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Decade of Research in Review at the Auburn University Stormwater Research Facility

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Abstract

Sediment remains one of the most commonly occurring pollutants affecting the U.S.'s water bodies, as identified by the United States Environmental Protection Agency (USEPA) (*1*). Construction activities largely accelerate soil erosion and subsequent sediment deposition. The National Pollutant Discharge Elimination System Construction General Permit requires construction operators to implement erosion and sediment control (E&SC) plans to minimize downstream implications from sediment-laden discharge. However, E&SC practices are often designed from "rules of thumb" and lack scientific, performance-based evidence in their design and implementation. The Auburn University Stormwater Research Facility (AU-SRF), previously the Auburn University Erosion and Sediment Control Testing Facility (AU-ESCTF), is an outdoor research center dedicated to evaluating E&SC practices and products commonly used on highway construction projects. Large-scale test apparatuses and methods at AU-SRF are designed to mimic construction site conditions, including rainfall, flow rates, topography, and soil characteristics, to evaluate existing and novel E&SC practices. Since its inception in 2008, AU-SRF has provided small-, medium-, and large-scale testing evaluations for numerous Departments of Transportation and product manufacturers. Findings from controlled testing have continued to inform the selection, design, implementation, and maintenance of E&SC practices used on construction sites and protect downstream waters and infrastructure. In the first decade, AU-SRF has directed 13 research projects and produced more than 30 peer-reviewed publications and 100 professional presentations. As AU-SRF grows into its second decade and efforts reach outside of the southeastern region, the mission to advance knowledge through E&SC research and development, product evaluation, and training remains constant. This review synthesizes the research produced from large-scale testing at AU-SRF to date and presents ongoing projects.

Keywords

infrastructure, roadway design, hydrology and hydraulics and stormwater, erosion, general, runoff, scour, stormwater facilities, stormwater management, stormwater quality

Sediment remains at the forefront of detrimental pollutants entering the U.S.'s waters. An estimated 3.9 billion tons (3.5 billion metric tons) of sediment is discharged from construction sites into U.S. water bodies annually (*2*). This is enough to entirely fill Lake Guntersville, the largest Alabama Lake and prized largemouth bass fishery, with 26 ft (8 m) of sediment. Sediment and sorbed pollutants (e.g., heavy metals, nutrients, fertilizers, petrochemicals, construction chemicals) discharged from construction sites affect downstream water quality. These consequences may include, but are not limited to: (*a*)

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increased siltation and turbidity, which hinders aquatic habitats, feeding, and reproduction, (*b*) reduced conveyance capacities leading to flooding, and (*c*) poor public perception and economic pressure from decreased recreation and increased treatment costs (*3*).

Under the Clean Water Act of 1972, the National Pollutant Discharge Elimination System (NPDES) Construction General Permit (CGP) was created and requires stormwater pollution prevention plans (SWPPPs) to be implemented on construction projects exceeding one acre (0.4 ha) in disturbance (*1*). The SWPPP includes a comprehensive plan for the design, installation, and maintenance of erosion and sediment control (E&SC) practices, many of which have been historically used without performance data. Traditionally, rules of thumb were used in E&SC design, and accepted as "best" management practices; however, failed practices and management techniques led to decreasing water quality and increased regulation. The risk of hefty fines and stop-work orders for poor stormwater and pollution management from enforcement agencies ignited testing, research, training, and education within the E&SC field. Initial testing and research efforts emerged through field testing, but researchers quickly realized unpredictable weather events and contractor activities inhibited repeatable, reliable, scientific-based results. While these field studies provided a starting point for E&SC practice testing, McLaughlin et al., Fang et al., Zech et al., and Donald et al. all acknowledge the challenges incurred during field testing (*4–7*). In addition to these studies, Kaufman, and Chapman et al. also called for credible, scientific results when designing and implementing E&SC plans (*8*, *9*).

A handful of laboratories, including those at TRI Environmental, Penn State University, North Carolina State University, Texas A&M Transportation Institute, the University of Illinois Urbana-Champaign, and the Auburn University Stormwater Research Facility (AU-SRF) (previously the Auburn University Erosion and Sediment Control Testing Facility [AU-ESCTF]) have created controlled environments for large-scale testing of E&SC practices. These testing facilities aim to mimic field conditions for repeatable, scientific-based design, installation, and maintenance of stormwater management practices. Tests conducted at these facilities are primarily driven by or adapted from test methods set by ASTM or American Association of State Highway and Transportation Officials (AASHTO) (*10–12*).

Over the past decade, AU-SRF has substantially contributed to the existing knowledge base within the E&SC industry through more than 30 peer-reviewed publications, 100 professional presentations, and annual training events and workshops. As AU-SRF enters its second decade, this paper aims to synthesize the research produced thus far and present its ongoing projects and capabilities. Additional E&SC literature exists beyond the bounds of this review and has contributed significant and pivotal scientific findings to the industry. This review intends to document the methods and findings from AU-SRF to inform and promote future stormwater management research for the betterment of the industry and environmental stewardship.

AU-SRF Overview

AU-SRF is an outdoor research center aimed to improve and develop stormwater technologies and strategies, situated at the National Center for Asphalt Technology (NCAT) Test Track Facility in Opelika, AL, U.S. It was designed and constructed in 2009 to evaluate E&SC practices implemented by the Alabama Department of Transportation (ALDOT) during roadway construction, but hosts research projects for additional state highway agencies and product manufacturers. Researchers at AU-SRF have designed sediment, flow, and rainfall introduction apparatuses to evaluate the design, installation, and maintenance of ditch checks (DC), inlet protection practices (IPP), sediment basins, sediment barriers (SB), and erosion control practices. The findings from these projects have been presented in academic journals, technical reports, conference proceedings, reflected in Department of Transportation (DOT) standards, and communicated within the industry at annual in-person training events and continuously through social media platforms.

Since its inception, AU-SRF has aimed its mission to create "environmental stewards within the construction industry by developing improved E&SC stormwater technologies and practices; advancing the body of knowledge through research and development, product evaluation, and training" (*13*). This mission is a conglomerate of three primary focus areas: (1) research and development (R&D), which occurs through large-scale, performance-based testing; (2) product evaluation, conducted through third-party, standardized testing methods; and (3) training at hands-on field days and workshops for knowledge and technology transfer. Researchers at AU-SRF are constantly engaged with the industry and identify industry needs through field and training events, professional organizations and meetings, mentorship, and connections with former graduate students who entered the workforce.

AU-SRF recently entered its second decade, and the area and capabilities of the outdoor laboratory were expanded. The once 2.25 acre (1.00 ha) facility recently gained an additional 7.5 acre (3.04 ha) through expansion activities. The expansion included two new storage ponds to increase the original water storage volume from 73,000 to 253,993 ft^3 (2,067 to 7,192 m^3). AU-SRF before

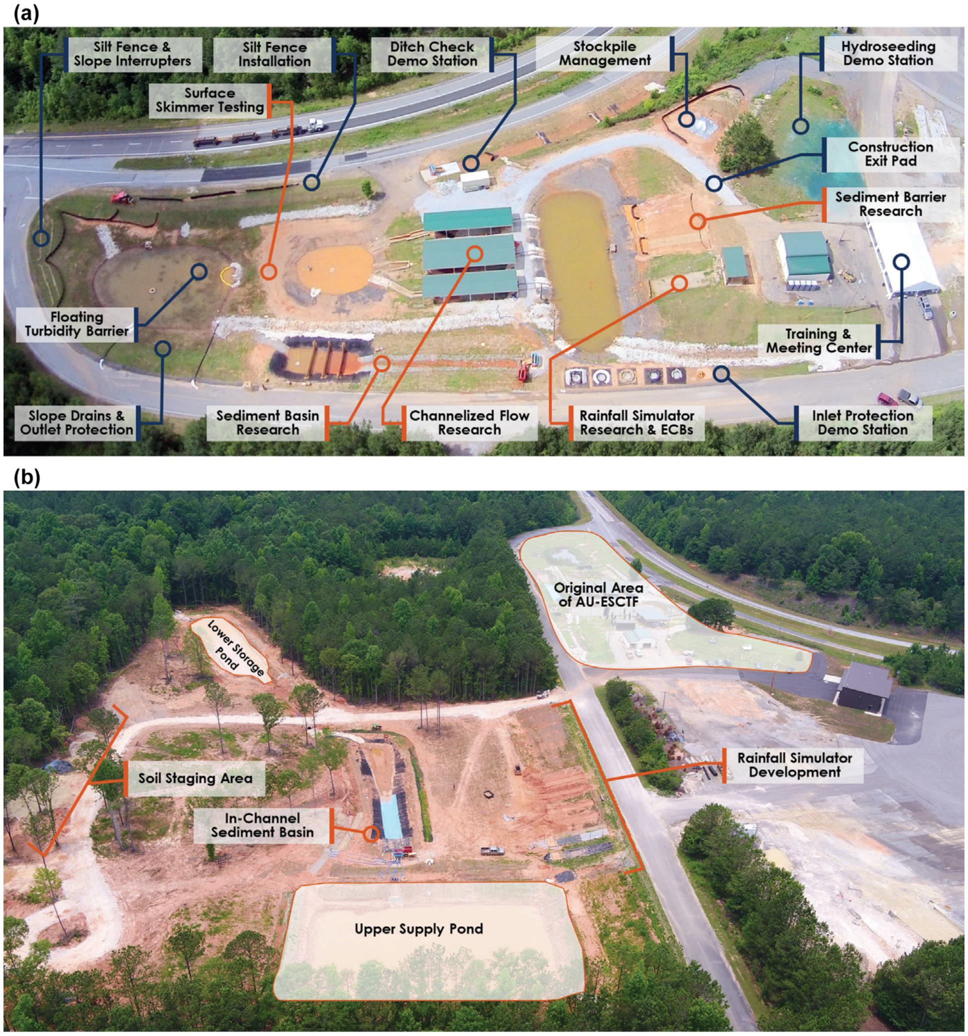

Figure 1. Auburn University erosion and sediment control test facility: (*a*) before expansion, and (*b*) post expansion (2021).
Note: AU-ESCTF = Auburn University Erosion and Sediment Control Testing Facility; ECB = Erosion Control Blanket.

and after the expansion is pictured in Figure 1, *a* and *b*, respectively.

Erosion and Sediment Control Research

This review incorporates the existing, formative literature generated from, and associated with, AU-SRF and presents ongoing projects and capabilities. The projects reviewed are listed in Table 1.

Sediment Barriers (SB)

SBs, commonly referred to as perimeter controls, envelop disturbed areas as a last line of defense before site discharge. SB projects at AU-SRF have ranged from small- to large-scale testing (*2*, *6*, *12*, *14–19*, *23*, *24*, *29*).

In the year leading to the development of AU-SRF, researchers began investigating silt fence (SF) as an SB. Design guidance suggested that SF include tiebacks, or J-hooks, to avoid flow bypass and minimize erosion at the toe of installed fences; however, there was no quantitative evidence of its effectiveness. An intermediate-scale (1:6) testing apparatus was developed to compare a standard installed SF and an SF with tiebacks. The model was 8 by 8 ft (2.4 by 2.4 m) and situated at a 3H:1V slope. A rainfall intensity of 3 in./h (7.6 cm/h) was uniformly applied to a fully saturated silty sand soil to compare erosion and sediment capture exhibited by the standard SF and SF with J-hook. The average sediment discharge from the standard SF and SF with J-hook installations were 13,912 g and 1,455 g, respectively. The SF with J-hook acted as a temporary detention basin and provided

Table 1. Summary of the Reviewed Literature

Practice	Author/year	Test type	Topic
Sediment barriers	Zech et al. (*14*)	Small-scale	Evaluation of silt fence tie backs
	Zech et al. (*15*)	Method	Silt fence tie back design method
	Zech et al. (*6*)	Field	Field evaluation of silt fence tie backs
	Bugg et al. (*3*)	Large-scale	Development of large-scale sediment barrier testing apparatus and methodology
	Bugg et al. (*16*)	Large-scale	Evaluation of silt fence installations
	Whitman et al. (*17*)	Large-scale	Evaluation of wire-backed and nonwoven silt fence installations
	Whitman et al. (*18*)	Large-scale	Evaluation of innovative and manufactured sediment barrier products
	Whitman et al. (*19*)	Large-scale	Evaluation of silt fence dewatering board
	Whitman et al. (*18*)	Small-scale	Development of geotextile testing for silt fence applications
	Liu et al. (*20*)	Model	Silt fence design excel tool
Ditch checks	Donald et al. (*7*)	Large-scale	Development of large-scale ditch check testing apparatus and methodology
	Donald et al. (*21*)	Large-scale	Evaluation of wattle ditch checks
	Donald et al. (*22*)	Large-scale	Evaluation of silt fence ditch checks
	Donald et al. (*23*)	Method	Hydraulic method for ditch check evaluation
	Whitman et al. (*24*)	Small-scale	Hydraulic performance evaluation of wattles
	Schussler et al. (*25*)	Field	Field evaluation of wattle and silt fence ditch check installations
Inlet protection/catch basin	Perez et al. (*26*)	Large-scale	Development of large-scale inlet protection practices testing apparatus and methodology
	Perez et al. (*27*)	Large-scale	Evaluation of inlet protection practices
	Basham et al. (*28*)	Large-scale	Development of large-scale catch basin insert testing apparatus and methodology
Sediment basin	Fang et al. (*5*)	Field	Field evaluation of Alabama DOT sediment basin
	Perez et al. (*29*)	Large-scale	Development of large-scale sediment basin testing apparatus and methodology
	Perez et al. (*30*)	Large-scale	Evaluation of sediment basin with lamella settler
	Liu et al. (*31*)	Bench- scale	Optimization of bench-scale lamella settlers
	Perez et al. (*32*)	Model	Sediment basin design excel tool
	Schussler et al. (*25*)	Field	Field evaluation of Iowa DOT sediment basins
Erosion control	Shoemaker et al. (*33*)	Small-scale	Evaluation of anionic polyacrylamide as erosion control
	Ricks et al. (*34*)	Small-scale	Evaluation of mulches and hydromulches as erosion control
	Ricks et al. (*35*)	Large-scale	Development of large-scale rainfall simulator
Unmanned aerial vehicle	Perez et al. (*26*)	Case study	Unmanned aerial vehicle erosion and sediment control site inspections
	Kazaz et al. (*36*)	Case study	Object detection of stormwater practices using unmanned aerial systems
Other	Perez et al. (*26*)	Method	Selection of erosion and sediment control based on regional hydrology

Note: DOT = Department of Transportation.

3.6 times the storage volume provided by the standard installation. Temporary detention allowed sedimentation to occur, which provided more treatment than filtration, as previously hypothesized (*14*).

Following this small-scale research effort, SF tiebacks were evaluated on a 600 ft (183 m) section of a 3H:1V fill slope on an ALDOT construction site in Auburn, AL. A 300 ft (91 m) linear SF segment and 300 ft (91 m) SF segment with tie backs were installed next to each other and observed for field performance during four storm events ranging in rainfall depths of 0.4–2.5 in. (1.0–6.4 cm). The tieback system distributed the total sediment load between the six tieback sections and prevented erosion at the toe of the slope; however, the linear SF segment had concentrated flow at the toe of the fence, resulting in erosion and downstream scour. Failure was expected for the linear SF segment if not maintained (*6*).

Zech et al. developed a method to design and place SF tiebacks along the perimeter of a construction site (*15*). The method implemented the Soil Conservation Service (SCS) curve number method to estimate construction site runoff volume from a storm. The storage capacity of SF tiebacks could be compared with the runoff from the given drainage area. This method provided designers information on the adequacy of the SF included in E&SC plans (*15*). Perez et al. expanded methods from Zech et al. for efficient sizing methods of E&SC practices based on Technical Release–55 (*15*, *16*). Geographic information system (GIS) mapping was used to collect information on regional hydrology, such as rainfall and soil curve number. Multiple linear regressions were used to predict storm volumes, peak flow rates, and 30, 60, and 90 min peak volumes. Such models would minimize extensive hydrologic analysis but allow E&SCs to be selected and sized according to site characteristics.

While the J-hooks proved to enhance sediment capture, researchers cautioned that the increased storage would increase hydrostatic pressure on the SF and could result in catastrophic failure (*14*, *15*). Subsequent large-scale testing of SBs quantified this impact and provided structural and dewatering improvements. A large-scale testing apparatus was developed at AU-SRF, which included a simulated flow and sediment introduction system. Trash pumps deliver water from a supply pond to an equalizing tank with a weir, where valves are used to achieve the desired flow depth and associate rate. Sediment is introduced using a hydraulic-driven conveyor belt. The calibrated flow and sediment are mixed in a trough, and the sediment-laden flow is applied to a 20 ft (6.1 m) wide test slope. The 3H:1V impervious test slope was constructed of sheet metal with several diversion vanes to ensure well-mixed water and sediment delivery. A 12 ft by 20 ft (3.7 m by 6.1 m) earthen section was exposed upstream of the installed practice to represent field-like conditions. The test setup provided space to simulate design criteria for 0.25–0.50 acre (0.10–.20 ha) per 100 ft (30.5 m) of installed SBs. The SB testing apparatus is shown in Figure 2 below (*2*).

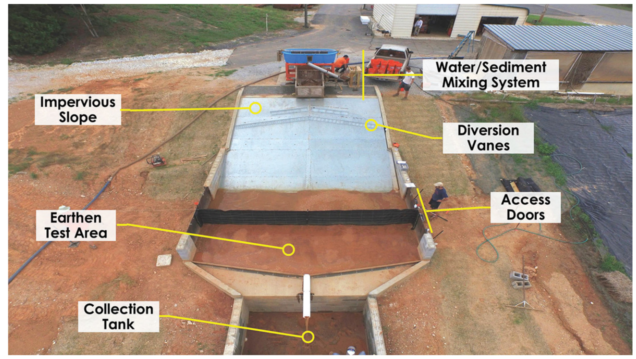

Figure 2. Sediment barrier (SB) testing apparatus.

Flow and sediment introduction were modeled using historical rainfall data from a 2-year, 24 h storm applied to a determined drainage area with an associated curve number. With this information, the peak 30 min discharge was determined and used with the Modified Universal Soil Loss Equation (MUSLE) with the other required parameters, including volume of runoff, peak flow, erodibility, length-slope, cover management, and erosion practice factors.

Analyzed parameters included structural integrity monitored through photographs, erosion and sediment deposition tracked in topographical surveys, ponding depth, pool length, discharge flow rates, turbidity, and total suspended solids (TSS) of water quality samples from four locations. Water sampling locations were: (1) on test slope, (2) immediately upstream of SB, (3) immediately downstream of SB, and (4) at discharge pipe (*2*).

After developing the apparatus, Bugg et al. conducted testing on ALDOT SF installations: (*a*) manual trenched and (*b*) sliced installation of a wire-reinforced geotextile (*16*). The ALDOT standard included a 32 in. (81.3 cm) tall geotextile trenched or sliced into the ground and connected to steel woven wire reinforcement with galvanized C-rings. The wire backing was attached to studded 0.95 lb/ft T-posts, which was lighter than AASHTO standards, with aluminum wire ties. Posts were spaced the maximum allowable 10 ft (3 m) on-center. The Alabama Soil and Water Conservation Committee (AL-SWCC) SF was also tested. This installation implemented a woven, polypropylene-reinforced SF and a 2 by 2 in. (5.1 by 5.1 cm) hardwood stake configuration, spaced 4 ft (1.2 m) on-center, installed to a height of 24 in. (*16*).

Sediment retention for each of the three installations was 82.7, 66.9, and 90.5%, respectively. The two ALDOT installations experienced structural failure during simulated rain events. In each failure episode, the center post deflected, causing overtopping of the impounded stormwater. The deflection in the steel post hindered the impoundment capability, thus limiting sedimentation. When compared with the AL-SWCC trenched SF, the hardwood posts did not deflect. In addition to post material, the AL-SWCC installation had post-placement at 4 ft (1.2 m) on-center, compared with ALDOT's 10 ft (3 m), which may have also aided in maintaining the structural integrity. The maintained structural integrity provided adequate time for sedimentation. Additionally, the woven geotextile used in the AL-SWCC installation had a lower flow-through value, which aided impoundment; however, the lower flow-through rate increased hydrostatic forces acting on the SF (*16*).

Continued large-scale testing was conducted in the SB apparatus at AU-SRF, evaluating eight modifications of wired-backed, nonwoven SF installations (*17*). The performance of the ALDOT standard evaluated by Bugg et al. was used as the performance baseline (*3*). Variations to the standard included decreasing geotextile height, increasing T-post weight, decreasing post spacing, and adding a trench offset. Each installation was tested in three 30 min tests. Of the modifications, an installation with a fence height of 24 in. (61.0 cm), anchored with T-posts spaced 5 ft (1.5 m) on-center, and offset 6 in. (15.2 cm) downstream of the trench performed best. A total of 93% of sediment was retained with 0.18 ft (0.004 m) post deflection. Whitman et al. named this installation the "heavy-duty SF" (HDSF), which is referenced again in a subsequent comparison study of SB in 2019 (*17*, *18*). Whitman et al. concluded that increasing T-post weight and decreasing spacing increased SF performance (*17*).

Whitman et al.'s 2019 study evaluated manufactured SB practices, including two manufactured SF systems, three nonproprietary sediment retention barrier (SRB) installations, and three manufactured SRBs in the SB apparatus at AU-SRF (*17*). The HDSF was used as the study baseline (*17*). The two manufactured SF systems included a Georgia DOT Type C and multi-belted SF (MBSF). Compared with the HDSF, impoundment depths decreased by 25% and 55%, and flow increased by 27% and 45%, respectively, for the GDOT Type C and MBSF. GDOT Type C and MBSF sediment retention was 90% and 85%, respectively. Whitman et al. considered all tested systems and concluded that impoundment depths of 1 ft (0.3 m) or greater consistently retained 90% of sediment; however, impoundment depths of greater than 1.5 ft (0.5 m) had no increase in sediment retention capability (*18*). SRBs were the only products in the study to improve water quality (*18*).

Whitman et al.'s study aimed to design and evaluate an SF that maintained its sediment retention and water quality standard but dewatered at a controlled rate to relieve increased hydrostatic pressure (*19*). This study also examined support posts for structural integrity and developed guidance for adequate post spacing. The large-scale testing apparatus at AU-SRF was used to evaluate and compare performance between the HDSF and an alternative installation. The alternative installation implemented the same technique but had an additional component: a 24 by 24 in. (31 by 61 cm), 0.75 in. (1.9 cm) thick, plywood dewatering board. Four 1 in. (2.5 cm) dewatering orifices were drilled along the centerline of the plywood board every 3 in. (7.6 cm) above the ground surface. A V-notch weir was cut along the top of the board, with its invert at 18 in. (45.7 cm) above the ground. A geotextile underlay with riprap was installed at the back toe of the dewatering board to minimize downstream scour. SF installations were compared for sediment retention, water quality, and effluent flow rate (*19*).

The SF installation, including the dewatering board, exhibited 96% sediment retention by volume. Despite the dewatering board decreased dewatering time from 24 + h to 4 h, the sediment retention by volume was not adversely affected. The sediment retention of the dewatering board installation proved to be consistent with the average sediment retention (91%) of SF systems previously evaluated by Whitman et al. (*17*, *23*). The average turbidity was 944 nephelometric turbidity units (NTU) with the dewatering board installed, compared with ˜1,000 NTU without a dewatering board. However, there were differences exhibited during dewatering. The standard installation was blinded with sediment after repeated loading and thus had water retention exceeding 24 h, whereas the dewatering board allowed the alternative installation to dewater in 4 h. In addition to the dewatering board, five post types were evaluated in an automatic load testing machine to determine maximum post spacing. Three metal T-posts with unit weights of 0.95, 1.25, and 1.33 lb/ft (01.4, 1.9, and 2.0 kg/m), respectively, and two hardwood posts with cross-section dimensions of 1.3 by 1.6 in. (3.3 by 4.1 cm) and 1.8 by 1.8 in. (4.6 by 4.6 cm), respectively, were each tested three times, for a total of 15 tests. Structural analyses indicated that maximum spacing for these posts should be 3.9, 5.91, 7.9, 4.9, and 4.92 ft (1.2, 1.8, 2.4, 1.5, and 1.5 m), respectively (*19*).

Following Whitman et al.'s studies on design and installation improvements, researchers constructed a small-scale flume test to evaluate effluent flow rates, sediment retention, and water quality impacts of varying SF geotextiles (*18*, *19*). While ASTM D5141 exists to evaluate the filtering performance of geotextiles, flow and sediment introduction rates are limited (*9*). Whitman et al.'s modified method applied regionally specific hydraulic and sediment loading expected for the peak 30 min of the 2-year, 24 h storm to test realistic parameters. Previous AU-SRF studies found that filtering is a secondary function of SFs, and most sediment is removed through sedimentation (*14*). Thus, filtering performance tests like ASTM D5141 were not indicative of the entire treatment provided by a given geotextile. Two nonwoven and three woven SF geotextiles were individually installed in a 4 by 16 by 3 ft (1.2 by 4.8 by 0.9 m) polypropylene-lined wooden flume. Water and sediment introduction occurred on a 3H:1V slope that transitioned to 1%, where the SF installation was located. Flow introduction followed the methodology from Bugg et al. (*3*). However, sediment was introduced by hand at a rate of 7.5 lb/min (3.3 kg/min). All geotextiles tested had reported effluent flow rates ranging from 93 to 324 gallon per minute (GPM)/ft^2 (3,784 to 13,183 liter per minute (LPM/m^2) during ASTM clean water tests. During Whitman et al.'s sediment-laden tests, flow rates were reduced to a range of 0.86 to 10.45 GPM/ft^2 (35.2 to 425.7 LPM/m^2) during testing and 0.18 to 0.96 GPM/ft^2 (7.4 to 39.2 LPM/m^2) during dewatering. Data collection indicated that flow rates were 43% lower for nonwoven than woven geotextiles and had average sediment retention of 97% and 91%, respectively. Water quality analyses indicated that, during flow, 46% of turbidity reduction occurs as a result of sedimentation, whereas turbidity reduction during dewatering occurs through filtration (19%) (*24*).

SB research at AU-SRF has developed testing methods to evaluate SF design, and installation and performance-based metrics to evaluate support posts and geotextiles used in SF applications. AU-SRF SB research revealed that SBs provide primary treatment through sedimentation, which guided design improvements, including the HDSF, dewatering board, and selection of support posts and SF material. These design improvements are now reflected in the ALDOT standard drawings. For ease of implementation, Liu et al. developed an Excel-based design tool for SF SBs. Regional hydrologic and volumetric parameters are considered, as well as yield size and estimate maintenance requirements for SF SB segments in linear, j-hook, and c-configurations (*20*).

Ditch Checks (DC)

Check dams (CDs), are installed within conveyance channels to intercept flow, decrease flow velocity, and create impoundments of subcritical flow. Such impoundments reduce erosive forces and shear stress along the channel surface and promote sedimentation. DCs are commonly assembled from various materials, including SF, wattles, riprap, sandbags, hay bales, and other proprietary products (*20*). AU-SRF designed and installed a testing apparatus to evaluate channelized flow E&SC practices. The research includes methods for hydraulic performance characteristics and installation methods for wattle and SF DCs (*10*, *23*).

The large-scale channelized flow apparatus at AU-SRF, shown in Figure 3, was designed considering ASTM D7208-06 (*11*). The trapezoidal test channel had a longitudinal slope of 5% with a depth of 1.5 ft (0.5 m) and top and bottom widths of 13 ft (4 m) and 4.0 ft (1.2 m), respectively. In total, the channel is 40 ft (12 m) long with a 25 ft (7.5 m) sheet-metal-lined section and 15 ft (4.6 m) earthen section for practice installation. Flow introduction followed the methods as described in Bugg et al. (*3*). Eight cross-sections spaced 3 ft (91.4 cm) apart lengthwise, and eight cross-sections spaced 1 ft (30.5 cm) apart were used to mark points for erosion and sedimentation, water depth, and velocity measurements (*7*).

In total, seven wheat straw wattle installations were tested with varied staking configurations, geotextile underlays, trenching, and ground anchoring. The control installation was the previous ALDOT standard: concave upstream wattle, secured through the media with wooden stakes every 2 ft (0.6 m), and driven at least 1.5 ft (0.5 m) into the ground. After testing, results indicated that the subcritical impoundment length was improved by 99%, including teepee staking, geotextile underlay, and sod stapling. Results from this testing influenced ALDOT to modify their detail for enhanced impoundment, decreased channel erosion, and increased sediment capture (*7*).

Figure 3. Photo of ditch check (DC) test apparatus.

In continued testing, Donald et al. evaluated the hydraulic performance exhibited by five wheat-straw-filled, two excelsior-fiber-filled, and one synthetic-fiber-filled wattles. The installation determined as most feasible and effective (MFE) was repeated for each wattle type (*7*). Water depth and velocity measurements were taken once steady-state flow was achieved. Researchers determined that reducing the velocity head and increasing depth defined a DC's ability to impound flow. Results indicated that fill density, rather than material, was the most significant mitigating factor for creating and sustaining impoundments at medium and high flow conditions (*21*).

The methodology described in Donald et al. was replicated to evaluate various SF DC installations (*21*). The baseline installation used ALDOT's standard detail requiring a 45° V-shaped installation, pointed downstream, concave to the flow path. T-posts were to be installed at the center of the V and on either side. Posts were spaced 10 ft (3 m), with a 6 by 6 in. (15.2 by 15.2 cm) trench, wire backing reinforcement, and 32 in. (81.3 cm) above ground height. The ALDOT standard was compared with four other modified installations with varied energy dissipaters, underlays, and dewatering weir at the vertex. The best-performing installation included: a weir, geotextile splash pad and stone energy dissipater, and geotextile underlay pinned to the channel bottom. The ALDOT pinned installation was then subjected to a longevity test with sediment-laden runoff introduced, following the methodology from Bugg et al. (*3*). After six tests in 2 months, pre- and post-test surveys indicated that 91.2% of sediment introduced was retained; however, some erosion occurred downstream of the practice, potentially because of flows from quickly dewatering returning to supercritical flow state (*22*).

The increased height of SF DCs, compared with alternative DCs, allows longer spans of a channel to be protected because of impoundment depth, which minimizes the quantity and cost of DCs needed in a single channel. This research determined that a weir on SF DCs allows the practice to control its discharge to enhance the structural integrity and sediment capture. The weir, splash pad, and appropriate ground anchoring improved structural integrity and were adopted by ALDOT (*22*).

Donald et al. developed a hydraulic performance criterion to compare wattle DCs in varying channel and flow conditions (*23*). The performance considered sub- and super-critical flows to characterize DC performance. Donald et al. plotted the Froude number (F), considering flow velocity, gravity, and hydraulic depth, versus water depth (y) to specific energy (E) ratios (i.e., y/E) for open-channel flow. A third-order polynomial relationship was generated after plotting the data. An inflection point was identified on the curve at $y/E = 0.75$ and F of approximately 0.8. This indicated a change in flow behavior that would improve impoundment and increase sedimentation potential with a decreasing F. This research allowed large-scale test data to be normalized and compared, despite varying flow conditions (*23*).

Building on Donald et al.'s performance criterion, Whitman et al. evaluated the effects of wattle fill material and encasement on hydraulic performance through clean water tests (*23*, *37*). Eight wattles were tested in a hydraulic flume at Iowa State University and classified into one of the four following classes: (C1) least effective at sustaining subcritical flows and had depth and length ratio percent differences less than 20% and 30%, respectively; (C2 and C3) indicated depth percent differences ranging from 10% to 20% and length percent differences ranging from 20% to 30% for C2, and 10% to 20% for C3; (C4) most effective at maximizing subcritical flows with only miscanthus-grass-filled wattles qualifying, with a depth and length percent difference less than 10%. Results suggest that excelsior wattles fall into C1; wheat straw wattles into C2; coconut coir, wood chip, and synthetic wattles into C3; and miscanthus wattles into C4 (*37*).

Considering the DC research at AU-SRF, Schussler et al. conducted a field evaluation of wattle and SF DC installations on an Iowa DOT project (*38*). Wattle installations included the standard excelsior wattles staked through the netting and fill material every 2.0 ft (0.6 m) on-center (*38*). The modified installation incorporated natural fiber underlay pinned to the channel and teepee staking pattern to secure the wattle and minimize buoyancy. The modified installation eliminated undercutting and resulted in a 1,158% increase in sediment retention by volume. The standard SF DC included a geotextile supported by steel T-posts and installed perpendicular to flow. A modified SF DC increased sediment retention by 304% and incorporated design improvements found at AU-SRF, including V-shape with weir and wire reinforcement (*38*).

AU-SRF developed methods to evaluate DC practices, which has led to improvements in installation in ALDOT and beyond. DC test apparatuses at AU-SRF are continually maintained for future DC evaluations.

Inlet Protection Practices (IPPs) and Catch Basin Inserts (CBIs)

Storm drains collect and convey stormwater runoff to a subsurface system. This subsurface drainage system is installed and connected early in construction phases and leaves inlets susceptible to erosion and collection of sediment. IPPs are required during construction to impound stormwater, prevent erosion, and promote sedimentation, to minimize the offsite transport of sediment. In post-construction applications, CBIs are manufactured systems installed into existing storm drain inlets or catch basins to treat runoff before it enters the subsurface system, to minimize clogging or transport of pollutants. Large-scale testing apparatuses for both IPP and CBIs have been constructed at AU-SRF considering ASTM D7351-07 and are shown in Figure 4, *a* and *b*, respectively (*12*).

An IPP test channel was designed and installed at AU-SRF according to ALDOT median stormwater conveyance channels. The channel measured 44 ft (13.4 m) in length and 19 ft (5.8 m) in width, with a 4 ft (1.2 m) channel bottom, and is situated at a 5% slope where 20 ft (6.1 m) of the channel is sheet metal, and 24 ft (7.3 m) is earthen with a 4 ft (1.2 m) storm drain inlet structure.

A water introduction system was designed to achieve and monitor flow rate, as described in previous sections. Sediment was introduced through a 6.0 in. (15.2 cm) grain auger, calibrated to meet the desired introduction rate. Data collection included pre- and post-test channel surveys, ponding length and depth, flow velocity, and water quality (turbidity and TSS). In tests conducted for ALDOT, an IPP was subjected to a flow rate of 1.25 ft^3/s (0.035 m^3/s) and sediment loading rate of 46.7 lb/min (21.2 kg/min) for a 30 min test to mimic the peak flow of a 2-year, 24 h storm in Alabama (*27*, *39*). ALDOT IPPs, including aggregate, sandbag, SF, and wattle barriers, were evaluated in the test channel at AU-SRF. Installation techniques varied to improve structural integrity and thus sediment retention (*27*).

The standard ALDOT aggregate IPP detailed a 1.5 by 5.5 in. (3.8 by 14 cm) raised lumber board installed 2 ft (61 cm) outside the inlet. A rock berm with 1 ft (30.5 cm) top and 1H:1V slopes installed on top of a geotextile underlay served as the IPP. Clean water tests resulted in a dewatering time of 2 min. The MFE installation replaced the lumber with concrete blocks and

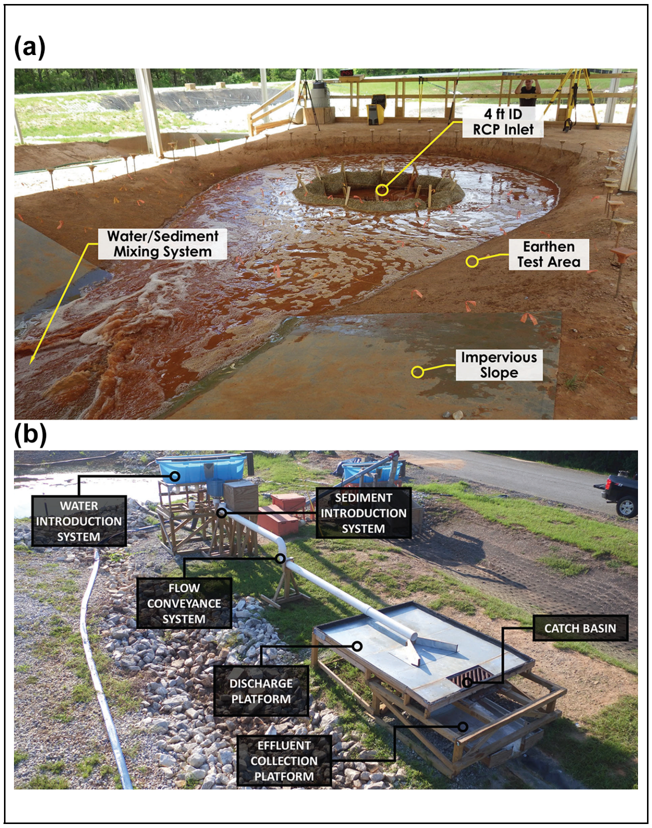

Figure 4. Test apparatus: (*a*) inlet protection practices (IPP) test apparatus, and (*b*) catch basin insert (CBI) test apparatus.
Note: RCP = Reinforced Concrete Pipe.

wrapped the blocks and rock in geotextile. These improvements increased the impoundment length by 110% and increased the dewatering time to 13 min (*27*).

The ALDOT sandbag IPP called for 8 ft (2.4 m) diameter stacked sandbags, ensuring no gaps. To minimize dislodging of sandbags and short-circuiting, an underlay was added under the installation. In addition, the diameter was decreased to 6 ft (1.8 m), and the middle row of sandbags was rotated 90°. This installation increased the impoundment length by 171% and dewatered in 120 min (*27*).

The industry-typical SF IPP created a 7 by 7 ft (2.1 by 2.1 m) square around the inlet and used T-posts and wire back to support the geotextile. During testing, the installation failed because of the hydrostatic pressuring, causing cave-in. The SF IPP installation included lumber bracing along the top perimeter of the SF square with diagonal bracing. The SF was blinded with sediment, so a dewatering board was added to aid dewatering and decreased the time 24 + h to 90 min (*27*).

The last tested IPP was a wattle barrier. The ALDOT standard wattle IPP called for a 20 in. (50.8 cm) diameter wattle installed in a 5 ft (1.5 m) diameter circle around the inlet and secured by wooden stakes spaced 3 ft (1 m) apart. During testing, the wattle became buoyant and allowed the flow to pass underneath. A geotextile underlay was added, and the wattle was secured to the channel bottom with sod staples and stakes to combat the buoyancy. Impoundment length was increased by ten times, with a dewatering time of 9 min (*27*). This study aided ALDOT and DOTs with similar IPPs to improve standard designs and selection of IPP type.

In later testing, Ohio Department of Transportation (ODOT) was interested in evaluating CBIs for post-construction applications. The Ohio EPA specified that TSS must be reduced by 80% from post-construction practices, but lacked scientific data for approved designs and products (*40*). Researchers at AU-SRF designed an apparatus (Figure 4*c*) where a manufactured ODOT Type 3A catch basin frame was installed (*41*). The flow was introduced following the procedure in Bugg et al. but implemented a V-notch weir (*3*). A 0.75 in. (1.91 cm) feeder controlled sediment introduction. Flow and sediment mixed when introduced into a 20 ft (6.1 m) long, 6 in. (15.2 cm) diameter, polyvinyl chloride (PVC) pipe at a 2% slope. The pipe surfaced on the 8 by 8 ft (2.4 by 2.4 m) drainage platform, even with the top of the catch basin. Raised plywood was installed to mimic a curb (*28*).

Flow and sediment introduction rates were adopted from the ODOT Location and Design Manual, Volume Two, which used the rational method with a curve number of 0.9 and rainfall intensity of 0.65 in./h (16.5 mm/h), but can be adapted for other geographical locations (*42*). Researchers selected a small, medium, and large drainage area for testing. CBIs were evaluated for sediment retention and TSS reduction. A nonproprietary CBI was developed from nonwoven geotextile with an apparent opening size of 300 μm for preliminary testing. The bag also had an overflow cutout. TSS removal was 57%, 53%, and 49% at the low, medium, and high flow conditions, respectively. Overflow conditions were reached in the medium and high flow conditions, reducing efficiency because of the discharge of untreated water. This research developed an apparatus and testing methods to analyze proprietary and nonproprietary CBIs quantitatively.

Research on IPPs and CBIs has informed designers nationwide on practice efficiency and improved design. Enhanced performance of such practices minimizes sediment and pollutants reaching the U.S.'s subsurface drainage system and minimizes intensive maintenance and water treatment (*28*).

Sediment Basin

Sediment basins are a temporary sediment control practice typically employed on construction sites to detain sediment from stormwater runoff before discharge. Sediment basins are heralded in the construction industry for effective sediment capture; however, design and

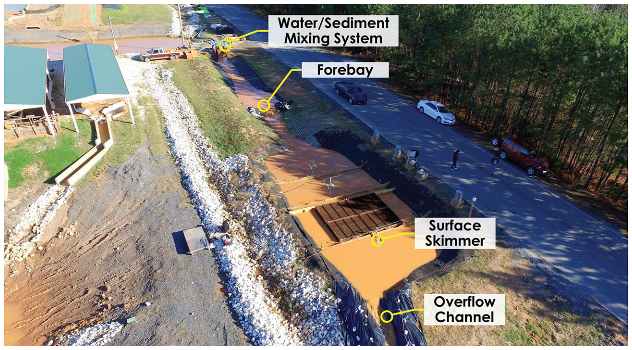

Figure 5. Sediment basin at the Auburn University Stormwater Research Facility (AU-SRF).

installation techniques vary nationwide. In the past decade, researchers at AU-SRF have conducted field-, large-, and small-scale projects to evaluate the performance of sediment basins.

Before developing a sediment basin testing apparatus at AU-SRF, Fang et al. monitored a sediment basin during highway construction for 3 months in Franklin County, AL. The basin was designed to ALDOT standards, incorporating a surface skimmer for dewatering, three coir baffles for flow dissipation, and flocculant introduction in the inflow channel for increased capture, and followed United States Environmental Protection Agency (USEPA) sizing criteria of 3,600 ft^3 of volume per drainage acre (252 m^3/ha). Automated water sampling was employed at inflow, within, and discharge locations of the basin for turbidity and TSS analysis, but programming the samplers to characterize the inflows and performance of the basin accurately was challenging. Changing site conditions caused runoff rates, volumes, and durations to vary (*5*). Limitations to the monitoring effort included unpredictable site conditions, representative sampling, and reliance on contractors for construction, instrumentation, and treatment within the sediment basin, highlighting the need for controlled, large-scale testing of sediment basins to accurately depict performance.

To eliminate influence from unpredictable field variables, a large-scale sediment basin was designed and installed at AU-SRF to evaluate performance with reproducible results. The installed basin had a total volume of 2,790 ft^3 (79.0 m^3) and is shown in Figure 5. The 3,600 ft^3/acre (252 m^3/ha) design criterion was applied, and flow and sediment rates were calculated to mimic the local 2-year, 24 h rain event. Modeling the SCS Type III local 2-year, 24 h storm event over a 0.242 acre (0.0.98 ha) area resulted in a flow rate of 1.50 ft^3/s (0.042 m^3/s) for a 30 min experimental test. The peak discharge from this storm was plugged into the MUSLE to estimate sediment yields based on individual storm events. The estimated soil loss resulted in 1,348 lb. (611 kg), (44.9 lb./min [20.4 kg/min]) for 30 min (*43*).

During large-scale testing, the sediment basin performance was evaluated when incorporating baffles, an excavated sump, and lamella settling technology using a triplicate testing regime. Each component was installed in a clean and empty basin and tested three times (filling and dewatering completely). Data collection during testing included analysis of water quality, flow rate, basin storage, sediment deposition, and sediment sampling for particle characterization to evaluate the performance of the basin in response to each installation. After the MFE design was selected, the basin was tested in filling and overflow conditions. Preliminary results indicated that the excavated sump upstream of the basin had no significant effect on the performance of the capture efficiency of the basin. However, the area allowed for capture and storage of sediment within the channel where dredging and maintenance activities would be easier to perform. The second treatment, modified coir baffle system with reduced percent open areas (POA) (10.9% versus 21.7% POA), was less effective in treating turbidity within the basin than the standard baffle. Testing high-rate lamella settlers within the third bay, in both an (*a*) upward flow and (*b*) parallel flow, provided turbidity reduction of 18.2% and 29.0%, respectively (*30*).

Following the increased turbidity reduction exhibited in the basin by the lamella settlers, three small-scale reactors were designed to study optimized settling with lamella plates. The three reactors included: (a) control with no plates, (b) reactor with nine plates at 1.0 in. (2.5 cm) spacing, and (c) reactor with 18 plates spaced 0.5 in. (1.3 cm). Lamella plates were 9.8 by 10 in. (25 by 25.4 cm) and installed at a 55° angle. Five synthetic soils were individually mixed with water and introduced into the tanks to achieve one of three study residence times (0.5, 1.0, and 1.5 h) at three different concentrations (500 mg/L, 1,000 mg/L, and 5,000 mg/L). Turbidity reduction and particle size distribution were recorded to optimize the design of the small-scale settlers. The highest turbidity removal rates were exhibited using a 1.5 h residence time with 18 plates spaced 0.5 in. (1.3 cm). Turbidity reduction ranged from 62.8% to 90.0%. A full-factorial method model was developed to predict turbidity reduction from inflow concentration, plate spacing, and residence time using the measured data. This study is expected to guide designers in implementing full-scale lamella settlers in sediment basins and provide turbidity reduction predictions (*31*).

As a product of the large-scale sediment basin testing at AU-SRF, Perez et al. developed an open-source, hydrologic-based design tool, SEDspread. This tool allows designers to select site-specific parameters, including sizing factor (i.e., 2-year, 24 h storm, or 3,600 ft^3/acre

[252 m^3/ha]). Additionally, soil and storm data were derived from geospatial data for an entered U.S. mailing zip code. The tool then produces the basin capacity, configuration, and dewatering rate to achieve regulation. If desired, SEDspread contains a section for baffle design, where the user can indicate the number of bays and post spacing. The tool uses this user data, with the basin geometry, to determine the length of each bay, the number of required posts, the height of the baffle, and the total length of the required material. A case study was performed on two local construction site sediment basins in Auburn, AL, which compared site basin design and implementation to SEDspread outputs. The two studied basins were sized for 3,600 ft^3/acre (252 m^3/ha) criteria and volumetrically undersized for the 2-year, 24 h storm, according to SEDspread, by a factor of three, a similar conclusion reached during fieldwork by Fang et al. and Perez et al. (*5*, *32*).

Sediment basin research from AU-SRF has been incorporated into the ALDOT standard drawings and the AL Handbook for E&SC and serves as an example for basin design throughout the U.S.. Outside of Alabama, SEDspread's unique capability to be customized with geospatial data allows designers nationwide to create and verify sediment basin designs. Following research at AU-SRF, Schussler et al. field monitored a single in-series, in-channel sediment basin design for Iowa DOT, which indicated negligible turbidity and TSS reductions (*25*). Researchers aimed to incorporate and test design improvements on an in-channel basin during construction; however, timeline, contractor, and area constraints did not allow for installation and evaluation (*25*). Instead, researchers at AU-SRF are continuing work on the in-channel sediment basin design and product testing on post-construction detention dewatering mechanisms.

Erosion Control (EC)

In addition to the many sediment control practices researched at AU-SRF, hydromulches and rolled EC products have been investigated at small, medium and large scales. EC practices aim to prevent the dislodgment of soil by covering or stabilizing bare soil.

When beginning research on EC products at AU-SRF, a small-scale rainfall simulator apparatus was constructed to simulate the 2-year, 24 h storm in central Alabama. Rainfall was simultaneously applied to two 4 by 2 by 0.25 ft (1.2 by 0.6 by 0.08 m) plots, which mimicked a 3H:1V fill slope. The plots were packed to 95% density with native Alabama soils. The plots were treated with various doses of anionic polyacrylamide (PAM) (15, 25, and 35 lb/acre [16.8, 28, and 39.2 kg/ha]) through two treatments: dry and semi-dissolved solutions, and subjected to four 15 min rainfall events, totaling 4.4 in. (11.2 cm), and compared with a bare-soil test for sediment retention and turbidity reduction. Dry PAM, applied at a rate of 35 lb/acre (39.2 kg/ha), reduced soil loss by 50% and turbidity up to 97%. The semi-dissolved PAM, applied at the same rate with a 48 h drying period, reduced soil loss by 76% and turbidity by 69%. While both applications provided increased treatment compared with the bare-soil test, researchers suggested the dried PAM performed better as an SC, and semi-dissolved PAM performed better as EC, as indicated by soil loss and turbidity reduction values (*33*).

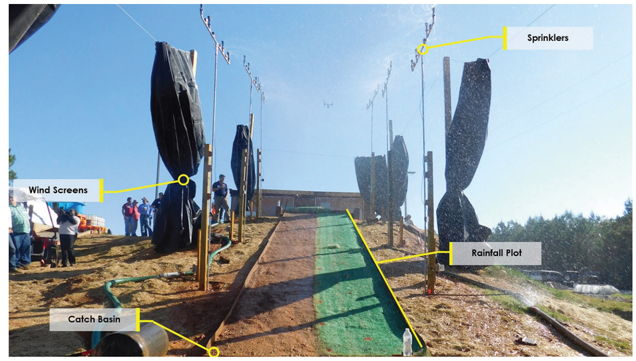

Figure 6. Rainfall simulator plot.

Using the same rainfall simulator apparatus and analysis methods, researchers continued testing on two mulches and four hydromulches. All hydromulches were applied according to manufacturer recommendations. The treatments to the baseline, bare-soil test included: (1) conventional straw, crimped; (2) conventional straw, tackified; (3) wood-fiber hydromulch (2,000–2,500 lb/acre [2,241–2,802 kg/ha]); (4) straw and cotton hydromulch (2,000 lb/acre [2,241 kg/ha]); 5) cotton-fiber-reinforced matrix hydromulch (3,500 lb/acre [3,923 kg/ha]); and 6) bonded-wheat-fiber matrix hydromulch (3,000 lb/acre [3,362 kg/ha]). When compared with the bare-soil test, the mulches reduced turbidity by 80%, 98%, 85%, 92%, 95%, and 99%, respectively, and soil loss by 96%, 98%, 94%, 97%, 99%, and 100%, respectively (*34*). Turbidity and sediment loss reduction values indicated that mulches were an effective EC; however, researchers advised that future EC studies be conducted through full-scale testing. As AU-SRF grew, a 40 by 8 ft (12 by 2.4 m), 3H:1V slope was constructed with ten sprinklers to supply uniform rainfall, as shown in Figure 6 (*35*).

When designing the first plot at AU-SRF, researchers considered ASTM D6459-15, the standard for determining the performance of rolled EC products under rainfall simulation (*44*). The standard applies the Revised Universal Soil Loss Equation (RUSLE) to determine the soil erodibility (*K*) of the soil used and cover management factor (*C*), provided by a rolled product. The rainfall simulator at AU-SRF targeted to meet the rainfall intensities of 2.0, 4.0, 6.0 in./h (50.8, 101.6, and 152.4 mm/h) for 20 min each, consecutively, for a total test time of 60 min (*25*). Four 14 ft (4.27 m) sprinklers were installed on each length side and one sprinkler on each width side to achieve this. Windscreens were installed to prevent the influence of outside environmental elements. During calibration testing, the sprinklers provided rainfall intensities with relative errors ranging between 1.17% and 4.00%, and uniform rainfall distributions of 85.7% to 87.5% (*35*). Data analysis from product testing on the slope is ongoing.

In addition to the current rainfall slope, six 3H:1V plots and six 4H:1V plots are being constructed. The plots will be filled with three different soil types to analyze EC products for their application on various topographies and soils. Construction is expected to finish in 2022.

Technology Transfer and Training

In addition to scholarly contributions, AU-SRF disseminates stormwater knowledge gained from research through various channels, including social media platforms, such as LinkedIn™, Twitter™, YouTube™, Facebook™, and in-person conference and training events. Since 2014, AU-SRF has opened annually to practitioners to teach design, installation, and maintenance methods in a combination of classroom and hands-on activities. The training event includes a 1.5-day hands-on installer training event that includes a half-day of classroom instruction and a full day of field instruction, and a 1-day field day where runoff events are simulated in the large-scale apparatuses. This allows practitioners to observe the impoundment and sediment retention efficiencies of varying E&SC installations and products during sediment-laden flow. Demonstration areas include: hydroseeding; construction exit pad and housekeeping; stockpile management; SBs; erosion control blankets; DC practices; channelized flow; surface skimmers; floating turbidity barrier; SF installation; perimeter control techniques and slope interrupters; slope drains, outlet control, and level spreader; sediment basin; inlet protection practices; and pipe inlet protection (*45*).

More than 750 participants have attended training events at AU-SRF, including regulators, inspectors, supervisors, installers within DOTs, county and city agencies, private builders and engineers, the environmental community, and citizens. As a result of pre- and post-training event surveys distributed to participants, Perez et al. found that technical knowledge level was increased by an average of 82% and 36% for the hands-on and field day training, respectively (*45*). Classroom activities and demonstration areas are continually developed and advanced with ongoing research at AU-SRF to fulfill the training portion of the mission statement.

Conclusions

Since its inception, AU-SRF has promoted a desire to improve how construction stormwater is managed in Alabama. An initial desire to challenge or confirm, through scientific testing, traditionally accepted "best" management practices created learning opportunities to create more effective practices. Over the past decade, an intentional effort to communicate research findings and advance the state of practice in Alabama and beyond has produced practical and implementable outcomes. Despite project sponsorship being primarily supported by ALDOT, the contributions of AU-SRF have been shared far beyond state borders and have influenced design and research decisions. Project findings have been presented at conferences targeting designers, practitioners, and academics; demonstrated at training events; and disseminated publicly on social media platforms, such as LinkedIn™, Twitter™, YouTube™, Facebook™. While there are still many states with traditional construction stormwater management approaches, many "rule of thumb" E&SC designs are being phased out with the availability of empirically based design guidance.

Perez et al. report perspectives from ALDOT, including "ALDOT has decided that it must go beyond mere regulatory compliance to realize its (environmental) vision" (*45*). Additional takeaways state that research and training from AU-SRF have led to "effective and economical means of protecting Alabama waters." Although ALDOT first adopted SF DCs with dewatering weirs and wattles with alternative staking patterns and underlays, Schussler et al. field evaluated similar installations during the expansion of Highway U.S. 30 in Tama County, Iowa, for 5 months (*38*). Sediment retention from these enhanced DCs was significantly more than the standard SF and wattle DC installations, which were parallel-monitored. The observations and findings from this field study resulted in implementable improvements for DC design and installations to aid in the structural integrity of practices and stabilization of conveyance channels. As a result, Iowa DOT began implementing the modified DC designs on several projects in the second half of 2020.

Researchers at AU-SRF are cognizant that DOTs are constrained to balance a cost-conscious budget and adequate stormwater management program and consider the additional costs when designing modified practices and testing. Schussler et al. conducted a cost-performance analysis of various DC installations, which indicated the cost per cubic foot of sediment retained was less for the modified practices than traditional practices (*25*). Future studies aim to include similar analyses. There are many additional challenges in the industry that require investigation, including, but not limited to, practice performance in treatment train and flocculants in the stormwater industry. As the facility enters its second decade, researchers aim to address these issues, build on existing knowledge, and begin research on post-construction stormwater treatment measures.

This paper reviewed the formative literature on the development of AU-SRF. While this review covers the completed, publicly funded research, it is not all-inclusive of the efforts made at AU-SRF and additional facilities to progress the E&SC field. Additional literature exists on unmanned aerial vehicles for E&SC inspections (*26*, *36*) but was not included in this review. Ongoing research is being conducted including additional SB systems, detention practices, EC, and flocculant applications. As AU-SRF grows into its expansion and efforts reach outside of the southeastern U.S., the mission to advance knowledge through research and development, product evaluation, and training remains constant.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: M.A. Perez, W.N. Donald, J.B. Whitman, W.C. Zech, and X. Fang; data collection: M.A. Perez, W.N. Donald, J.B. Whitman, W.C. Zech, and X. Fang; analysis and interpretation of results: J.C. Schussler, M.A. Perez, W.N. Donald, J.B. Whitman, W.C. Zech, and X. Fang; draft manuscript preparation: J.C. Schussler, M.A. Perez, and B. Fagan. All authors reviewed the results and approved the final version of the manuscript.

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