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# EFFECTS OF GRADE CONTROL STRUCTURES ON FISH PASSAGE, BIOLOGICAL ASSEMBLAGES AND HYDRAULIC ENVIRONMENTS IN WESTERN IOWA STREAMS: A MULTIDISCIPLINARY REVIEW

J. T. THOMAS,[a]* M. E. CULLER,[b,1] D. C. DERMISIS,[c] C. L. PIERCE,[d] A. N. (THANOS) PAPANICOLAOU,[c] T. W. STEWART[e] and C. J. LARSON[f]

[a] *Hungry Canyons Alliance, Golden Hills RC&D Office, PO Box 189, Oakland, Iowa 51560-0189, USA*
[b] *Missouri Department of Natural Resources, Macon, Missouri 63552, USA*
[c] *IIHR-Hydroscience and Engineering, Department of Civil and Environmental Engineering, University of Iowa, Iowa City, Iowa 52242-1585, USA*
[d] *US Geological Survey, Iowa Cooperative Fish and Wildlife Research Unit, Iowa State University, Ames, Iowa 50011, USA*
[e] *Department of Natural Resource Ecology and Management, Iowa State University, Ames, Iowa 50011, USA*
[f] *Iowa Department of Natural Resources, 5744 Lewis Road, Lewis, Iowa 51544, USA*

## ABSTRACT

Land use changes and channelization of streams in the deep loess region of western Iowa have led to stream channel incision, altered flow regimes, increased sediment inputs, decreased habitat diversity and reduced lateral connectivity of streams and floodplains. Grade control structures (GCSs) are built in streams to prevent further erosion, protect infrastructure and reduce sediment loads. However, GCS can have a detrimental impact on fisheries and biological communities. We review three complementary biological and hydraulic studies on the effects of GCS in these streams. GCS with steep (≥1:4 rise : run) downstream slopes severely limited fish passage, but GCS with gentle slopes (≤1:15) allowed greater passage. Fish assemblages were dominated by species tolerant of degradation, and Index of Biotic Integrity (IBI) scores were indicative of fair or poor biotic integrity. More than 50% of fish species had truncated distributions. After modification of GCS to reduce slopes and permit increased passage, IBI scores increased and several species were detected further upstream than before modification. Total macroinvertebrate density, biomass and taxonomic diversity and abundance of ecologically sensitive taxa were greater at GCS than in reaches immediately upstream, downstream or ≥1 km from GCS. A hydraulic study confirmed results from fish passage studies; minimum depths and maximum current velocities at GCS with gentle slopes (≤1:15) were more likely to meet minimum criteria for catfish passage than GCS with steeper slopes. Multidisciplinary approaches such as ours will increase understanding of GCS-associated factors influencing fish passage, biological assemblage structure and other ecological relationships in streams. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: biotic integrity; fish assemblages; fish passage; grade control structures; hydraulic characteristics

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## INTRODUCTION

Land use changes and channelization of streams during the first half of the 20th century caused the instability of the western Iowa stream channels. These anthropogenic changes, coupled with highly erosive loess soils occurring in the deep loess region of western Iowa resulted in severe down-cutting and widening of stream channels, in turn resulting in an estimated $1.1bn loss in damages to public and private infrastructure (by exposing buried bridge pilings, culvert outlets, utility lines, etc., and increasing their likelihood of failure), loss of farmland and increased sediment loads (Baumel, 1994). Streams that were historically wetlands or shallow meandering streams transformed into deep, non-meandering ditches with incised banks reaching 9 m in depth, and are known locally as ‘hungry canyons’. These streams have altered flow regimes (Hansen, 1971) with reduced channel roughness, resulting in greater peak flow velocities, greater peak discharges and flashier storm hydrographs. These factors impact physical and chemical habitat and, hence, biological communities in these streams (Baker *et al*., 2004). These scoured channels have lost much of their original habitat. For example, many of these streams are devoid of riffle-pool sequences. Because of extreme down-cutting, many channels have also lost lateral connectivity with former floodplains, except during very high discharge events. Many streams are starting to establish a new, narrower floodplain in the ditch bottom by widening of the channel due to bank failure. Bank erosion in conjunction with extensive channel bed erosion has dramatically increased sediment loads (Simon and Rinaldi, 2000).

Altered flow regimes, instream habitat loss, loss of floodplain connectivity and high sediment loads associated with

*Correspondence to: J. Thomas, Hungry Canyons Alliance, Golden Hills RC&D Office, PO Box 189, Oakland, Iowa 51560-0189, USA.
E-mail: john@goldenhillsrcd.org
[1]M. E. Culler was formerly M. E. Litvan

channel incision often cause reduced aquatic biodiversity (Hansen, 1971; Shields *et al*., 1994; Bravard *et al*., 1997; Cooper *et al*., 1997; Shields *et al*., 1998; Raborn and Schramm, 2003). Fish habitat has been shown to be adversely affected by streambed degradation (Shields *et al*., 1994; Raborn and Schramm, 2003). Bunn and Arthington (2002) noted that in highly altered environments, invasive species may find it easier to outcompete native species. This may explain the high biomass of invasive species such as common carp (*Cyprinus carpio*) in western Iowa streams (e.g. Palic *et al*., 2007). At a larger scale, sediment and nutrient loading from western Iowa will ultimately affect the Missouri and Mississippi Rivers (e.g. decreased dam storage due to siltation) and the Gulf of Mexico (e.g. hypoxia) (Rabalais *et al*., 2002) because of longitudinal connectivity of these river systems.

One solution to limit channel incision and erosion, protect infrastructure and reduce sediment loads is to build grade control structures (GCSs) (Figure 1). There are many types of GCS in western Iowa (Thomas, 2007), but GCSs at sites that may support important fish populations are most often riprap weirs (Figure 1A–C). Weirs are constructed with vertical steel sheet pile, typically driven into the streambed 6.1 m, with a riprap and concrete grout slope immediately downstream, a riprap stilling basin downstream of the weir slope and riprap covered banks. Limestone bedrock is the only natural riprap material available in western Iowa and is found in relatively thin ledges (<2.4–3.1 m), whereas boulders greater than 0.77 $m^3$ are very rare because of bedding planes and stratification. Limestone riprap tends to fracture because of freeze/thaw processes and then move under higher flow conditions, so concrete grout has recently been used at many sites to keep the riprap in place. Weirs are placed at regular intervals (approximately 1.6–4.8 km) to locally decrease the stream slope, change the stream profile from an erosive steep incline to a stable stair-step pattern and prevent the formation and propagation of knickpoints (i.e. migratory streambed fronts). These GCSs allow a controlled drop in stream elevation, prevent further streambed and streambank degradation, reduce sediment loads and turbidity and increase oxygen concentrations in the water column. GCSs have proven to be very economical, with every dollar invested protecting more than $4.24 in property value and 889 kg of soil (Thomas, 2009).

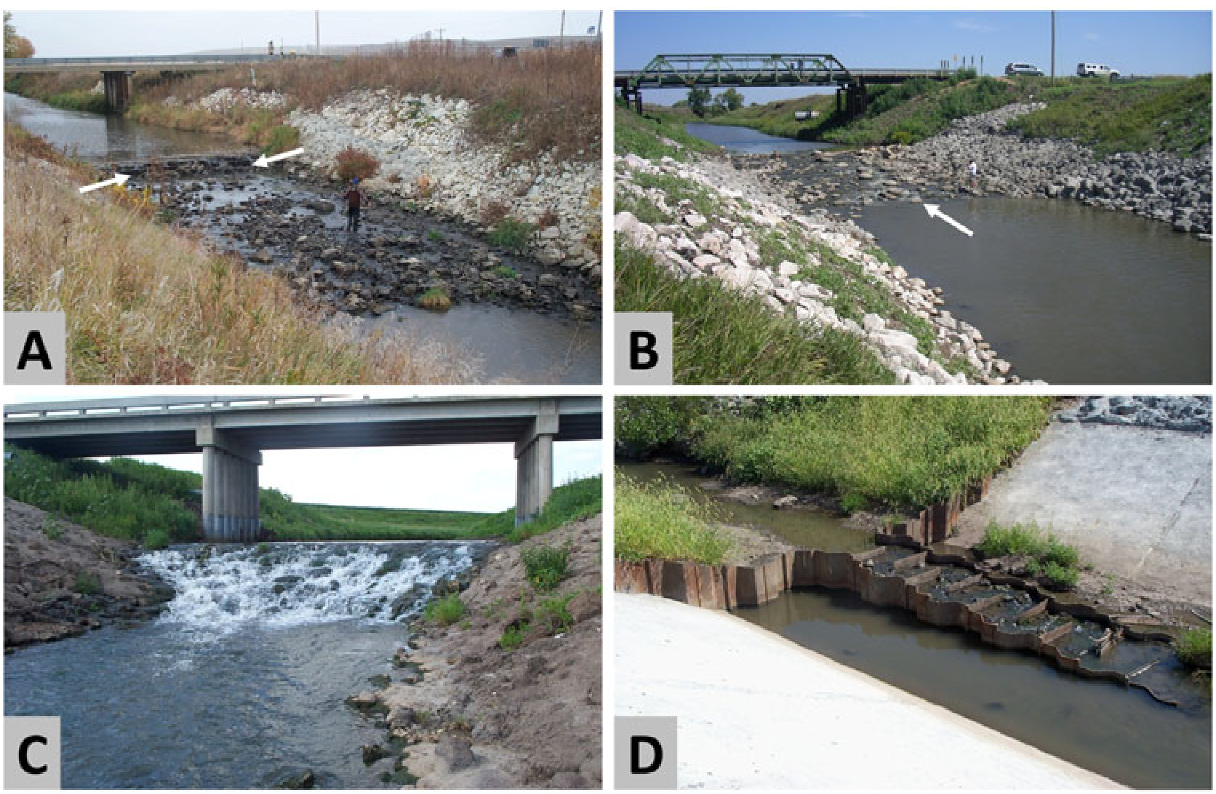


Figure 1. Examples of grade control structures (GCS) in western Iowa streams. Photographs were taken at low-flow conditions. (A) Sheet pile weir with loose riprap slope, originally built at 1:20 (rise : run), but note how rock has moved away from the sheet pile weir (white arrows). (B) Sheet pile weir with 1:20 grouted riprap slope and manufactured blocks intermittently placed in the central low-flow portion of the slope extending above the adjoining rock (white arrow). (C) Sheet pile weir with 1:4 grouted riprap slope. (D) Sheet pile weir with 1:20 fish ladder and steel baffles. This figure is available in colour online at wileyonlinelibrary.com/journal/rra



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Grade control structure may also increase diversity of local streambed habitat, hydraulic features and biota. Riprap used to construct GCS adds coarse substrate to western Iowa streams that are otherwise primarily dominated by silt and sand. Riprap has been shown to support more abundant and diverse fish assemblages than naturally occurring substrates in other settings (e.g. White *et al*., 2009). GCS can affect flow characteristics in their vicinity and create a scour pool below the structure (Shields *et al*., 1995). These changes in flow and habitat conditions may result in different fish and macroinvertebrate communities near and far away from these structures and increased biological diversity within the stream (Tiemann *et al*., 2004). Artificial riffles have been shown to support macroinvertebrates at levels similar to natural riffles within the same stream, and modification of local hydraulic conditions by GCS may actually increase habitat for benthic macroinvertebrates (Gore and Hamilton, 1996, Ebrahimnezhad and Harper, 1997). Increased macroinvertebrate abundance in streams altered by GCS could enhance food resources for resident fish assemblages, possibly resulting in improved growth and body condition (Shields *et al*., 1995). Increased depth and diversity of substrate types near GCS may also increase diversity, growth and reproductive potential of fish communities near GCS (Shields and Hoover, 1991). Scour holes below GCS may support better fisheries than naturally occurring pools because of their increased stability (Cooper and Knight, 1987). However, some studies have shown that fish community structure does not differ between unaltered stream reaches and reaches with GCS (Raborn and Schramm, 2003).

Streams in western Iowa are warm-water systems where native fish assemblages are generally dominated numerically by small-bodied species such as sand shiners (*Notropis stramineus*), red shiners (*Cyprinella lutrensis*), creek chub (*Semotilus atromaculatus*), bigmouth shiners (*Notropis dorsalis*) and flathead chub (*Platygobio gracilis*), as well as large-bodied species such as channel catfish (*Ictalurus punctatus*), black bullhead (*Ameiurus melas*) and yellow bullhead (*Ameiurus natalis*) (Palic *et al*., 2007; Rowe *et al*., 2009). Routine sampling and angler reports in several western Iowa streams before and after GCS construction indicated a decline in channel catfish and other species, and it is thought that GCS may have contributed to these population changes (Larson *et al*., 2004). In fact, there is emerging evidence that GCS may be serious impediments to fish passage (Ovidio and Philippart, 2002), restricting fish species distributions in streams.

In the past 40 years, more than 750 GCSs have been built in western Iowa. Despite efforts of numerous government agencies to control streambed degradation, the problem is still widespread, necessitating construction of more GCSs, which in turn may further impede fish passage and degrade fish assemblages and fisheries. A key parameter controlling effects of GCS on fish passage may be downstream slope (Figure 2), which in western Iowa ranges from vertical to a relatively gentle slope of 1:20 (rise : run). Although fish passage may be less restricted by GCS with gentle slopes, the gentler the slope, the greater the construction cost because of the additional length. For example, the cost of a GCS with a 1:20 downstream slope is approximately $40 000(US) more than the same GCS with a 1:4 downstream slope. There may be a somewhat steeper slope than 1:20, which would cost less yet still allow relatively unimpeded fish passage.

The Hungry Canyons Alliance, a locally formed and managed regional organization of counties in western Iowa, and the Iowa Department of Natural Resources commissioned multidisciplinary research (Larson *et al*., 2004; Papanicolaou and Dermisis, 2006; Litvan *et al*., 2008a-c; Dermisis and Papanicolaou, 2009) to determine (i) effects of GCS on the biophysical nature of western Iowa streams, (ii) the GCS slope striking the optimum balance between allowing fish passage while minimizing construction costs, and (iii) effects of GCS on fish and macroinvertebrate assemblages. The purpose of this review is to synthesize results of this research.

## MATERIALS AND METHODS

Thirty-four GCSs in western Iowa were examined in these studies (Table I, Figure 3). As indicated in Table I, not all objectives covered in this review were examined at every GCS. The slopes of four GCSs on Turkey Creek were

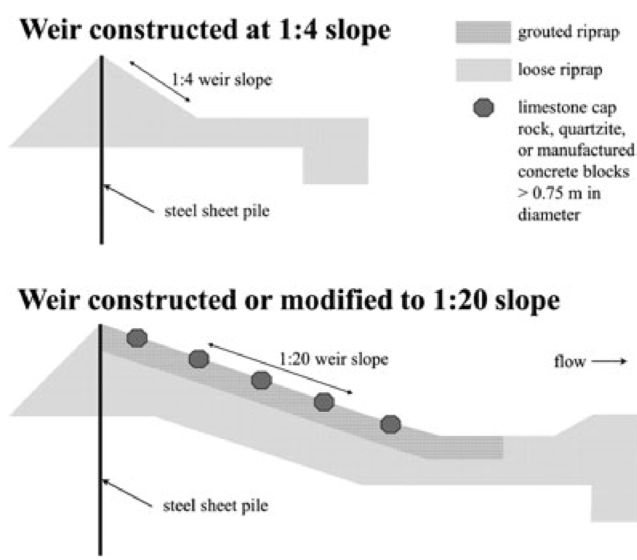


Figure 2. Simplified longitudinal profile diagram of weirs, contrasting steeply sloped (1:4) and gently sloped (1:20) weirs. A vertical slope (not shown) can result from riprap moving away from the sheet pile on the downstream side. Diagrams are not to scale.



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Table I. Characteristics of grade control structures studied in western Iowa streams

| GCS | Stream | Study | | GCS type[3] | Modified? | Drainage area ($km^2$) | Grade control (m) | Weir Slope (rise : run) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Citation[1] | Type[2] | | | | | Premodified | Designed | Estimated | Measured |
| 1 | Walnut Creek | 2004 | FP | SPLR | Yes | 365.2 | 1.52 | 1:4 | 1:20 | 1:20 | |
| 2 | Walnut Creek | 2004, 2008c | FP, MA | SPLR | | 261.6 | 1.10 | | 1:20 | 1:20 | |
| 3 | Walnut Creek | 2004, 2008c | FP, MA | SPLR | Yes | 256.4 | 1.46 | 1:4 | 1:20 | 1:20 | |
| 4 | Walnut Creek | 2004, 2008c, 2009 | FP, MA, HC | SPLR | Yes | 248.6 | 1.22 | 1:4 | 1:20 | | 1:16 |
| 5 | Walnut Creek | 2004, 2008c, 2009 | FP, MA, HC | SPLR | | 207.2 | 1.22 | | 1:20 | | 1:22 |
| 6 | Walnut Creek | 2004, 2008c | FP, MA | SPLR | | 202.0 | 1.22 | | 1:20 | 1:20 | |
| 7 | Walnut Creek | 2004 | FP | SPGR | | 158.5 | 1.22 | | 1:5 | 1:4 | |
| 8 | Turkey Creek | 2004, 2009 | FP, HC | SPLR | | 300.4 | 0.91 | | 1:10 | | 1:12 |
| 9 | Turkey Creek | 2004 | FP | SPLR | | 222.7 | 0.91 | | 1:4 | 1:4 | |
| 10 | Turkey Creek | 2004 | FP | SPLR | | 186.5 | 0.91 | | 1:4 | Vertical | |
| 11 | Seven Mile Creek | 2004 | FP | SPGR | | 310.8 | 1.22 | | 1:4 | 1:4 | |
| 12 | Seven Mile Creek | 2004 | FP | SPLR | | 249.4 | 1.22 | | 1:4 | Vertical | |
| 13 | Seven Mile Creek | 2004 | FP | SPLR | | 246.8 | 0.91 | | 1:4 | 1:1 | |
| 14 | Turkey Creek | 2008a, b | FP, FA | SPGR | Yes | 300.4 | 0.91 | 1:14.3 | 1:15 | | 1:18.3 |
| 15 | Turkey Creek | 2008a, b | FP, FA | LRR | | 238.3 | 0.61 | | ??? | | 1:12.6 |
| 16 | Turkey Creek | 2008a, b | FP, FA | SPGR | Yes | 222.7 | 0.91 | 1:12.7 | 1:15 | | 1:17.9 |
| 17 | Turkey Creek | 2008a, b | FP, FA | SPLR | Yes | 186.5 | 0.91 | Vertical | 1:15 | | 1:15.2 |
| 18 | Turkey Creek | 2008a, b | FP, FA | SPLR | | 155.4 | 0.91 | | 1:10 | | 1:17.1 |
| 19 | Turkey Creek | 2008a, b | FP, FA | SPLR | | 136.8 | 0.91 | | 1:10 | | 1:9.6 |
| 20 | Indian Creek | 2009 | HC | SPGR | | 80.0 | 1.22 | | 1:4 | | 1:4 |
| 21 | David's Creek | 2009 | HC | SPLR | | 72.4 | 1.22 | | 1:20 | | 1:20 |
| 22 | Keg Creek | 2009 | HC | SPGR | | 202.3 | 0.70 | | 1:20 | | 1:25 |
| 23 | Walnut Creek | 2009 | HC | SPLR | | 114.0 | 0.91 | | 1:4 | | 1:5 |
| 24 | West Nodaway River | 2009 | HC | SPLR | | 264.2 | 0.91 | | 1:20 | | 1:25 |
| 25 | Turkey Creek | 2009 | HC | SPLR | | 155.4 | 0.91 | | 1:10 | | 1:14 |
| 26 | Indian Creek | 2009 | HC | SPLR | | 38.8 | 0.91 | | 1:4 | | 1:6 |
| 27 | Boyer River | 2009 | HC | SPGR | | 575.0 | 0.91 | | 1:20 | | 1:22 |
| 28 | Otter Creek | 2009 | HC | SPGR | | 77.7 | 1.22 | | 1:20 | | 1:22 |
| 29 | Coon Creek | 2009 | HC | HPGR | | 41.2 | 1.22 | | 1:6 | | 1:6 |
| 30 | Beaver Creek | 2009 | HC | HPGR | | 36.8 | 1.22 | | 1:6 | | 1:6 |
| 31 | Miller Creek | 2009 | HC | SPGR | | 20.7 | 1.22 | | 1:4 | | 1:4 |
| 32 | Silver Creek Tributary | 2009 | HC | SPGR | | 7.0 | 0.91 | | 1:10 | | 1:14 |
| 33 | Mosquito Creek | 2009 | HC | SPGR | | 134.4 | 1.22 | | 1:15 | | 1:16 |
| 34 | Long Branch Creek | 2009 | HC | SPGR | | 68.4 | 1.22 | | 1:4 | | 1:4 |
| 35 | Tarkio River | 2009 | HC | FL | | 445.5 | 0.91 | | 1:20 | | 1:20 |
| 36 | Tarkio River | 2009 | HC | FR | | 212.4 | 0.91 | | 1:15.5 | | 1:15.5 |
| 37 | East Tarkio River | 2009 | HC | FL | | 98.4 | 0.91 | | 1:20 | | 1:20 |
| 38 | Snake Creek | 2009 | HC | FR | | 34.6 | 0.91 | | 1:14.5 | | 1:14.5 |

Locations of GCS are shown by number in Figure 3
Note that GCS 8 and 14, 9 and 16, 10 and 17, and 18 and 25 are the same structures studies at different times and under different hydraulic conditions.
[1]Citations are as follows: 2004, Larson *et al*. (2004); 2008a, Litvan *et al*. (2008a); 2008b, Litvan *et al*. (2008b); 2008c, Litvan *et al*. (2008c); 2009, Dermisis and Papanicolaou (2009).
[2]Study types are as follows: FP, fish passage; FA, fish assemblage; MA, macroinvertebrate assemblage; HC, hydraulic characteristics.
[3]Grade control structure types are as follows: SPGR, steel sheet pile weir with grouted riprap slope; SPLR, steel sheet pile weir with loose riprap slope; HPGR, steel H-pile and hog-panel crib weir with grouted riprap; LRR, loose riprap and broken concrete riffle; FL, fish ladder (sheet pile weir with concrete floor and sideslopes and central grouted riprap fish passage with baffles); FR, fish ramp (sheet pile weir with concrete floor and sideslopes and central grouted riprap fish passage).



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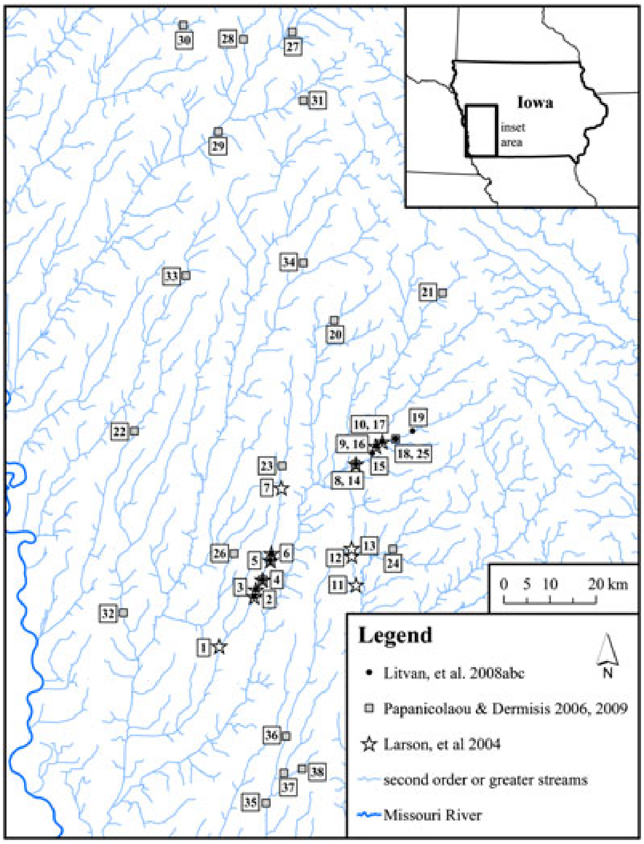


Figure 3. Locations of grade control structures (GCS) studied in western Iowa streams. Numbers correspond with GCS identified by number in Tables 1–3. Symbols identify GCS by study. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

measured at different times by the studies resulting in different measured weir slopes; these four GCSs are listed twice in Table I to reflect this.

### *Biological studies*

Larson *et al*. (2004) studied the passage of channel catfish, black bullheads, flathead chubs and creek chubs over GCS in three western Iowa streams from 2001 to 2003 (Table I, Figure 3). GCSs in all three streams were originally built with a steep (1:4) slope but were modified to a gentle slope (1:20) in Walnut Creek (Figure 2). GCSs in Turkey Creek and Seven Mile Creek were left unmodified with steep slopes as controls. Mark-recapture methods were used to document fish passage over GCS. Fish were captured with hoop nets and minnow traps baited with soy cake. Slopes of weirs were assumed to match original engineering design specifications in this study, but poststudy measurements of three weirs (Table I) revealed that actual slopes differed slightly from specifications.

Following the study by Larson *et al*. (2004), several GCSs were modified to promote greater fish passage by reducing their slopes (Figure 1B). The grouted riprap weir slopes were built to be rough and uneven to dissipate stream energy. Large rocks or manufactured blocks were placed in the central portion of the slope, extending above the adjoining rock, to increase energy dissipation and promote fish passage by increasing the number of resting areas for fish. Fish pass over weirs by repeating the cycle of swimming for short ‘bursts’ followed by resting in the hydraulic shadow of flow obstructions (Katopodis, 1992; Newbury and Gaboury, 1993). By reducing the weir slope, a longer structure is created, making these resting areas necessary to compensate for the greater distances fish must swim to pass over them.

Using mark-recapture methods similar to Larson *et al*. (2004), Litvan *et al*. (2008a) focused on the potential for successful passage of channel catfish, black bullheads, yellow bullheads and creek chubs over GCS with slopes intermediate between steep (1:4) and gentle (1:20) slopes. Litvan *et al*. (2008a) limited their study to Turkey Creek, where several GCSs existed with intermediate slopes (Table I, Figure 3). In addition, they assessed changes in fish passage success after three GCSs were modified to reduce their slopes. Rather than assuming accuracy of slope specifications, weir slopes were measured by the investigators in this study.

In a companion study, Litvan *et al*. (2008b) quantified the fish assemblage structure in Turkey Creek at sites both immediately downstream from GCS and ≥1 km from GCS (Table I, Figure 3). Sampling was accomplished using a combination of backpack electrofishing, hoop nets and minnow traps and was done before and after GCS modification to assess effects of modification and passage on fish assemblages. Fish assemblage structure was expressed by the Index of Biotic Integrity (IBI), a 12-component multimetric index commonly used in stream health assessments (Simon, 1999). The IBI was calibrated for Iowa streams on a scale of 0–100, with scores of 0–25 indicating poor biotic integrity; 26–50, fair; 51–70, good; and 71–100, excellent (Wilton, 2004).

Litvan *et al*. (2008c) quantified benthic macroinvertebrate density, biomass and taxa richness at GCS, immediately upstream and downstream (5–50 m) from GCS, and at locations ≥1 km from GCS in Walnut Creek (Table I, Figure 3). Samples were obtained using a D-frame kicknet and the USEPA wadeable stream bioassessment protocol (Barbour *et al*., 1999). Several physicochemical variables were quantified at each sampling site and related to invertebrate assemblage characteristics, including substrate composition, depth, current velocity, wetted channel width, overhead canopy cover, dissolved oxygen, pH and water temperature.

### *Hydraulic study*

Papanicolaou and Dermisis (2006) and Dermisis and Papanicolaou (2009) studied the hydraulic characteristics




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of GCS in numerous western Iowa streams, including Walnut and Turkey Creeks, during fall and spring seasons, to assess a range of flow conditions. Twenty-two GCSs (Table I, Figure 3) were selected for determination of hydraulic characteristics, including eight riprap weirs (Figure 1A), ten grouted riprap weirs (Figure 1B, C) and four fish ladder weirs (baffled and unbaffled) (Figure 1D). The drainage area of these GCSs varied between approximately 7 and 570 $km^2$. A ground survey was performed to determine the slope for each weir and to provide background information for the acoustic Doppler velocimeter (ADV) and large-scale particle image velocimetry (LSPIV) measurements described below.

Measurements of mean flow characteristics (water depth Y and stream velocity V) were performed during a low-flow season (fall) for all 22 GCSs and repeated during a high flow season (spring) for eight representative GCSs. Mean point velocity measurements (sampling rate, 10 Hz) at low-flow conditions (fall) were conducted upstream of, on top of and downstream of each GCS using a SonTek FlowTracker handheld ADV. Based on the recorded ($Y$, $V$) pairs around the GCS, Froude number ($Fr$) was calculated to identify the macrohabitat types as pool ($Fr < 0.18$), run ($0.18 \leq Fr \leq 0.41$) or riffle glide ($Fr > 0.41$).

Mean areal velocity measurements at moderate to high flows (spring) were performed upstream of each GCS using the LSPIV technique. In conjunction with bathymetry data, the LSPIV technique was used to determine stream discharge (Kim, 2006).

Lastly, turbulence measurements were performed during low-flow conditions (fall) in the vicinity of two representative GCS (a riprap weir and a baffled fish ladder weir) using a high-frequency ADV (sampling rate 25 Hz) to determine instantaneous velocities, turbulent intensities, Reynolds stresses and characteristic eddy length scales (e.g. Fox *et al.*, 2005) in three dimensions.

## RESULTS

### *Fish passage*

Over a 3-year period, 10–28% of marked and recaptured channel catfish and 15–30% of recaptured flathead chubs and creek chubs passed over GCS with a 1:20 slope (Larson *et al.*, 2004). However, within the same sampling period, no marked individuals of these three fish species passed over GCS with a 1:4 slope. This initial study established that GCSs with gentle slopes of 1:20 permit passage of important fish species in these systems, but that the steeper 1:4 slope impeded passage.

Litvan *et al.* (2008a) conducted a detailed study across a range of slopes that were intermediate between those examined by Larson *et al.* (2004). Fish passage was documented to occur over GCS with slopes ranging from 1:12.6 to 1:18.3 (Table II). Channel catfish and black bullhead passed upstream over GCS slopes ranging from 1:12.6 to 1:18.3, yellow bullhead passed upstream over GCS with slopes of 1:12.6 and 1:15.2 and creek chub passed upstream over GCS of 1:15.2 to 1:17.9. No fish passage was observed over one GCS with a vertical face and another with a 1:12.7 slope. Three GCSs, with slopes ranging from a vertical face to 1:14.3, were modified during the study, with post-modification slopes ranging from 1:15.2 to 1:18.3. All three allowed greater passage after modification than before modification. Before modification, only 1% of recaptured fish (two channel catfish) were documented moving over the unmodified GCS. Following modification, 16% of recaptured fish (including channel catfish, yellow and black bullhead and creek chub) were documented moving over modified GCS. Collectively, results of Litvan *et al.* (2008a) established that GCS with slopes roughly equal to or gentler than 1:15 can accommodate passage of ecologically and economically important fish species in western Iowa streams.

### *Fish and macroinvertebrate assemblages*

Fish assemblages at sites immediately downstream from GCS and ≥1 km from GCS were dominated by species tolerant of degradation, and IBI scores were indicative of fair or poor biotic integrity (Litvan *et al.*, 2008b). More than half of the species had truncated distributions, being present in downstream sections but absent in areas upstream of GCS. After modification of three GCS to reduce slope and permit passage, IBI scores increased by an average of 4.6 points, and several species were detected further upstream than before modification. An IBI score change of ±4 points has been shown to be statistically significant (Fore et al. 1994), so the mean IBI increase of 4.6 in Turkey Creek is likely a real increase. Absence of channel catfish upstream of GCS in Turkey Creek and other western Iowa streams was one

Table II. Numbers of fish passing over grade control structures of differing slopes in Turkey Creek, Iowa (from Litvan et al. 2008a)

| GCS | Modification period | Slope | Channel catfish | Black bullhead | Yellow bullhead | Creek chub |
|---|---|---|---|---|---|---|
| 17 | Before | Vertical | 0 | 0 | 0 | 0 |
| 15 | – | 1:12.6 | 6 | 25 | 1 | 1 |
| 16 | Before | 1:12.7 | 0 | 0 | 0 | 0 |
| 14 | Before | 1:14.3 | 2 | 0 | 0 | 0 |
| 17 | After | 1:15.2 | 2 | 21 | 6 | 2 |
| 18 | – | 1:17.1 | 0 | 6 | 1 | 2 |
| 16 | After | 1:17.9 | 4 | 26 | 0 | 2 |
| 14 | After | 1:18.3 | 6 | 5 | 0 | 0 |

Grade control structures listed twice were studied before and after slope modification. GCS characteristics shown in Table I; locations shown in Figure 3. Dashes (–) indicate no GCS modifications. GCS/modification combinations listed in descending order of slope (steep to gentle).




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of the original concerns about effects of GCS on fish passage, and after modification channel, catfish were detected over 7 km further upstream, having passed over one of the modified GCS.

Litvan *et al*. (2008c) assessed the macroinvertebrate assemblage characteristics and characterized the habitat at GCS and reaches upstream and downstream of GCS, and reaches located ≥1 km from GCS. They noted significantly greater coarse substrate and current velocities and shallower depths at GCS compared with areas upstream and downstream from GCS. Total macroinvertebrate density, biomass and taxonomic diversity were greater at GCS than in reaches located ≥1 km upstream and downstream of GCS. Taxa indicative of higher stream quality, including Ephemeroptera and Trichoptera, were abundant at GCS but rare immediately upstream, downstream and ≥1 km from GCS. Interestingly, Litvan *et al*. (2008c) sampled a single reach ≥1 km from any GCS that was unique in having a natural riffle with coarse substrate. Macroinvertebrate abundance and diversity at this site and at GCS sites were similar.

### *Hydraulic characteristics*

Performance of each GCS was described in terms of meeting requirements for catfish passage as determined by the Iowa DNR (Hocutt, 1973; Beecham *et al*., 2007): a minimum flow depth ($Y_{min}$) of 0.31 m and a maximum velocity ($V_{max}$) of 1.22 m s$^{-1}$, equal to the burst velocity of catfish. The best performing GCSs have minimum flow depths greater than 0.31 m and maximum velocities less than 1.22 m s$^{-1}$; the worst performing GCS did not meet either requirement (Table III).

Depths and velocities ($Y$, $V$) on top of GCS rarely met both flow requirements for catfish passage (Table III). For almost all weirs, the minimum depth requirement was violated ($Y$ varied between 0.12 and 0.70 m) and the maximum velocity requirement was occasionally violated ($V$ varied between 0.17 and 2.37 m s$^{-1}$). Mean point flow velocities averaged for each weir did not violate the maximum velocity requirement but still rarely met the depth requirement. Because of relatively low flows during the fall of 2004 measuring period, the three GCSs with the smallest drainage areas did not have any measurable flow going over the GCS (Table III). No weirs with slopes >1:12 met both fish passage requirements (Table III, Figure 4). The slope category with the most structures in or bordering the region meeting both requirements in Figure 4 was <1:16. All GCS with slopes <1:16 that met the depth requirement also met the velocity requirement (Tables III and IV). Velocities on the downstream slope of GCS were about 10 times greater in magnitude than the upstream approach flow. Froude numbers revealed the presence of pool conditions upstream and downstream of GCS, whereas riffle-glide conditions were recorded on top of the GCS. In general, depth and velocity measurements during low-flow conditions (fall season) were ideal for evaluating performance of GCS concerning the minimum flow depth requirement. Depths and velocities measured upstream of GCS met catfish passage requirements at all locations (Dermisis and Papanicolaou, 2009).

The limiting factor ($Y_{min}$ or $V_{max}$) for fish passage was different depending on drainage area (Table III). When the drainage area is small (<51.8 km$^2$), the best GCS are gently sloped (<1:16) weirs because $Y_{min}$ is the limiting factor for fish passage, and gently sloped weirs will provide deeper flows than weirs with steeper slopes. When the drainage area is large (>259 km$^2$), the best GCS are gentle (<1:16) to intermediate sloped (1:10–1:16) weirs because $V_{max}$ is the limiting factor for fish passage, and gentle to intermediate slopes will produce slower velocities than weirs with steeper slopes. When the drainage area is intermediate (between 51.8 and 259 km$^2$), the best GCS are either gentle

Table III. Depth ($Y$), velocity ($V$) and flow state ($Fr$) at grade control structures with differing drainage areas and slopes in western Iowa streams (from Papanicolaou and Dermisis, 2006, and Dermisis and Papanicolaou, 2009)

| GCS | Slope | Drainage area (km$^2$) | $Y$ (m) | $V$ (m s$^{-1}$) | $Fr$ |
|---|---|---|---|---|---|
| Small drainage areas | | | | | |
| 31 | 1:4 | 20.7 | – | – | – |
| 30 | 1:6 | 36.8 | – | – | – |
| 26 | 1:6 | 38.9 | 0.18 | **0.80** | 0.60 |
| 29 | 1:6 | 41.2 | 0.12 | **0.22** | 0.20 |
| 32 | 1:14 | 7.0 | – | – | – |
| 38 | 1:14.5 | 34.7 | 0.12 | 2.37 | 2.17 |
| Intermediate drainage areas | | | | | |
| 34 | 1:4 | 68.4 | 0.18 | **0.66** | 1.17 |
| 20 | 1:4 | 80.0 | 0.18 | **0.95** | 0.71 |
| 23 | 1:5 | 114.0 | 0.15 | **0.77** | 0.63 |
| 25 | 1:14 | 155.4 | 0.15 | **0.56** | 0.46 |
| 36 | 1:15.5 | 212.4 | 0.12 | 1.80 | 1.66 |
| 33 | 1:16 | 134.4 | **0.34** | **1.07** | 0.88 |
| 4 | 1:16 | 248.6 | **0.34** | 1.40 | 1.41 |
| 21 | 1:20 | 72.5 | **0.30** | **1.19** | 0.67 |
| 37 | 1:20 | 98.4 | 0.20 | **0.60** | 0.14 |
| 28 | 1:22 | 77.7 | 0.15 | **1.20** | 0.99 |
| 5 | 1:22 | 207.2 | NA | NA | NA |
| 22 | 1:25 | 202.3 | **0.40** | **0.70** | 0.94 |
| **Large drainage areas** | | | | | |
| 8 | 1:12 | 300.4 | 0.12 | **0.37** | 0.33 |
| 35 | 1:20 | 445.5 | 0.24 | **1.10** | 0.33 |
| 27 | 1:22 | 575.0 | **0.46** | **0.86** | 0.55 |
| 24 | 1:25 | 264.2 | 0.21 | **1.07** | 1.19 |

Values shown are for the ($Y$, $V$) pair, which best meets fish passage requirements on top of each GCS. Data from fall of 2004. Depth and velocity values meeting or exceeding requirements for catfish passage are in bold. Dashes (–) indicate no flow. GCS details shown in Table I; locations shown in Figure 3. GCS listed in descending order of slope (steep to gentle) within drainage area classes.



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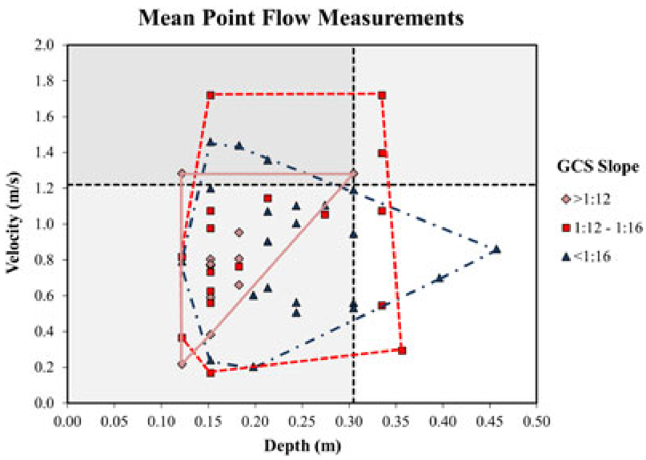


Figure 4. Relationships of mean point velocity with depth of flow on top of loose riprap, grouted riprap and baffled fish ladder weirs in western Iowa streams. Minimum convex polygons outline the range of observed values of depth and velocity for GCS grouped by slope category. The upper left quadrant (dark shading) does not meet the depth or velocity requirements for fish passage, whereas the lower right quadrant (no shading) meets both requirements. The other two quadrants (light shading) meet only one of the requirements. Taken from Papanicolaou and Dermisis (2006) and Dermisis and Papanicolaou (2009). This figure is available in colour online at wileyonlinelibrary.com/journal/rra

(<1:16) to intermediate sloped (1:10–1:16) weirs because both $Y_{\min}$ and $V_{\max}$ are limiting factors for fish passage. Without considering drainage area, the best performance was exhibited by gently sloped (<1:16) weirs and fish ladders with baffles. The worst performing GCS were weirs with slopes steeper than 1:16 and fish ladders without baffles.

Turbulence measurements showed that weirs generated lower levels of turbulence compared with fish ladders with baffles; however, stresses on all GCS were $\leq 5.3\,\mathrm{N\,m^{-2}}$ (Dermisis and Papanicolaou, 2009), which is much less than $1600\,\mathrm{N\,m^{-2}}$ needed to cause fish mortality (e.g. Cada *et al*., 2006). Turbulent flow measurements illustrated that fish ladders with baffles formed eddies 30% larger than the average catfish fork length of 0.3 m, which is enough to disorient fish.

Lastly, with respect to the different type of GCS, fish ladders were often observed to catch debris, probably because of the large quantity of vertical steel sheet pile exposed. Grouted riprap slopes were observed to degrade less quickly and were more resistant to large flow events than ungrouted riprap slopes (Dermisis and Papanicolaou, 2009).

## DISCUSSION AND CONCLUSIONS

Our study focused on streams in southwest Iowa, but our results should improve understanding of GCS effects on stream biophysical features and fish passage in other regions. A synthesis of our hydraulic and biological studies reveals that as GCS slope increases from relatively gentle slopes <1:16 to steep slopes >1:12, depth and velocity conditions are less likely to meet known standards for fish passage, and complementary studies of fish passage over GCS of varying slopes confirm that fish passage is indeed reduced as slope increases (Table IV).

Recent studies conducted elsewhere have demonstrated the potential for GCS to influence fish species composition and diversity and reduce or prevent upstream fish passage (Ficke and Myrick, 2009). Ficke and Myrick (2009) found that five species of fishes moved downstream over a GCS with a vertical face and mean drop height of 63 cm, but that only two of these species, and relatively few individuals, exhibited upstream movement over this GCS. In several instances, GCS have been installed in streams to enhance fish habitat, despite acknowledgement that such structures might function as barriers to fish migration (Shields and Hoover, 1991; Shields *et al*., 1998; Thompson, 2002; Raborn and Schramm, 2003). Results from fish community analyses conducted in degraded Mississippi streams were consistent with the hypothesis of GCS-mediated improvements in fish habitat. Fish species composition was different, and overall diversity was higher, at sampling stations above and below GCS than in sections of a comparable stream without GCS (Shields and Hoover, 1991; Shields *et al*., 1998). However, in another study of degraded streams in the southeastern United States, Raborn and Schramm

Table IV. Summary of hydraulic conditions and fish passage at grade control structures with differing slopes in western Iowa streams

| Slope category | Depth over weir for fish passage | Velocity over weir for fish passage[1] | Turbulent flow characteristics for fish passage | Documented fish passage |
|---|---|---|---|---|
| >1:12 | Poor (8) | Poor (0) | – | No |
| 1:12–1:16 | Fair (28) | Good (60) | – | Yes |
| <1:16 | Fair (27) | Good (100) | Good (100) | Yes |

Hydraulic conditions detailed in Papanicolaou and Dermisis (2006) and Dermisis and Papanicolaou (2009). Numbers in parentheses are percentages of GCS meeting requirements for catfish passage. Dashes (–) indicate no measurements. Fish passage described in Larson *et al*. (2004) and Litvan *et al*. (2008a)
[1]If depth requirement met.



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(2003) found that fish species diversity in the vicinity of GCS composed of a 1.2-m-high rip-rap dam with 0.5-m-high rip-rap sills located downstream did not differ from diversity in channelized stream sections without GCS (Raborn and Schramm, 2003).

Existing design recommendations for artificial riffles and riprap weirs generally include a slope recommendation of 1:20 (Newbury and Gaboury, 1993), although some designs range in slope from 1:15 to 1:30 (Food and Agriculture Organization of the United Nations, 2002). In southwestern Iowa streams, vertical or steeply sloping ($>$1:12) GCS will restrict fish passage, whereas gently sloping ($\leq$1:12) GCS will allow passage of the fish species examined. However, extremely low and high water conditions can restrict passage regardless of GCS design. In addition, because not all fish species, nor juveniles of any species, were included in this study, gently sloping GCS may still act as a barrier to movement for some species or sizes of fish. GCS can have a local positive effect on fish and macroinvertebrates with respect to increased habitat diversity and abundance. Although GCSs increase local habitat diversity, they may prevent passage of fish if not properly designed or maintained, causing fragmentation of streams, ultimately leading to decreased abundance and diversity. All GCSs tested produced low levels of turbulence, indicating that turbulent stresses will not cause mortality to fish migrating over a GCS. Because fish ladders often catch debris and riprap is not as strong or as resistant to high events, future GCS in western Iowa should incorporate a grouted riprap slope. Weirs with slopes $\leq$1:15 are now recommended for all GCS in western Iowa because they have been shown to allow fish passage for several important species and are less expensive than 1:20 GCS.

Although the importance of hydraulic characteristics to biological processes in streams has been acknowledged for some time (e.g. Statzner *et al*., 1988), there is currently an increase in multidisciplinary applications of hydraulics to understanding biological phenomena in streams (Lancaster and Downes, 2009; Nikora, 2009; Rice *et al*., 2010). As an example of this trend, the studies reviewed here were instrumental in creating design criteria for future GCSs to be built in western Iowa that not only protect streams from channel incision but also allow for fish passage and better biological connectivity of the stream systems.

This review illustrates the value of a multidisciplinary approach to solving environmental problems in situations such as western Iowa streams, where societal needs and environmental quality can appear to be in conflict. Complementary biological studies (Larson *et al*., 2004; Litvan *et al*., 2008a–c) and a hydraulic study (Papanicolaou and Dermisis, 2006; Dermisis and Papanicolaou, 2009) were undertaken to address environmental effects of GCS, which have been largely successful in serving their original purpose. Together, these studies not only determined the effects of GCS but also demonstrated that the deleterious environmental effects of GCS can be mitigated without excessive cost and without compromising the original functions of GCS. In addition, they identified previously undocumented environmental benefits of GCS.

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