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# Effects of Grade Control Structures on Fish Passage, Biological Assemblages and Hydraulic Environments in Western Iowa Streams: A Multidisciplinary Review

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## 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 ( $\geq 1:4$  rise : run) downstream slopes severely limited fish passage, but GCS with gentle slopes ( $\leq 1:15$ ) 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  $\geq 1$  km from GCS. A hydraulic study confirmed results from fish passage studies; minimum depths and maximum current velocities at GCS with gentle slopes ( $\leq 1:15$ ) 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.

## Keywords

biotic integrity, fish assemblages, fish passage, grade control structures, hydraulic characteristics

## Disciplines

Aquaculture and Fisheries | Natural Resources Management and Policy

## Comments

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

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## 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 ( $\geq 1:4$  rise:run) downstream slopes severely limited fish passage, but GCS with gentle slopes ( $\leq 1:15$ ) 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  $\geq 1$  km from GCS. A hydraulic study confirmed results from fish passage studies; minimum depths and maximum current velocities at GCS with gentle slopes ( $\leq 1:15$ ) 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

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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<sup>3</sup> 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](http://wileyonlinelibrary.com/journal/rra)



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

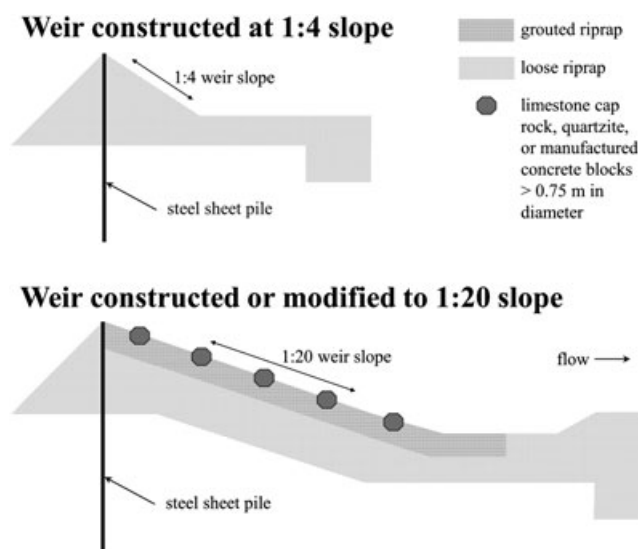


Figure 2. Simplified longitudinal profile diagram of weirs, contrasting steeply sloped (1:4) and gently sloped (1:20) weirs. A vertical slope (not shown) can result from riprap moving away from the sheet pile on the downstream side. Diagrams are not to scale

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

GCS	Stream	Study		GCS type <sup>3</sup>	Modified?	Drainage area (km <sup>2</sup> )	Grade control (m)	Weir Slope (rise : run)			
		Citation <sup>1</sup>	Type <sup>2</sup>					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.

<sup>1</sup>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, Dermis and Papanicolaou (2009).

<sup>2</sup>Study types are as follows: FP, fish passage; FA, fish assemblage; MA, macroinvertebrate assemblage; HC, hydraulic characteristics.

<sup>3</sup>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).

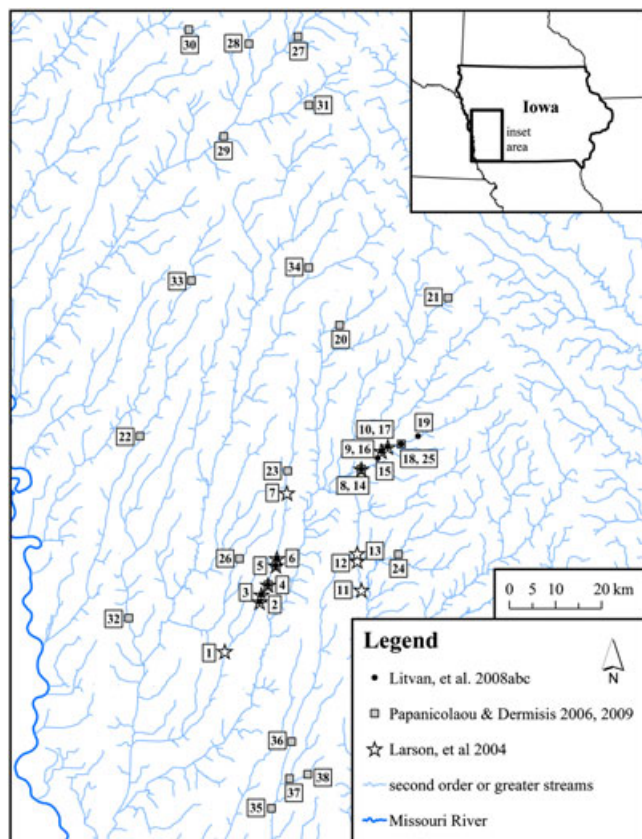


Figure 3. Locations of grade control structures (GCS) studied in western Iowa streams. Numbers correspond with GCS identified by number in Tables 1–3. Symbols identify GCS by study. This figure is available in colour online at [wileyonlinelibrary.com/journal/rra](http://wileyonlinelibrary.com/journal/rra)

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  $\geq 1$  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  $\geq 1$  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



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<sup>2</sup>. 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  $\geq 1$  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  $\pm 4$  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).



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  $\geq 1$  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  $\geq 1$  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  $\geq 1$  km from GCS. Interestingly, Litvan *et al.* (2008c) sampled a single reach  $\geq 1$  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  $1.22 \text{ m s}^{-1}$ , 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  $1.22 \text{ m s}^{-1}$ ; 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  $2.37 \text{ m s}^{-1}$ ). 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

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

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 ( $<51.8 \text{ km}^2$ ), 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 ( $>259 \text{ km}^2$ ), 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  $259 \text{ km}^2$ ), the best GCS are either gentle

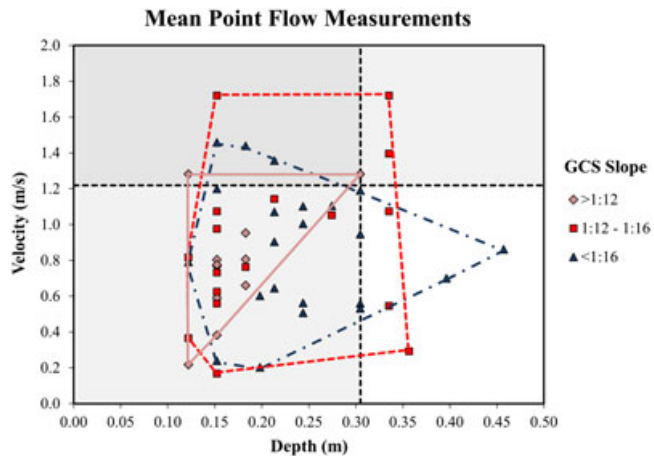


Figure 4. Relationships of mean point velocity with depth of flow on top of loose riprap, grouted riprap and baffled fish ladder weirs in western Iowa streams. Minimum convex polygons outline the range of observed values of depth and velocity for GCS grouped by slope category. The upper left quadrant (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](http://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  $\leq 5.3 \text{ N m}^{-2}$  (Dermisis and Papanicolaou, 2009), which is much less than  $1600 \text{ N m}^{-2}$  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 <sup>1</sup>	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)

<sup>1</sup>If depth requirement met.

(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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#### REFERENCES

- Baker DB, Richards RP, Loftus TT, Kramer JW. 2004. A new flashiness index: characteristics and applications to Midwestern rivers and streams. *Journal of the American Water Resources Association* **40**(2): 503–522. DOI: 10.1111/j.1752-1688.2004.tb01046.x.
- Barbour MT, Gerritsen J, Snyder BD, Stribling JB. 1999. *Rapid bioassessment protocols for use in streams and wadeable rivers: periphyton, benthic macroinvertebrates, and fish*. 2nd edition. EPA/841-B-99-002. US EPA, Office of Water, Assessment and Watershed Protection Division: Washington, District of Columbia
- Baumel C. 1994. Impact of degrading western Iowa streams on private and public infrastructure costs. In *Stream Stabilization in Western Iowa*, Hadish GA, Braster M (eds). Iowa DOT HR-352. Golden Hills Resource Conservation and Development: Oakland, Iowa; 4-1–4-39.
- Beecham RV, Minchew CD, Parsons GR. 2007. Comparative swimming performance of juvenile pond-cultured and wild-caught channel catfish. *North American Journal of Fisheries Management* **27**: 729–734. DOI: 10.1577/M04-219.1.
- Bravard JP, Amoros C, Pautou G, Bornette G, Bournaud M, Creuzé Des Châtelliers M, Gibert J, Peiry JL, Perrin JF, Tachet H. 1997. River incision in south-east France: morphological phenomena and ecological effects. *Regulated Rivers: Research & Management* **13**: 75–90. DOI: 10.1002/(SICI)1099-1646(199701)13:1<75::AID-RRR444>3.0.CO;2-6.
- Bunn SE, Arthington AH. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* **30**(4): 492–507. DOI: 10.1007/s00267-002-2737-0.
- Cada G, Loar J, Garrison L, Fisher R, Neitzel D. 2006. Efforts to reduce mortality to hydroelectric turbine-passed fish—locating and quantifying damaging shear stresses. *Environmental Management* **37**(6): 898–906. DOI: 10.1007/s00267-005-0061-1.
- Cooper CM, Knight SS. 1987. Fisheries in man-made pools below grade-control structures and in naturally occurring scour holes of unstable streams. *Journal of Soil and Water Conservation* **42**: 370–373.
- Cooper CM, Testa S, Shields FD. 1997. Invertebrate response to physical habitat changes resulting from rehabilitation efforts in an incised unstable stream. In *Management of Landscapes Disturbed by Channel Incision*, Wang SSS, Langendoen EJ, Shields FD (eds). University of Mississippi: Oxford, Mississippi; 887–892.



- Dermis DC, Papanicolaou AN. 2009. Fish passage over hydraulic structures in Midwestern Rivers of the USA. *International Journal of River Basin Management* **7**(4): 313–328.
- Ebrahimzad M, Harper DM. 1997. The biological effectiveness of artificial riffles in river rehabilitation. *Aquatic Conservation: Marine and Freshwater Ecosystems* **7**: 187–197. DOI: 10.1002/(SICI)1099-0755(199709)7:3<187::AID-AQC219>3.0.CO;2-B.
- Food and Agriculture Organization of the United Nations (FAO). 2002. *Fish Passes: Design, Dimensions, and Monitoring*. FAO: Rome.
- Ficke AD, Myrick CA. 2009. A method for monitoring movements of small fishes in urban streams. *North American Journal of Fisheries Management* **29**: 1444–1453.
- Fore LS, Karr JR, Conquest LL. 1994. Statistical properties of an index of biotic integrity used to evaluate water resources. *Canadian Journal of Fisheries and Aquatic Sciences* **51**: 1077–1087.
- Fox JF, Papanicolaou AN, Kjos L. 2005. Eddy taxonomy methodology around a submerged barb obstacle within a fixed rough bed. *Journal of Engineering Mechanics* **131**(10): 1082–1101. DOI: 10.1061/(ASCE)0733-9399(2005)131:10(1082).
- Gore JA, Hamilton SW. 1996. Comparison of flow-related habitat evaluations downstream of low-head weirs on small and large fluvial ecosystems. *Regulated Rivers: Research & Management* **12**: 459–469. DOI: 10.1002/(SICI)1099-1646(199607)12:4/5<459::AID-RRR413>3.0.CO;2-T.
- Hansen DR. 1971. *Effects of Stream Channelization on Fishes and Bottom Fauna in the Little Sioux River, Iowa*. ISWRR1 38. Iowa State Water Resources Research Institute: Ames, Iowa.
- Hocutt CH. 1973. Swimming performance of three warmwater fishes exposed to a rapid temperature change. *Chesapeake Science* **14**(1): 11–16.
- Katopodis C. 1992. *Introduction to Fishway Design*. Freshwater Institute, Department of Fisheries and Oceans: Winnipeg, Manitoba.
- Kim Y. 2006. *Uncertainty Analysis of Non-intrusive Measurement of River Discharge Using Image Velocimetry*. Ph.D. Dissertation, The University of Iowa: Iowa City, Iowa.
- Lancaster J, Downes BJ. 2009. Linking the hydraulic world of individual organisms to ecological processes: putting ecology into ecohydraulics. *River Research and Applications* **25**. DOI: 10.1002/rra.1274.
- Larson CJ, Atchison GJ, Menzel BW. 2004. Annual progress report to the Iowa Department of Natural Resources Fisheries Bureau for an evaluation of effects of weirs in Walnut Creek on fish abundance and movement. Project Report, Contact No: 03-8250-01. Iowa Department of Natural Resources Cold Springs Southwest Regional Office: Lewis, Iowa.
- Litvan ME, Pierce CL, Stewart TW, Larson CJ. 2008a. Fish passage in a western Iowa stream modified by grade control structures. *North American Journal of Fisheries Management* **28**: 1384–1397. DOI: 10.1577/M07-097.1.
- Litvan ME, Pierce CL, Stewart TW, Larson CJ. 2008b. Fish assemblages in a western Iowa stream modified by grade control structures. *North American Journal of Fisheries Management* **28**: 1398–1413. DOI: 10.1577/M07-098.1.
- Litvan ME, Stewart TW, Pierce CL, Larson CJ. 2008c. Effects of grade control structures on the macroinvertebrate assemblage of an agriculturally impacted stream. *River Research and Applications* **24**: 218–233. DOI: 10.1002/rra.1063.
- Newbury RW, Gaboury MN. 1993. *Stream Analysis and Fish Habitat Design*. Newbury Hydraulics, Ltd.: Gibsons, British Columbia.
- Nikora V. 2009. Hydrodynamics of aquatic ecosystems: an interface between ecology, biomechanics and environmental fluid mechanics. *River Research and Applications* **25**. DOI: 10.1002/rra.1291.
- Ovidio M, Philippart JC. 2002. The impact of small physical obstacles on upstream movements of six species of fish. *Hydrobiologia* **483**: 55–69. DOI: 10.1023/A:1021398605520.
- Palic D, Helland L, Pedersen BR, Pribil JR, Grajeda RM, Loan-Wilsey AK, Pierce CL. 2007. Fish assemblages of the upper Little Sioux River basin, Iowa, USA: relationships with stream size and comparison with historical assemblages. *Journal of Freshwater Ecology* **22**: 69–79.
- Papanicolaou A, Dermis D. 2006. *Field Investigation of Hydraulic Structures Facilitating Fish Abundance and Passage Through Bridges in Western Iowa Streams*. Iowa DOT TR-521. University of Iowa: Iowa City, Iowa.
- Rabalais NN, Turner RE, Scavia D. 2002. Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi River. *BioScience* **52**(2): 129–142.
- Raborn SW, Schramm HL. 2003. Fish assemblage response to recent mitigation of a channelized warmwater stream. *River Research and Applications* **19**: 289–301. DOI: 10.1002/rra.704.
- Rice SP, Lancaster J, Kemp P. 2010. Experimentation at the interface of fluvial geomorphology, stream ecology and hydraulic engineering and the development of an effective, interdisciplinary river science. *Earth Surface Processes and Landforms* **35**: 64–77. DOI: 10.1002/esp.1838.
- Rowe DC, Pierce CL, Wilton TF. 2009. Fish assemblage relationships with physical habitat in wadeable Iowa streams. *North American Journal of Fisheries Management* **29**: 1314–1332. DOI: 10.1577/M08-192.1.
- Shields FD, Hoover JJ. 1991. Effects of channel restabilization on habitat diversity, Twenty Mile Creek, Mississippi. *Regulated Rivers: Research & Management* **6**: 163–181. DOI: 10.1002/rrr.3450060303.
- Shields FD, Knight SS, Cooper CM. 1994. Effects of channel incision on base flow stream habitats and fishes. *Environmental Management* **18**(1): 43–57. DOI: 10.1007/BF02393749.
- Shields FD, Knight SS, Cooper CM. 1995. Incised stream physical habitat restoration with stone weirs. *Regulated Rivers: Research & Management* **10**: 181–198. DOI: 10.1002/rrr.3450100213.
- Shields FD, Knight SS, Cooper CM. 1998. Rehabilitation of aquatic habitats in warmwater streams damaged by channel incision in Mississippi. *Hydrobiologia* **382**: 63–86.
- Simon A, Rinaldi M. 2000. Channel instability in the loess area of the Midwestern United States. *Journal of the American Water Resources Association* **36**(1): 133–150.
- Simon TP (ed.). 1999. *Assessing the Sustainability and Biological Integrity of Water Resources Using Fish Communities*. CRC Press: Boca Raton, Florida.
- Statzner B, Gore JA, Resh VH. 1988. Hydraulic stream ecology: observed patterns and potential applications. *Journal of the North American Benthological Society* **7**: 307–360.
- Thomas JT. 2007. Grade control in western Iowa streams. In *Stream Restoration Design Part 654 National Engineering Handbook*. United States Department of Agriculture Natural Resources Conservation Service; CS12-1–CS12-20.
- Thomas JT. 2009. Hungry Canyons Alliance: Streambed Stabilization in Western Iowa. In *Proceedings of the 2009 World Environmental & Water Resources Congress*, May 17–21, ASCE-EWRI: Kansas City, Missouri.
- Thompson DM. 2002. Long-term effect of instream habitat-improvement structures on channel morphology along the Blackledge and Salmon Rivers, Connecticut, USA. *Environmental Management* **29**: 250–265.
- Tiemann JS, Gillette DP, Wildhaber ML, Edds DR. 2004. Effects of lowhead dams on riffle-dwelling fishes and macroinvertebrates in a midwestern river. *Transactions of the American Fisheries Society* **133**: 705–717. DOI: 10.1577/T03-058.1.
- White K, Gerken J, Paukert C, Makinster A. 2009. Fish community structure in natural and engineered habitats in the Kansas River. *River Research and Applications* **25**. DOI: 10.1002/rra.1287.
- Wilton TF. 2004. *Biological Assessment of Iowa's Wadeable Streams*. Iowa Department of Natural Resources: Des Moines, Iowa.