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[Article]

Modular Experimental Riffle–Pool Stream System

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Abstract.—We describe a modular method for building a large, outdoor experimental stream system that has great flexibility for research projects in fish ecology, behavior, conservation, or management. The system has been in use for more than a decade at the University of Oklahoma Biological Station (Kingston, Oklahoma) and has been used with modification at four other research facilities in the Midwest. Here, we document the system in detail, including specifications for construction of the original system and modifications or improvements at other sites. The system uses commercially available, customized fiberglass round tank and trough units that can be configured in many different ways to create flowing pool and riffle habitats. The system appears to be a good mimic of small natural streams based on system flow rates, establishment of natural substrates and cover, stream chemistry relative to that of a natural creek, and fish behaviors. At least 39 fish species have been used successfully in 1–14-month experiments in these systems and approximately half have reproduced. The system offers great flexibility of design to experimenters, is cost effective, and may be of interest at other facilities that research basic biology, conservation, or management of stream fishes.

There is a long history of use of experimental streams with a wide range of designs for research in fish biology and ecology (Warren and Davis 1971). Gelwick and Matthews (1993) reviewed 40 studies since 1970 that used artificial systems for fish research and suggested that replicated, experimental stream units with reasonable mimicry of real stream systems (e.g., natural substrates, complex habitats, more natural stream configurations) and careful investigator control of conditions should increase research capabilities in fish biology. They cautioned, as did Warren and Davis (1971), that experimental streams are not real ecosystems, so investigators must be keenly aware of (1) important factors that are included in their systems (e.g., natural habitats, spawning opportunities) versus those that may be excluded (e.g., drought and flood, unless experimentally included; immigration or emigration of individuals) and (2) general limitations to "microcosm" or "mesocosm" research (Carpenter 1996; Skelly 2002). However, if those limitations are taken into account, experimental stream systems offer many positive opportunities for advancing knowledge in fish ecology or behavior. The 22 studies reviewed by Warren and Davis (1971) and the 40 reviewed by Gelwick and Matthews (1993) showed a wide range of approaches for building experimental streams: small

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FIGURE 1.—Photograph of the original modular experimental stream system under construction at the University of Oklahoma Biological Station showing alternating pool and riffle units; one end is open to show point of attachment for the next riffle unit. Concrete pads were poured with an overall allowable tolerance of only 0.25-in difference in height to assure uniform control of water level in all units. Plexiglas observation ports had not yet been added to pool units.

"table top" flow tanks with a simple "straight-walled" design; laboratory flumes designed to capture the natural sinuosity of streams (e.g., Fausch and White ?2 1983); and very large outdoor systems with permanent channels hundreds of meters long (Swift et al. 1993). Many systems were highly simplified to allow focus on only one or a few aspects of fish behavior. However, during studies of algae-grazing minnows (Gelwick and ?3 Matthews 1992), we became aware of the need for an improved, relatively inexpensive design to provide alternating riffle and pool habitats of a size that promotes the natural behaviors of small fishes. Only a few designs incorporating complex riffle–pool habitats had previously been constructed (Swift et al. 1993); most were limited to small laboratory designs or large and expensive outdoor designs with a permanent structure (e.g., made of concrete) that made future modification of the stream configurations impractical.

Here, we provide a detailed description of a system of outdoor, modular, riffle–pool streams we designed which, with various modifications of the original design, is now in use at six universities or state fisheries facilities. The original set of streams (Figure 1) of this system was built at the University of Oklahoma Biological Station (UOBS) near Kingston, Oklahoma, in 1992 (Gelwick and Matthews 1993), followed by a second, slightly modified set at UOBS in 1994. Additional modifications have been made in sets of streams at the Heart of the Hills Fisheries Science Center near Kerrville, Texas, by the Texas Parks and Wildlife Department (TPWD); the Konza Prairie Biological Station (KPBS) of Kansas State University, Manhattan; Southern Illinois University–Edwardsville (SIUE); and the University of Southern Mississippi (USM), Hattiesburg. Construction of an additional set is under way at the University of Oklahoma Aquatic Research Facility in Norman, Oklahoma. Since construction of the original streams, numerous ecological or behavioral experiments with fish (Table 1), crayfish, or both in these systems have been conducted by faculty, agency biologists, and graduate students, resulting in publications with both theoretical (Gelwick 2000; Gido and Matthews 2001; Matthews et al. 2001; Schaefer 2001) and conservation or management (Gido et al. 1999; Marsh-Matthews et al. 2002; Knight and Gido 2005) implications. The streams at UOBS have hosted experiments for three doctoral dissertations (Gelwick 1995; Schaefer 1999; Hargrave 2005) and two more in progress. At KPBS, one doctoral dissertation is in progress and one master's thesis was completed (Knight 2004). The systems have also been ?4 the basis for one master's thesis at TPWD (Thomas 2001), one master's thesis in progress at SIUE, one master's thesis in progress at USM, and more than a dozen other experiments for which manuscripts are in preparation by various authors.

Brief descriptions of this system are in published papers (e.g., Knight and Gido 2005), and figures

TABLE 1.—Fish species that have been used successfully in experimental stream units. Asterisks denote species that are known to have produced larvae in the streams.

Family	Species
Cyprinidae	Central stoneroller *Campostoma anomalum**
	Red shiner *Cyprinella lutrensis**
	Proserpine shiner *Cyprinella proserpina**
	Blacktail shiner *Cyprinella venusta**
	Steelcolor shiner *Cyprinella whipplei**
	Common carp *Cyprinus carpio*
	Manantial roundnose minnow *Dionda argentosa**
	Devils River minnow *D. diaboli**
	Warpaint shiner *Luxilus chrysocephalus**
	Common shiner *Luxilus cornutus*
	Redfin shiner *Lythrurus umbratilis*
	Texas shiner *Notropis amabilis**
	Bigeye shiner *N. boops**
	Sand shiner *N. stramineus*
	Topeka shiner *N. Topeka**
	Southern redbelly dace *Phoxinus erythrogaster**
	Bluntnose minnow *Pimephales notatus*
	Fathead minnow *Pimephales promelas*
	Bullhead minnow *Pimephales vigilax*
	Colorado pikeminnow *Ptychocheilius lucius*
Catostomidae	Bluehead sucker *Catostomus discobolus*
	Flannelmouth sucker *Catostomus latipinnis*
	Golden redhorse *Moxostoma erythrurum*
Fundulidae	Blackstripe topminnow *Fundulus notatus**
	Blackspotted topminnow *F. olivaceus**
Atherinopsidae	Brok silverside *Labidesthes sicculus*
Cyprinodontidae	Red River pupfish *Cyprinodon rubrofluviatilis**
Poeciliidae	San Felipe gambusia *G. clarkhubbsi**
	Tex-Mex gambusia *G. speciosa**
	Western mosquitofish *Gambusia affinis**
Percidae	Rio Grande darter *Etheostoma grahami*
	Orangebelly darter *E. radiosum*
	Orangethroat darter *E. spectabile**
	Channel darter *Percina copelandi*
Centrarchidae	Green sunfish *Lepomis cyanellus*
	Longear sunfish *Lepomis megalotis**
	Redear sunfish *Lepomis microlophus*
	Smallmouth bass *Micropterus dolomieu*
	Largemouth bass *Micropterus salmoides*

showing some ways in which the system has been used are provided by Gido et al. (1999; a unit = three pools and two riffles), Gido and Matthews (2001; unit = one pool and one riffle), and Schaefer (2001; unit = two pools and one riffle). A photograph of the original set of streams was published in Lamberti and Steinman (1993: their Figure 3). However, we have not previously published a detailed account of specifications and materials, or construction and operation of the system. Here, we document the basic modular system and modifications that have been added to enhance the original design. We emphasize that the system is very flexible, and we encourage other entities undertaking construction to innovate and to take advantage of differences in water sources, energy availability, or local environmental conditions. The system is not patented or restricted in use in any way, although the senior author would appreciate knowing of any future implementations of this system.

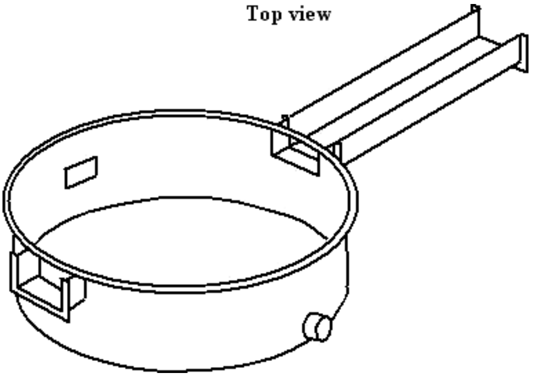

FIGURE 2.—Illustration of an experimental stream system modification used at the Konza Prairie Biological Station, Kansas State University, Manhattan, and other sites at which flange was placed on pool units, providing a flat junction with riffle units. The flat fit facilitates removal of a single riffle unit; due to the curved fit in the original streams, such removal is not possible without moving the pool units.

Methods

Fiberglass pool and riffle units.—Because the pool and riffle units are produced by commercial "fish farm" manufacturers in the United States, specifications are included in English units to facilitate ordering. The modular system consists of alternating round (pool) and straight-sided (riffle) units (Figure 1), each 183 cm (72 in) in length, bolted together in various combinations. A pool unit (Figure 1) consists of a round, 1,136-L (300-gal) fish culture tank, 183 cm in diameter and 90 cm tall (for operation, it is filled with water to a depth of approximately 50 cm over the substrate). The fiberglass walls are approximately 6.5 mm (0.25 in) thick and are coated inside and outside with a blue-gel coating approved by the U.S. Department of Agriculture (USDA) for production of food fish. The pool unit walls slope slightly outward so that if ice forms during winter operation, the water freezes upward at the surface rather than exerting lateral pressure that could burst the tank. The 1,136-L units at the UOBS were purchased from both Rowland Fiberglass (Ingleside, Texas) and the Red Ewald Company (Karnes City, Texas), and these units have virtually identical designs. A threaded 4-in drain with threaded cap installed near the bottom of each pool unit allows efficient draining, cleaning, and refilling of units. A riffle unit (Figure 1) is a custom-designed, straight-sided fiberglass unit measuring 183 × 46 cm (6 × 1.5 ft) wide and 38 cm (1.25 ft) tall; the walls and coatings are like those of the pool units. A curved

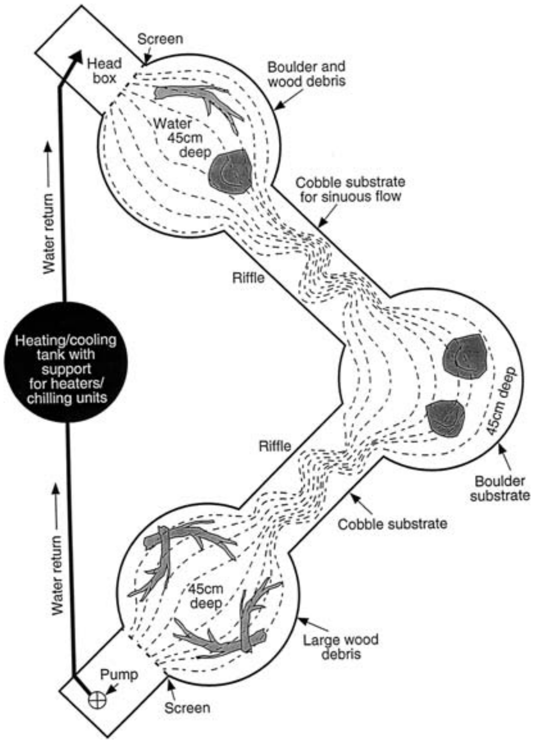

FIGURE 3.—Illustrated configuration of one of the eight units in the second University of Oklahoma Biological Station experimental stream system. Riffles–pools have a 90° angle to simulate a curved stream reach. Sinusoidal flow is present in riffles, and natural structure (boulders, wood debris) is added. The position of the heating–cooling tank in the water return system is shown.

flange at each end of the riffle unit allows connection to a hole cut in the curved wall of a pool unit. The method of joining pool and riffle units is modified to place the flange on the pool unit (rather than the riffle unit) in the design used at KPBS (Figure 2), TPWD, SIUE, and USM; this allows jointing of flat (rather than curved) surfaces when riffle and pool units are connected. Alternating pool and riffle units are bolted together with 0.5-in, stainless-steel bolts; a gasket (see Figure 1 for detail) cut from –0.25-in-thick polypropylene gasket material is placed between all units, and the inner surface of all connections is coated with clear silicone to enhance the seal between units. Some gasket materials can be toxic to fish (S. T. Ross, University of New Mexico, personal communication), so coating the inner surface of all connections with silicone also ensures that water is not in direct contact with the gaskets. In the SIUE and USM streams, weather stripping was used instead of polypropylene gasket material and worked well. Bolts are installed with the heads to the inside (water side) and are also coated with silicone to maintain watertight connections.

Pool units have a clear, 22- × 10-cm Plexiglas viewing port installed just below water level. Because the pool walls are curved, the Plexiglas is first cut to size, bent slightly with the aid of a hot air gun, and installed into a hole cut in the pool wall using two small bolts; the edges are then coated with silicone. As a cautionary note, cutting or drilling in fiberglass produces substantial amounts of fine fiberglass dust, so it is essential for personnel to wear appropriately fitted respirator units when conducting this work.

Substrate, shelter, and temperature regulation.—Pools and riffles are provided with substrates of natural gravel and cobble from nearby streams (UOBS: Brier Creek, Marshall County, Oklahoma; TPWD: Johnson Creek, Kerr County, Texas) or a quarried river rock (KPBS, SIUE). Various configurations of boulders, plants, or woody debris (Figure 3) have been added to mimic conditions in natural creeks. In most applications, pools have been deepest in the middle and their edges are sloped upward to the water's edge to provide uninterrupted access to riffles; therefore, benthic fishes like darters can enter or leave a riffle without encountering a vertical barrier. The second UOBS array (Figure 3) has a right-angle configuration; the deepest part of the middle pool is toward the outside, as would be the case in a natural sinusoidal stream. In that array, water from the footbox is pumped via a polyvinyl chloride pipe to a separate, 200-gal, round tank that has brackets to hold heaters or chillers for temperature modification. In riffle units, substrate can be kept level to promote uniform flow across the riffle or can be sculpted to produce sinusoidal flow by alternating small piles of substrate along the sides.

Water depths and recirculation of water.—The most important feature of installation is that the site must be almost perfectly level (Figure 1) to assure proper operation so that water is level across all pools and riffles within an experimental unit. Depth of water flowing across riffles is controlled by the depth to which the entire system is filled. Flow from pool to pool across riffles results from recirculation of water from a footbox to a headbox using pumps (UOBS, TPDW, and SIUE) or other small trolling motors (KPBS) to move water. In most experiments, we use a "splash" or "waterfall" return flow to aerate water.

At the UOBS, we have used Little Giant submersible pumps with a capacity of 10,450 L/h or 2,500 L/h, depending on the amount of current speed desired. The larger pumps can generate enough heat to slightly elevate temperatures within the systems; this can be important if precise temperature control is needed; they can also be used in high- versus low-flow experimental treatments. Most submersible pumps are designed to operate only at full speed (i.e., they should not be run more slowly by rheostat control or they will burn out rapidly). However, flow volume can be reduced by installing a valve on the outlet pipe that allows some flow to be redirected back into the return-flow trough (footbox). Most Little Giant pumps have lasted a year or more in constant operation. Water flow at TPWD is created by Beckett Big Versa PS3900A pumps that have a maximum output of 14,400 L/h. At SIUE and USM, Supreme magnetic-drive utility pumps of two sizes (output of 9,100 or 14,400 L/h) have been used. The Supreme pumps have an advantage of containing no oil, which eliminates any risk of oil leaks into the streams. Most fish avoid the intakes of pumps, but for some species we have used plastic-mesh screens installed in marine plywood frames coated with spar varnish to exclude fish from the pump intake. To minimize any risk of electrical shock by personnel working in the streams, pumps should be operated only on ground fault outlets complying with all local electrical codes.

At KPBS, where access to electrical power is limited, water in stream units is circulated using a variable-speed electric trolling motor. Water is drawn from the downstream end of a pool through a 15.2-cm-diameter pipe and forced into the top of the riffle by the propeller. The pipe is buried under the substrate to reduce the amount of energy required to lift above the water surface. The use of a large pipe and propeller-driven motor reduces friction and allows a large quantity of water to be moved with minimal power (Vogel 1994). Discharge in streams with this configuration can range from 7,200 (low speed) to 18,000 L/h (high speed) while drawing only 2–6 A (instead of 9 A for the Little Giant pumps) and can provide current velocities of 6.4 cm/s in 34-cm-deep riffles. This configuration thus provides natural levels of discharge while requiring only a minimal amount of power.

Modular configurations.—The system has been operated with various numbers of pools connected per experimental unit using 0.75-in marine plywood barriers (coated with spar varnish or with two-part epoxy paint approved by the USDA for fish containers) held in place with silicone in the middle of riffle units to separate the stream system into discrete sections. Barriers are pressure tested by filling one side while the other is empty to assure no leaking of water from one unit to another. An In different studies, an experimental unit has included configurations with 1, 2, 3, 6, or 12 pools and associated riffles; many other combinations of pools and riffles could be achieved easily. To connect 12 pools, all flowing as one stream, we used one additional riffle unit as a bridge between the last pools in two rows, which requires the rows to be placed exactly one riffle length apart and to have appropriate cutouts in the sides as well as the ends.

Cost of installation.—Costs will be unique to each site, depending on factors like leveling of terrain, pouring a concrete base versus using a gravel pad, and availability of electrical power and water. However, the fiberglass units, gaskets, bolts, shade cloth, supports, and other small expendable items, cost approximately US$1,000 for one pool and one riffle unit. Thus, the basic necessities for creating an array of 24 riffle–pool units might be purchased for under $25,000. This does not include site preparation, installation of any needed utilities, or labor. While initial setup can be costly for a single experiment, such a stream array can be assumed to operate for a decade or more with minimal maintenance or repair and therefore may be cost effective as a long-term investment in research capabilities.

Results and Discussion

Since 1992, experiments in this system have involved at least 39 fish species (Table 1), including minnows, suckers, mosquitofish, silversides, topminnows, pupfish, black bass, sunfish, and darters. All species used in experiments in these systems have remained in good condition, and behavior of fish has approximated that observed in natural streams (Matthews et al. 1994). Many fish have reproduced in these ?5
systems (Table 1). Even species as large as sunfish *Lepomis* spp. have built nests in the gravel beds of these systems and have produced young.

To initiate experiments, we typically fill the units, start flow, add a slurry of algae and biofilms scraped from stones in a natural stream, and allow approximately 2 weeks for establishment of algae and invertebrates before introducing fish. Abundant periphyton and invertebrates like chironomids, dragonflies, damselflies, and small snails typically become established. Excessive filamentous algae can be controlled, if desired, by Nature's Weed Control (Greener Pastures). This is an organic-based product (soybean oil) that causes lysis of filamentous algal cells and leaves no residue. Fish are not typically fed in these experiments but forage on the established array of available foods, including organisms introduced from natural streams (e.g., snails, amphipods) or those that fly in to oviposit during the experiment (e.g., dipterans, dragonflies, damselflies).

Experiments in these systems have ranged in duration from 1 month to more than a year, and operation during winter (even with ice on surfaces) has been successful. During long-term experiments, evaporation requires the addition of small amounts of water

TABLE 2.—Comparison of ecosystem parameters in natural and experimental streams at the Konza Prairie Biological Station (KPBS), Kansas; range or SD is reported where applicable. Unless otherwise noted, data were collected in October 2002 from Kings Creek and November 2002 in experimental streams.

Variable	Kings Creek	KPBS experimental streams
Discharge (L/s)	1–10	0–5
Through-flow (L/s)	1–10	0.0016–0.0027
Fish density (number/m^2)	8	8
Invertebrate colonization	Aerial and drift	Aerial
Invertebrate richness (taxa/m^2)	15 ± 5	3–5
Invertebrate abundance (number/m^2)	859-4017	After 40 d: 82–1781
Gross primary productivity (g/m^2/d^{-1})	1.8[a]	2.0–3.0
Respiration ($g \cdot m^{-2} \cdot d^{-1}$)	2.0[a]	2.0
Hyporheic A_s/A	0.17[b]	0.20
Pool surface area (m^2)	83 ± 71 (n = 35 pools)	3.4
Pool maximum depth (m)	0.62 ± 0.34 (n = 35 pools)	0.60
Specific conductance (μS/cm)	0.485[c]	0.490

[a] Source: Mulholland et al. (2001).
[b] Source: Dodds et al. (2000).
[c] Source: Gray (1997).

to maintain desired levels. In most applications, source water is merely added as needed (weekly or less). However, at KPBS a gradual inflow from a springwater source provides continuous make-up water similar to that in the units, and at TPWD make-up water from a natural spring source is controlled by a float valve. Gradual addition of make-up water has not markedly changed water quality during experiments. For example, in one year-long experiment at UOBS that involved seven experimental units of three pools and two riffles each, oxygen was always at or near saturation, varying by no more than 0.5 mg/L among units; temperature varied no more than 0.2°C among units; and conductivity ranged from about 385 to 490 micromhos (μmhos) among units. Mean conductivity was 436.0 μmhos (SD = 42.7) at the beginning of the year-long experiment and 405.3 μmhos (SD = 37.5) at the end. Thus, we assume that any changes due to make-up water or accumulation of ionic materials are likely to have negligible effects on fish, invertebrates, or plants during typical experimental applications.

With a single larger Little Giant pump in the UOBS systems, we achieve current speeds of up to 25 cm/s in riffles approximately 15 cm deep and having sinusoidal sculpting of rock structure; use of two pumps almost exactly doubles the current speeds if water levels are held constant. Current speeds measured near the substrate in pools during typical operation of a UOBS unit with flow driven by one large Little Giant pump showed that flow was fastest through the middle of the pool and lower along the sides and that some gyres of reverse flow occurred along the pool lateral edges (as is common below riffles in natural pools). If such a flow pattern is undesirable in a particular experiment, rock or stone baffles can be installed at the lower end of riffle units so that water exits into the next pool in a design other than straight flow. One additional consideration when adding substrate is the ratio of cross-sectional area of subsurface water (A_s; hyporheic zone) to the water column surface area (A). Matching the A_s/A of the constructed units with that of the natural stream will presumably facilitate comparison of productivity by allowing adequate space for heterotrophic activity.

Live, native rooted vegetation that has grown successfully in these systems (at TPWD) includes marsh seedbox *Ludwigia palustris*, sago pondweed *Potamogeton pectinatus*, cattail *Typha latifolia*, umbrella grass *Fuirena simplex*, musk-grass *Chara* spp., water willow *Justicia americana*, and corn speedwell *Veronica arvensis*. Green algae (*Spirogyra* spp. and *Rhizoclonium* spp.) introduced from Brier Creek grows readily in the UOBS streams, commonly forming with columns and floating mats like those we have studied intensively in the natural stream (Power et al. 1985; Gelwick and Matthews 1992). ?6

At TPWD, a monthly census of fish is carried out by drawing down the water level to isolate habitats, then pumping CO_2 into each habitat for 30 min. The CO_2 is a mild anesthetic and also replaces oxygen in the water. Anesthetized fish move to the surface of the water in search of oxygen and are captured, identified, and counted, then removed to coolers with freshwater for recovery. Fishes are returned to the artificial streams after the systems have been flushed and refilled. Using this technique, there has been virtually no mortality at any life stage, including newly hatched fishes.

In the KPBS streams, a 10.1-cm-diameter standpipe facilitates export of organic matter during simulated floods. Floods are simulated by feeding in springwater at a high rate and recirculating water rapidly by running the trolling motor at high speed. Suspended organic matter is flushed from the system by removing the standpipe, which mimics the export of materials that would occur in a natural flood. At UOBS, droughts were simulated in two summer-long experiments by drawing down water in target units over several days and allowing riffles to gradually emerge as barriers to fish movement between pools. At both SIUE and UOBS, bentonite has been used to maintain turbid water conditions in these experimental streams for weeks to months. Turbidity levels have been maintained (through weekly additions of sodium bentonite) at 80–100 nephelometric turbidity units (NTU) in SIUE streams, whereas levels are typically less than 10 NTU for unmanipulated streams.

A comparison between ecosystem parameters in the experimental streams at KPBS and Kings Creek (Table 2), which flows through KPBS, illustrates the benefits of and limitations to using these systems. The greatest difference between natural and experimental streams at KPBS is the limited through-flow and lack of invertebrate drift in the experimental streams. Because of a limited water source, it is difficult to experimentally replicate natural through-flow in a series of 24 experimental units. We predicted that the increased residence time would probably increase exposure of soluble nutrients to microbes and potentially lead to greater nutrient depletion (i.e., limitation) than in the natural stream. To correct for this, nutrient supplements can be added to the inflow to experimental streams to match nutrient loadings in the natural system. If there are differences in major functional groups of invertebrates, we suggest supplementing the experimental streams with invertebrates collected in drift nets from the natural stream.

Thus, at widely separated locations, these modular streams have been configured to mimic local conditions, and comparison of the experimental streams and a natural creek suggest that the experimental systems offer a substantial degree of "realism" while allowing investigators to control many features and obtain good replication. The pools and riffles are sufficiently large that fish have space for normal interspecific and intraspecific interactions, and because of their large size the systems should be less susceptible to the "bottle effects" of small units (sensu Schindler 1998). The microhabitats offer separation of prey from predators or of competitors from each other (which can cause problems in small, simple stream designs). The system allows great flexibility in configuration of units or experimental designs and thus can offer solutions to experimental needs at individual sites. Additionally, similar sets of streams at different geographic locations could encourage coordinated across-site comparisons for many studies of fish biology or ecology.

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