatique et la connectivité écologique.

INTRODUCTION

Despite known impacts of road culverts on aquatic ecosystems and the species that they support, traditional hydraulic design has dominated road culvert design for several decades (USFS 2008). These types of culverts, which we refer to as "hydraulic culverts," are aimed at minimizing structure size and cost by allowing as much water to flow through as is possible for a given flood flow. Historically, the consideration of aquatic ecosystems in culvert design and management has been a low priority relative to construction cost minimization (USGAO 2001). This oversight has resulted in high proportions of hydraulic culverts acting as potential barriers to ecological connectivity, limiting biological and geomorphic processes (e.g., USGAO 2001; Gibson et al. 2005; Burford et al. 2009; Januchowski-Hartley et al. 2014). The consequences of these barriers on ecological connectivity, as well as the identification of cost-effective solutions for remediation, are growing areas of study.

There are several reasons that hydraulic culverts can act as barriers to ecological connectivity, primarily by limiting aquatic organism passage that can have cascading, adverse impacts on stream ecology and aquatic habitat. Undersized or otherwise poorly designed hydraulic culverts have myriad geomorphic effects on streams, including, but not limited to, the modification of the stream's channel and morphology, bank erosion, and channel incision (Furniss et al. 1998). Channel constriction upstream of hydraulic culverts can increase stream flow within the structure to velocities that surpass the swimming abilities of fish species (Gibson et al. 2005; Januchowski-Hartley et al. 2014). In turn, heightened stream velocity can erode the streambed downstream from the structure and result in a vertical gap or "outlet drop" between the stream surface and the mouth

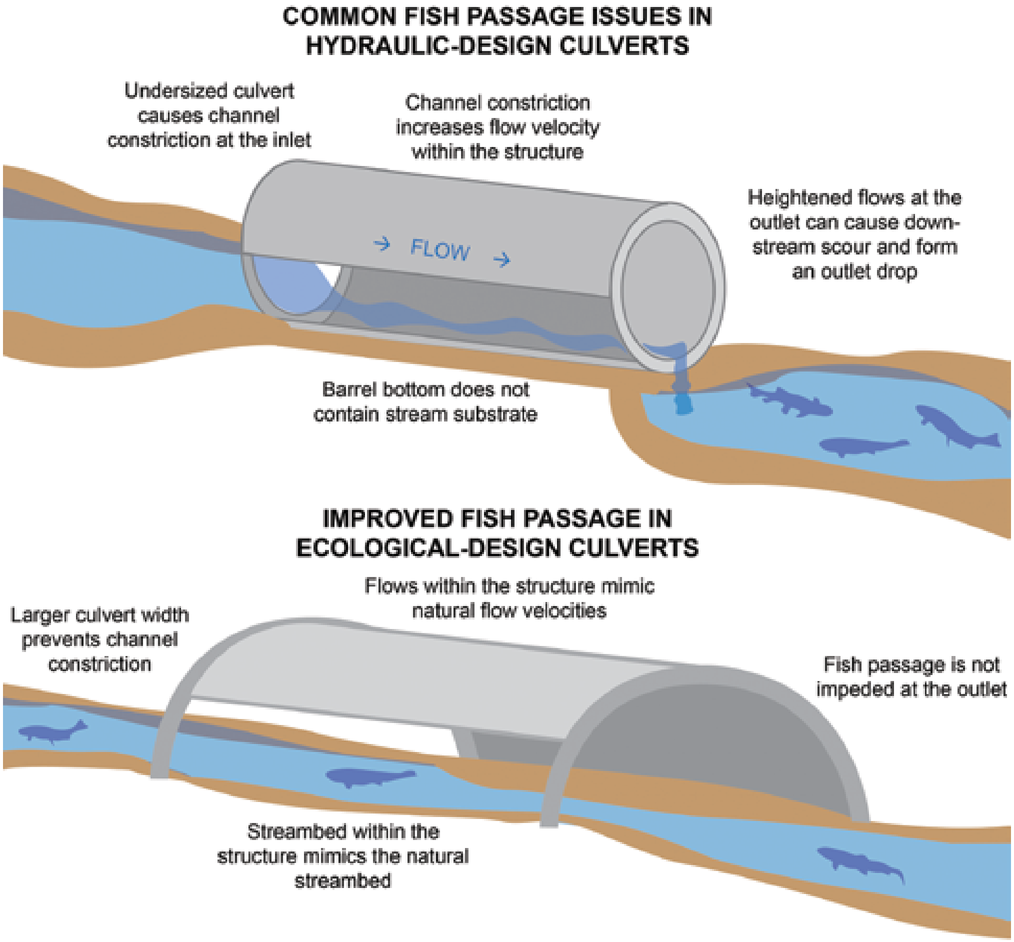

Figure 1. Schematics depicting (a) hydraulic and (b) ecological design culverts.

of structure (Figure 1). Outlet drops act as mini-waterfalls, limiting species' movement upstream (Norman et al. 2009; Poplar-Jeffers et al. 2009). In many cases, hydraulic culverts are also set too high, exacerbating this problem (NCHRP 2002). Hydraulic culverts can also disrupt sediment transport, which can cause culvert structural failure or increase the need for routine maintenance (Furniss et al. 1998; NCHRP 2002). Consequently, road culverts fragment aquatic ecosystems, affecting ecological processes, limiting species' access to spawning habitats, and reducing population connectivity (Fausch et al. 2002; Letcher et al. 2007).

In addition to their ecological benefits, ecological design culverts could have lower fiscal costs than hydraulic culverts, because of increased flood resiliency and reduced debris accumulation, which in turn reduce the need for periodic maintenance and replacement.

The potential ecological benefits gained from remediating hydraulic culverts have prompted the development of "ecological designs" that maintain natural stream conditions upstream, downstream, and within the culvert (Bates et al. 2003; Gillespie et al. 2014). "Ecological design culverts" refers to a variety of proposed structural changes to typical hydraulic culverts (Figure 1) that often employ wider widths, natural slope gradients, and natural streambeds within the structure to reduce the impact of the culvert on natural stream conditions and ecological processes (USGAO 2001; USFS 2008). Stream simulation, one type of ecological design culvert, is based on an artificial stream channel within the structure to encourage more natural fish passage through the structure (Bates et al. 2003; USFS 2008).

In addition to their ecological benefits, ecological design culverts could have lower fiscal costs than hydraulic culverts, because of increased flood resiliency and reduced debris accumulation, which in turn reduce the need for periodic maintenance and replacement (Gillespie et al. 2014). Despite the potential cost savings, the long-term fiscal benefits of ecological design culverts are rarely considered when making decisions about the allocation of resources. Upfront installation costs can make investments in ecological design culverts appear to be cost prohibitive under limited budgets (Gillespie et al. 2014). Given this gap in knowledge, there is a need for cost–benefit analyses (CBAs) to better our understanding of the trade-offs associated with remediating hydraulic culverts with ecological design culverts (Hansen et al. 2009; Diebel 2013; Neeson et al. 2015).

CBAs can monetize and assess decision-making impacts based on the net benefits of proposed alternatives (Boardman et al. 2010). Net benefits are estimated based on all costs accrued over the full lifetime of a project. In this article, we use CBA to quantify and monetize the relative costs and benefits of replacing hydraulic culverts with ecological design culverts. We build upon ideas presented by Gillespie et al. (2014) and predict the relative lifetime costs of ecological design culverts for a large set of road culverts in the midwest United States. Our CBA assesses two strategies: (1) a road culvert infrastructure planning regime that replaces existing hydraulic culverts with new hydraulic culverts and (2) an alternative regime that replaces existing hydraulic culverts with ecological design culverts. We use a sensitivity analysis to explore the effect of uncertainty in cost functions on the relative costs of the two strategies. We discuss the potential utility of CBA to identify fiscally and ecologically responsible solutions for culvert replacement.

METHODS

Road–Stream Crossing Inventory

We used an inventory of culverts at road–stream crossings collected by the Wisconsin Department of Natural Resources (WI DNR), University of Wisconsin–Madison, and The Nature Conservancy in 2011 and 2012 from the Green Bay watershed, Wisconsin and Michigan (Diebel 2013). The watershed is relatively flat and its streams have flashy hydrology because of low permeability soils and agricultural drainage. The entire data set included 1,615 culverts on Green Bay tributaries. We used stream bank-full width (width at which a stream overflows its channel into its floodplain; Leopold et al. 1964) to determine which existing culverts were most likely to be hydraulic culverts. We identified 998 culverts with widths less than or equal to bank-full width, and 46% of these undersized culverts had sufficient data to populate all inputs for our cost estimation (the installation cost estimator required data on certain structural variables, described further below). We used these 461 culverts for all subsequent CBAs (Table 1).

Culvert Lifetime Costs

We considered four lifetime cost components for culverts: replacement cost, catastrophic failure, routine maintenance, and flood damage maintenance over a 70-year time period. We used a method described by Neeson et al. (2015), which uses structure dimensions and unit costs of materials and labor to estimate culvert replacement cost. In brief, total project cost is equal to the sum of the costs of the culvert structure (market prices in 2009 in Wisconsin and Michigan), excavation (US$20/yard; volume estimated from structure dimensions), road resurfacing ($2,500 per lane for paved roads and $800 for gravel or dirt roads), and miscellaneous costs ($2,500–5,000 depending on structure size), plus 20% for design and construction oversight. The net replacement cost for ecological design culverts relative to a hydraulic culvert was then calculated as

$$\text{Net replacement cost} = RC_E - \left(RC_H + \frac{RC_H}{1.035^{35}}\right) ,$$

where hydraulic culvert replacement cost (RC_H) was based on a structure with the same width as the existing culvert, and ecological design culvert replacement cost (RC_E) was based on a culvert width 20% greater than the bank-full width of the stream, a standard for ecological design culverts (Commonwealth of Massachusetts 2012). We apply the 20% greater than bank-full

Table 1. Summary statistics of the culverts used in the analysis (n = 461). SD = Standard deviation.

Scenario	Mean	SD	Minimum	Median	Maximum
Bank-full width (m)	2.01	0.99	0.91	1.69	5.79
Culvert width (m)	1.08	0.62	0.18	0.91	4.11
Constriction ratio	0.55	0.20	0.14	0.53	1.00
Culvert length	14.19	10.73	2.44	12.80	140.21

width as a conservative approach. It is worth noting that other less stringent standards have been proposed by Bates et al. (2003) and USFS (2008). We assumed that hydraulic culverts required replacement occurring in the 35th year of the analysis based on projected 25- to 50-year lifetimes of hydraulic culverts (see Gillespie et al. 2014). All future costs were discounted at a rate of 3.5%.

Catastrophic culvert failure, especially during flood events, may prompt emergency culvert replacement. We estimated the relative costs of catastrophic failure for the two culvert design approaches as

$$\text{Expected failure benefit} = \sum_{0}^{70} \frac{f(t)_C * FC_t}{1.035^t} - \sum_{0}^{70} \frac{f(t)_E * FC_t}{1.035^t} ,$$

where $f(t)_C$ is the failure rate of hydraulic culverts and $f(t)_E$ is the failure rate of ecological design culverts based on assumed project lifetimes of 35 and 70 years, respectively (for failure rate methodology see Meegoda et al. 2009). Here, the culvert failure rate reflects the risk of failure as the structure approaches the end of its useful life. The failure rate increases over time due to several factors including abrasion from sediment moving through the structure. The wider width of ecological design culverts reduces abrasion by allowing sediment to pass through the culvert without impacting the structure (Gillespie et al. 2014). Reduced abrasion increases the anticipated service life of ecological design culverts (Gillespie et al. 2014); thus, we assume a lower failure rate for ecological design culverts. We assumed that failure cost (FC_t) in any given year (t) equaled the replacement cost adjusted downward to reflect that the culvert would have been replaced after 35 or 70 years in any case for both hydraulic and ecological design culverts, respectively, according to

$$FRC_{i,t} = \frac{L - t}{L} * RC_i ,$$

where $FRC_{i,t}$ is the failure replacement cost of culvert i in year t, L is the projected lifetime of the structure (35 or 70 years), and RC_i is the estimated hydraulic culvert replacement cost of the structure.

Culvert maintenance activities include preventative maintenance, clearing the structure of debris, and structural repairs (e.g., patching). Ecological design culverts do not typically require routine maintenance (Gillespie et al. 2014). We assumed that structural obstructions (e.g., debris, crushed culvert barrel), found in about 10% of culverts in Green Bay watershed data, indicated that a culvert required maintenance. We developed a probit model to estimate the probability that a given culvert required maintenance as a function of the constriction ratio (culvert width/bank-full width), given:

$$p(M)_i = \phi(ß_0 + ß_1 CR_i) ,$$

where $p(M)_i$ is the probability of maintenance in a given year for culvert i, Φ is the normal distribution, $ß_0$ and $ß_1$ are coefficients estimated by the model, and CR_i is the constriction ratio of culvert i. The model showed a statistically significant relationship between the probability of required maintenance and the constriction ratio; that is, the probability that a given culvert will require maintenance in a given year decreased as the width of the culvert approached and exceeded the width of the stream (see Supplementary Materials). The model predicted that a culvert sized at half of the bank-full width had a 13% probability of presenting a structural obstruction in any given year, compared to a probability of about 8% for a culvert sized at the bank-full width. In other words, the model suggests that culverts sized at the bank-full width are about 41% less likely to require maintenance than culverts sized at half the bank-full width in any given year. We determined lifetime maintenance costs as the sum of expected values of maintenance costs, given

$$\text{Reduced maintenance benefit} = \sum_{0}^{70} \frac{p(M)_E * 1{,}488}{1.035^t} - \sum_{0}^{70} \frac{p(M)_C * 1{,}488}{1.035^t},$$

where $p(M)_E$ is the modeled probability of maintenance for ecological design culverts (based on a constriction ratio of 1.2), $p(M)_C$ is the modeled probability of maintenance for hydraulic culverts (based on the constriction ratio of the existing culvert), and \$1,488 is an assumed maintenance cost based on values determined through a Minnesota Department of Transportation (MNDOT) survey of culvert maintenance costs (MNDOT 2015).

Culvert maintenance costs can also accrue from flood damages. We modeled the 25-year flood as a random event with an annual probability of 0.04 with an estimated repair cost of \$2,659 (based on the MNDOT survey data). It is possible that flood damages could accrue during more frequent and lesser flooding events (e.g., 10-year flood). However, we restrict flood damages to 25-year flood events to remain conservative. We assumed that ecological design culverts do not accrue flood damages due to the increased flood resiliency demonstrated by these structures (Barnard et al. 2015; Gillespie et al. 2014). Therefore, the reduced flood damage benefit is given as

$$FDB_i = \sum_{t=1}^{70} \frac{2{,}659}{1.035^t} | u(0,1) < 0.04,$$

where FDB_i is the flood damage benefit of culvert i, and the term $u(0, 1) < 0.04$ indicates that the model generated a random flood event when the value of a uniform distribution bounded by 0 and 1 took on a value less than 0.04.

Scenarios and Monte Carlo Analysis

We used three scenarios and a Monte Carlo analysis to explore the potential range of costs and benefits associated with replacing hydraulic culverts with ecological design culverts. The net benefit in each scenario is the net cost of hydraulic culvert replacement with an ecological design culvert after accounting for longer lifetime, benefits from reduced failure costs, reduced maintenance costs, and reduced flood damage costs of ecological design culverts. Our first scenario determined a point estimate for each of the four cost components outlined above. The point estimate provides a plausible single value for each of the benefit categories. Best- and worst-case scenarios provide reasonable "bookends" for the range of net benefits between the highest and lowest values of the net benefits of ecological design culverts. In the best-case scenario, we assumed that hydraulic culverts required three replacements during the analysis timeframe: in the first, 25th, and 50th years, whereas ecological design culverts only required a first-year replacement. In the worst-case scenario, we assumed that ecological design culverts provided no performance benefits other than increased lifetime and flood damage benefits and that hydraulic culverts would not require replacement until the 50th year of the analysis.

We used a Monte Carlo analysis to assess the sensitivity of our model to uncertain assumptions in our variables. We allowed three of our underlying assumptions to vary. First, we allowed the lifetime of the hydraulic culvert to vary randomly within a uniform distribution from 25 to 50 years according to typical project lifetimes (Gillespie et al. 2014). Second, we allowed our assumption for maintenance costs to vary randomly in a uniform distribution from \$36 to \$3,869, according to the minimum recorded maintenance cost and a value one standard deviation above the mean for 99 culvert cleanings, ditch cleanings, joint repairs, and hole repairs (MNDOT 2015). Third, we allowed our assumption for flood damage repair costs to vary randomly from \$521 to \$4,798 based on one standard deviation above and below the mean value of repairs associated with 40 resets (from MNDOT 2015 survey data). Catastrophic culvert failure is a high-cost, low-probability event. To be conservative, we did not include failure benefits in our Monte Carlo analysis. We performed 1,000 iterations to develop Monte Carlo estimates for the percentage of culverts that achieved positive net benefits.

Determinants of Net Benefits

We used ordinary least squares regression to study the primary determinants of the net benefits of culvert replacement with ecological design culverts. Based on the inputs to our costs and benefits, we developed four models:

1. $NB = ß_0 + ß_1 bw$
2. $NB = ß_0 + ß_1 bw + ß_2 cw$
3. $NB = ß_0 + ß_1 bw + ß_2 cw + ß_3 cl$
4. $NB = ß_0 + ß_1 CR$

where NB is net benefits (\$/culvert), bw is bank-full width (m), cw is culvert width (m), cl is culvert length (m), and CR is constriction ratio (culvert width/bank-full width). The net difference in lifetime costs between ecological design and hydraulic culverts determines the fiscal net benefit of culvert replacement with ecological design culverts.

RESULTS

Net Benefits of Ecological Design Culverts

The construction costs of ecological design culverts were \$40,700 on average, compared to about \$22,900 for hydraulic culverts. However, the lifetime costs of ecological design culverts were about \$13,300 lower than the lifetime costs of hydraulic culverts: \$3,300 compared to \$16,500 on average. The savings accrued from reduced lifetime costs exceeded the relatively higher upfront cost of ecological design culverts in 49% of replacements in our point estimate model. Essentially, our result suggests that ecological design culverts would be fiscally net beneficial in about 49% of culvert replacements. The proportion of fiscally net beneficial replacements ranged from 13% in the worst-case scenario to 76% in the best-case scenario (Figure 2). In 1,000 iterations of the Monte Carlo analysis, on average, 43% of culvert replacements were fiscally net beneficial.

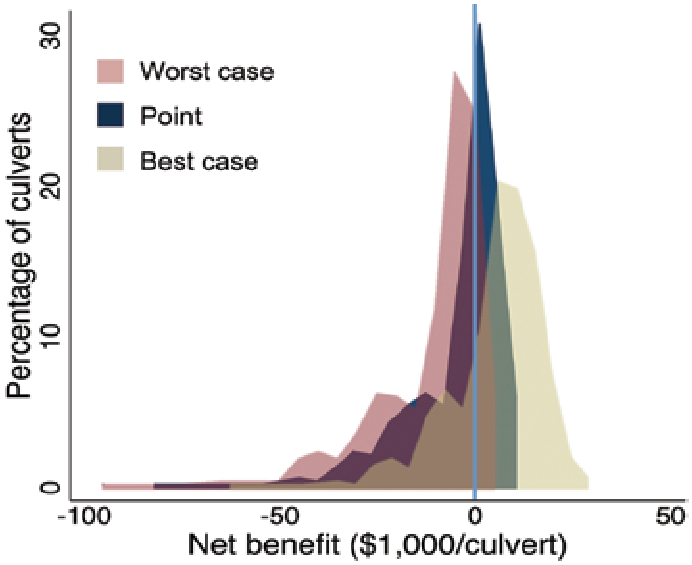

Figure 2. Area plot histograms of fiscal net benefits ($1,000/culvert) for the point estimate, worst-case scenario, and best-case scenario.

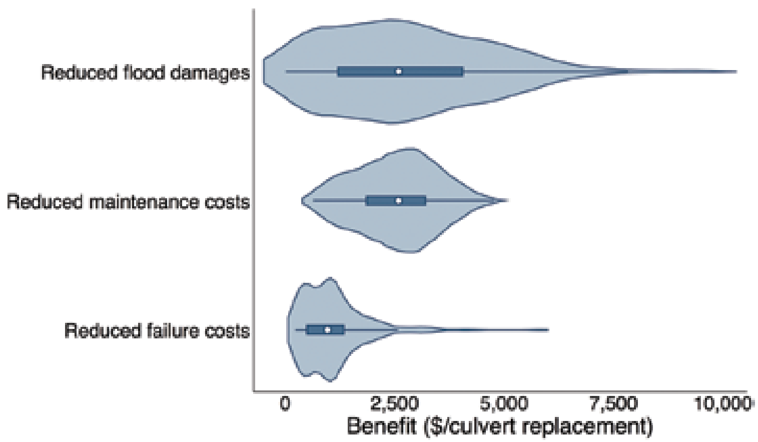

Figure 3. Area plots depicting the distribution of different measured benefits ($/culvert).

Table 2. Mean values for cost components from point estimate and worst-case and best-case scenarios.

Scenario	Lifetime replacement	Flood damage	Reduced maintenance	Expected failure	Net fiscal benefit
Worst case	−13,600	2,800	0	0	−10,800
Point estimate	−10,900	2,800	2,500	1,100	−4,500
Best case	−3,900	2,800	5,000	1,100	4,900

The average fiscal net benefit of hydraulic culvert replacement with ecological design culverts was −$4,500, with a plausible range of −$10,800 to $4,900 based on the worst- and best-case scenarios (Table 2). All benefits displayed considerable variation. Interquartile ranges spanned from −$16,524 to −$2,462 per replacement for net replacement cost, from $1,205 to $4,049 for flood damage benefits, from $1,856 to $3,197 for reduced maintenance benefits, and from $493 to $1,331 for the reduced failure benefit (Figure 3).

Determinants of Net Benefits

The largest determinants of net benefits were stream bank-full width and the width of the existing hydraulic culvert. Together these two factors explained about 80% of the variance in net benefits from our point estimate model (see Supplementary Materials). Fiscal net benefits were negatively correlated with bank-full width (i.e., culverts on larger streams exhibited lower net benefits), whereas net benefits were positively correlated with existing culvert width (Figure 4).

DISCUSSION

We used CBA to quantify and assess the relative lifetime costs and benefits of two strategies to road culvert remediation, namely, a road culvert infrastructure planning regime that replaces existing hydraulic culverts with new hydraulic culverts and an alternative regime that replaces existing hydraulic culverts with ecological design culverts. Our two main findings were that (1) in nearly half of all cases remediation with ecological design culverts is more cost effective over their lifetime than maintaining hydraulic culverts and (2) replacing hydraulic culverts with ecological design culverts may be most cost effective on smaller streams (i.e., those streams with <1.5 m bank-full width).

Our first finding supports our opening argument that CBA can be used over traditional planning emphasis on initial construction costs to give explicit consideration to long-term costs associated with different culvert remediation projects. To date, decision makers responsible for monitoring and replacing road culverts often place greater emphasis on cost minimization than ecological connectivity (Gillespie et al. 2014). However, our findings suggest that ecological considerations do not need to be mutually exclusive of other fiscal concerns related to culvert management. In nearly half of all cases, we found that culvert remediation that could restore ecological connectivity had lower lifetime costs than hydraulic culverts. Our approach allows decision makers to explicitly consider different types of costs and to demonstrate that upfront costs cannot be assumed to be an adequate indicator of long-term costs associated with managing ecologically and socially sustainable road infrastructure.

Our second finding suggests that replacing hydraulic culverts with ecological design culverts could be more cost effective on small streams

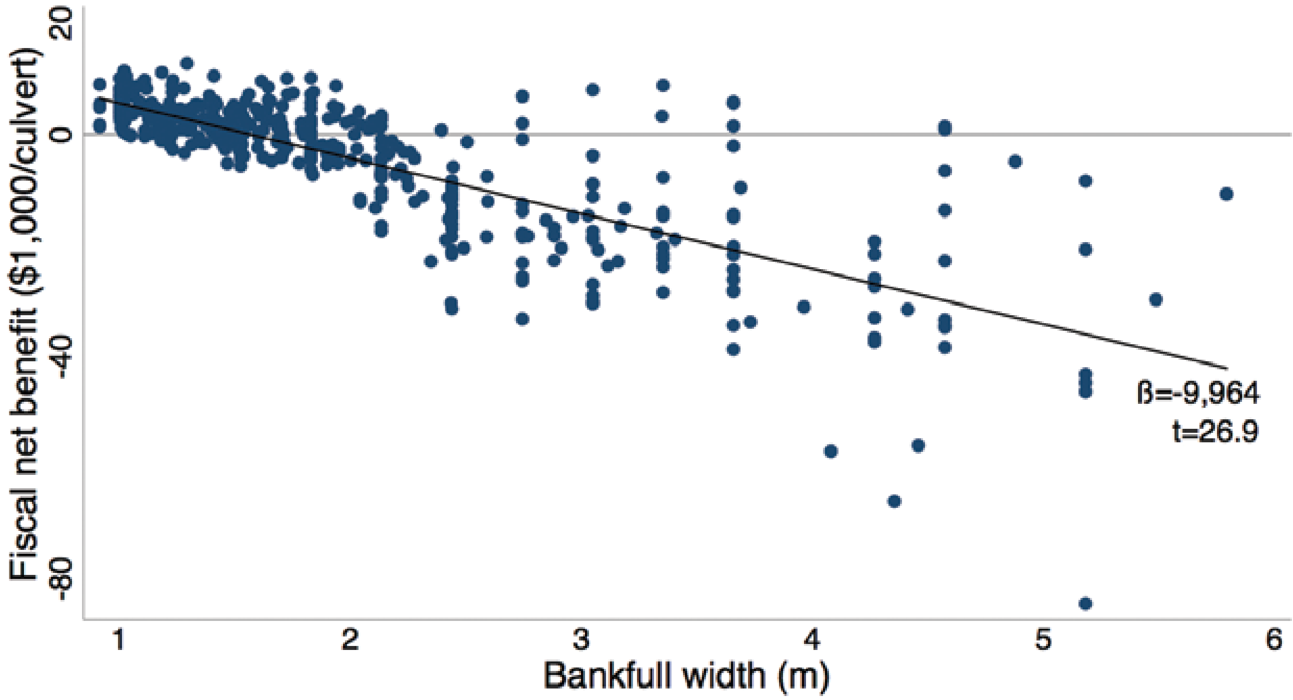

Figure 4. Relationship between fiscal net benefits ($1,000/culvert) and bankfull width (m).

(<1.5 m bank-full width) over larger ones. We found that more than 80% of ecological design replacements on small streams would return positive fiscal net benefits compared to just 30% of replacements on larger streams. This relationship is due, in part, to the fact that the costs of ecological design replacements were positive functions of stream size in our model, whereas the benefits (avoided costs) were less dependent on the stream size. Given our conservative assumption that ecological design culverts are sized at 20% wider than the bank-full width of the stream, our model estimates relatively high construction costs for larger culverts on larger streams that were not ultimately overcome by lower lifetime costs. In regions like the Laurentian Great Lakes, road culverts that act at least as partial barriers to migratory fishes also tend to occur on smaller (<1.5 m bank-full width) streams (Diebel 2013; Januchowski-Hartley et al. 2014). Around the world, small, headwater stream systems often support critical spawning habitat for migratory fishes and invertebrate species (USEPA 2014). Therefore, in addition to the lower cost of ecological design replacements on small streams, there are likely to be greater environmental benefits and potential higher return on investment than we were able to account for in our analyses.

Several underlying assumptions were necessary in our model. First, we made broad assumptions about culvert performance over 35- to 70-year periods based on culvert size and stream characteristics. Though these assumptions simplified the analysis, we acknowledge that culverts will deteriorate at different rates under various site-specific conditions. Further, the applicability of our results is constrained by the underlying culvert data set. However, our results are likely applicable to other regions with similar characteristics and illustrative of the potential benefits of lifetime cost considerations in culvert decision making in all contexts. Last, we assumed that ecological design culverts were sized at 20% greater than the bank-full width of the stream. This assumption resulted in high construction costs for ecological design culverts in our model that may overestimate the true construction costs of ecological design culverts designed under less stringent requirements. For example, relaxing our assumption so that ecological design culverts were sized at 10% over bank-full width would increase the percentage of ecological design culverts that yielded fiscal net benefits to about 58%. We therefore believe that our results represent a conservative estimate of the net benefits of ecological design culverts.

Our framework is the first to quantify the long-term fiscal benefits of ecological design culverts over more commonly used traditional hydraulic culverts and provides a flexible method for evaluating the lifetime costs and benefits associated with such culverts. Our approach can be made more comprehensive as more culvert data become available and methodologies related to monetizing socioecological costs and benefits are further refined. The integration of information on ecological as well as additional societal costs and benefits into CBA will provide a more comprehensive measure of the net benefits of ecological design culverts. A clear next step from our work would be to identify approaches for quantifying and monetizing ecological and societal benefits to be included in CBA. Where data are available, costs associated with travel delays, such as road washouts, damage to private property, maintaining access for emergencies, and threats to human safety could be used to represent societal costs of road culvert remediation (Gillespie et al. 2014). In addition, changes in tourism, recreation, and revenue from fish licenses in restored streams could be used to assign fiscal value to improvements in ecological connectivity.

Our approach complements previous studies that evaluate the ecological limitations of hydraulic culverts (Gibson et al. 2005; Gillespie et al. 2014; Januchowski-Hartley et al. 2014; Diebel et al. 2015), and it can be adapted to prioritize projects for ecological design culvert replacement wherever hydraulic culverts impede fish passage. Importantly, our approach has several advantages: (1) it allows decision makers to allocate public funds more transparently and (2) it can be used to identify fiscal costs of alternative projects, which can be overlooked when the focus is on ecological benefits, but that are equally important when communicating the need for alternative infrastructure to government and funding bodies. Overall, our approach adds to growing literature, and toolsets, aimed at improving the transparency, cost efficiency, and effectiveness of environmental management and conservation decision making (see Januchowski-Hartley et al. 2011; Adams et al. 2015; Neeson et al. 2015). Within this growing literature, we offer a fresh and alternative perspective to how the benefits of alternative infrastructure can be identified and potentially communicated to diverse decision-making groups.

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