Aquatic organism passage (AOP) in waterways-encapsulating structures, particularly culverts, is of growing concern to environmental regulatory agencies, and the Indiana Department of Transportation (INDOT) is seeking systematic responses to this concern in the hydraulic design of such structures. This study reviews (i) the literature on AOP in culverts, especially as it relates to design, and (ii) the two main AOP design approaches—namely, the “stream simulation” approach developed by the U.S. Forest Service (USFS) and an alternate approach developed for the Federal Highway Administration (FHWA). Both approaches require substantial additional data and analysis, which motivated the development of a simplified design procedure tailored to Indiana-specific conditions, requiring less data input and analysis, but which at the same time results in a structure complying with the current regional general permit (RGP) conditions. It also makes as much use of already existing INDOT standard specifications for riprap and coarse aggregates that would be used as backfill material to form a stable bed within the culvert.

**Findings**

Drawing on elements of both the USFS and FHWA approaches, the simplified procedure is intended for larger structures for which a culvert bed needs to be installed, and for expected Indiana conditions of low-gradient (<3%) and predominantly sandy or gravelly streams. It determines (i) the culvert span, (ii) the sump depth, and (iii) the design of the bed within the culvert. Similar to the USFS approach but unlike the FHWA approach, it determines the culvert span from observations of the ordinary high water mark (OHWM, or possibly bankfull) widths and also explicitly includes bank-like features. Similar to the FHWA approach but unlike the USFS approach, the proposed procedure for the culvert-bed design explicitly considers two layers—a surface layer and an armor sublayer beneath the surface layer. The armor sublayer substrate would generally consist of riprap-like material, which is intended to be immobile for all flows up to the peak discharge, while material in the surface layer is allowed to be mobile, but only if the natural stream material is also mobile for the same flow.

The proposed procedure differs from both the USFS and FHWA approaches in the choice of material for the armor sublayer and the surface layer, and the thicknesses of the two layers. For the armor sublayer, the simplified procedure makes as much use of the already existing INDOT standard specifications for riprap, and current INDOT practice as regards the permissible velocities for each riprap class, though some modifications are made. The main simplification is obtained through a “conservative” choice of material for the surface layer. Both the USFS and FHWA approaches attempt to replicate the natural channel material characteristics in the culvert bed, and so require a detailed characterization of the natural channel material. The proposed procedure requires only a gross assessment of the predominant channel material (e.g., sand, gravel or other) and then chooses a standardized bed mixture that should remain immobile for all material in a group (or subgroup). In many cases this could result in the culvert-bed substrate being much coarser than that of the natural stream, but it should result in a stable bed. The minimum thickness of the surface layer will usually be taken as equal to the flow depth under OHWM (or possibly bankfull) condition, while the minimum thickness of the armor sublayer would generally be the size of the stone used in the sublayer.
Because of their larger size compared to traditional culverts, AOP-designed structures are associated with higher installation (including material) costs. Depending on the ratio of the spans of the AOP-designed culvert and the traditional culvert, the ratio of the corresponding installation costs range from 1 to 3. It has been argued that the increased installation costs may be compensated partially or wholly by lower costs over their operational lifetime. Previous work on life-cycle cost analysis (including social/ecological costs) of AOP-designed culverts was reviewed, but it is concluded that reliable data and methodologies for an adequate quantitative analysis are not yet available.

The current RGP distinguishes between smaller and larger streams based on the OHWM width, such that larger streams (those with OHWM widths greater than 12 ft) need to comply with additional more specific (and onerous) conditions. While there may be some practical and theoretical justification for this criterion, the study explores alternative regulatory schemes formulated on the basis of habitat or biotic integrity indices, such as the Qualitative Habitat Evaluation Index (QHEI) or the fish-Index of Biotic Integrity (fish-IBI). These indices are intended to measure more directly habitat potential or present quality, and so they may yield more intuitive and flexible schemes with the same or even better ecological outcomes. The implications of different schemes based on QHEI and/or IBI were examined by considering the Indiana Department of Environmental Management (IDEM) database of QHEI and IBI measurements at numerous sites in Indiana as representative of possible culvert sites. For example, if a criterion QHEI <45 (IDEM considers QHEI <51 as poor habitat potential) is used instead of the current OHWM width of 12 ft, then a sizeable fraction (about 15%) of sites with OHWM widths greater than 12 ft might qualify for an exemption from the additional AOP requirements. Conversely, if the minimum OHWM width for the additional AOP requirements were reduced to 8 ft (instead of 12 ft), then a comparable fraction (about 11%) of smaller streams would then be subject to the additional AOP requirements.

**Implementation Plans**

INDOT’s hydraulic design guidelines for culverts are not entirely compliant with the current regional general permit specifications (except for a general catch-all qualification that all applicable environmental regulations should be complied with). The proposed guidelines were designed to comply with RGP specifications, and so it is recommended that INDOT adopt them as one (but perhaps not only) standard acceptable approach. In the proposed approach, the design of a stable bed within the culvert relies on the availability of standard material mixtures. For one class of stream substrates, namely a predominantly sandy-bed stream, an existing standard mixture was designated as adequate, but for other classes, other standard mixtures will need to be defined. An approach for such a definition was suggested, and it is recommended that other standard mixes be developed as part of the implementation. Discussions are being held with the Indiana Department of Environmental Management regarding current and future RGP conditions, and the results of these discussions may influence implementation.

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