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The cover image is aerial view of University of Minnesota East and West Bank campuses and the Mississippi River. Photographer Patrick O'Leary. Image via University of Minnesota.

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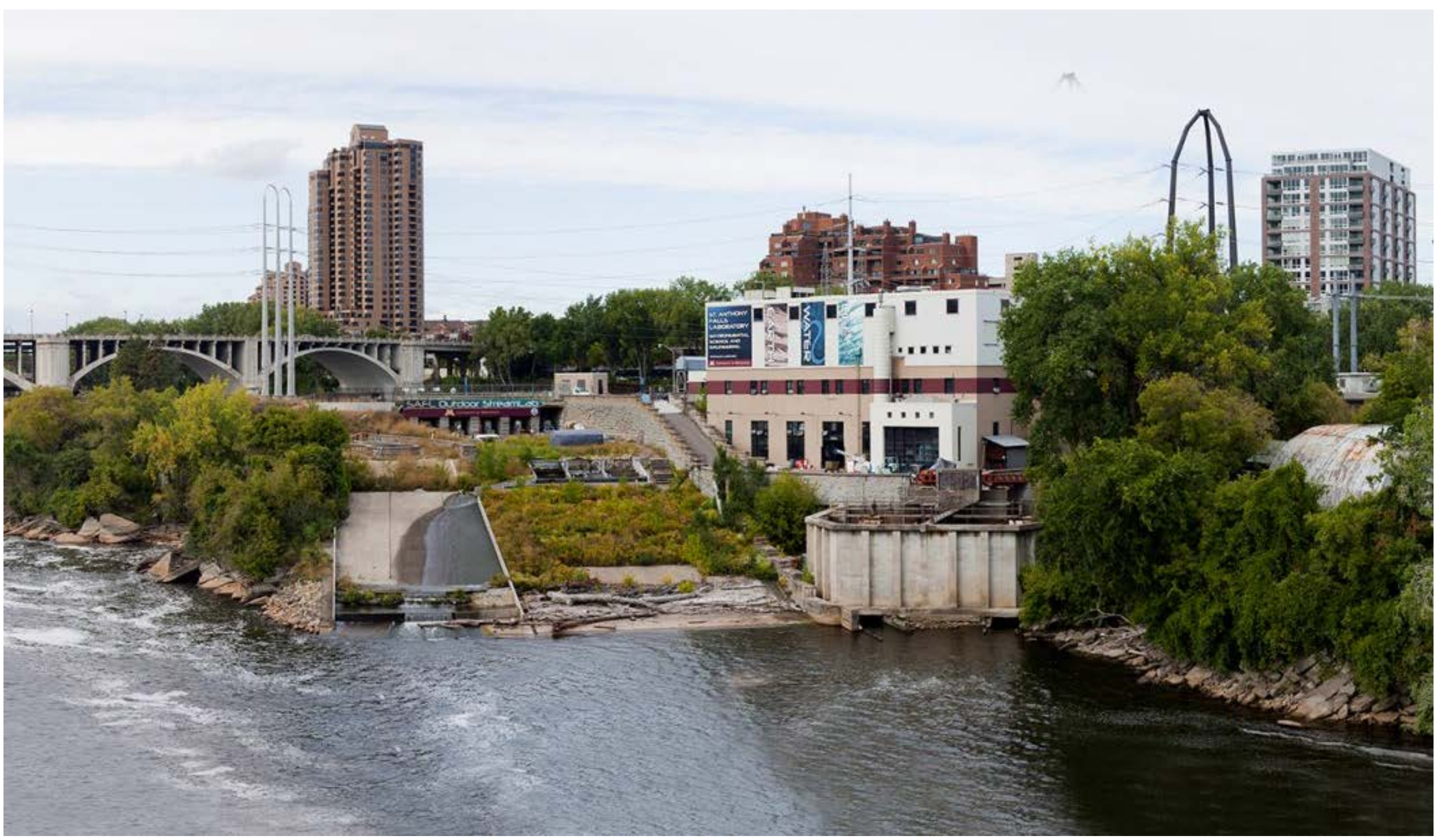
FEATURE

THE LAB ON THE RIVER: THE ST. ANTHONY FALLS LABORATORY AT THE UNIVERSITY OF MINNESOTA

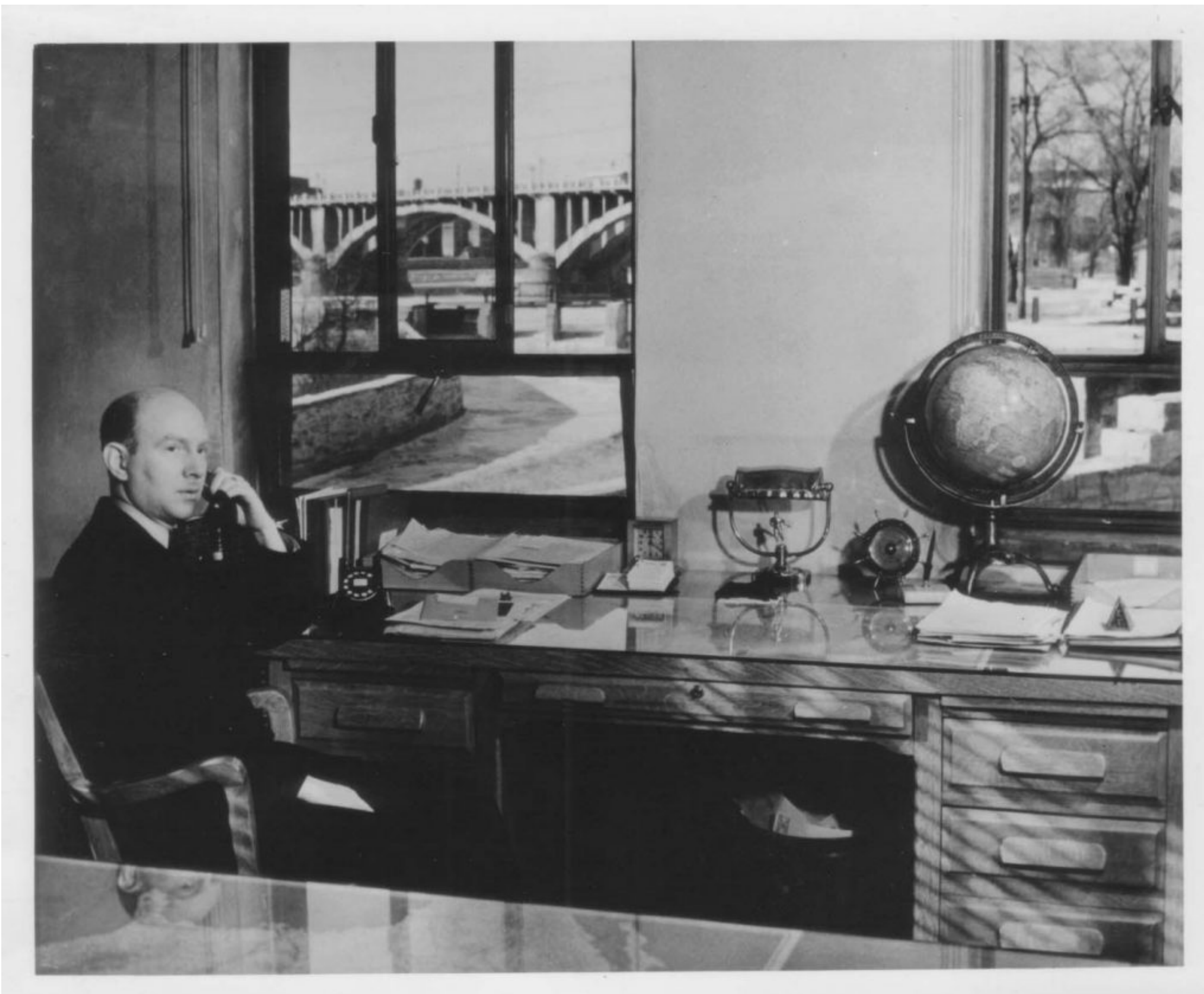
By Barbara Heitkamp

When viewing the Minneapolis skyline, one generally doesn't think of hydraulic research laboratories. Indeed, from the Stone Arch Bridge, or historic Main Street, or the balconies at the Mill City Museum or Guthrie Theater, the St. Anthony Falls Laboratory (SAFL) building looks rather nondescript. Yet, this facility, associated with the College of Science and Engineering at the University of Minnesota, is an interdisciplinary research facility whose work is focused at the intersection of fluid dynamics and major societal challenges in energy, environment, and health. SAFL can divert up to 2,200 gallons per second (300 cubic feet per second or cfs.) of Mississippi River through its collection of channels and basins for scientific research.



The St. Anthony Falls Laboratory, taken from the Minneapolis Stone Arch Bridge. Photographer Patrick O'Leary. Image courtesy of SAFL.

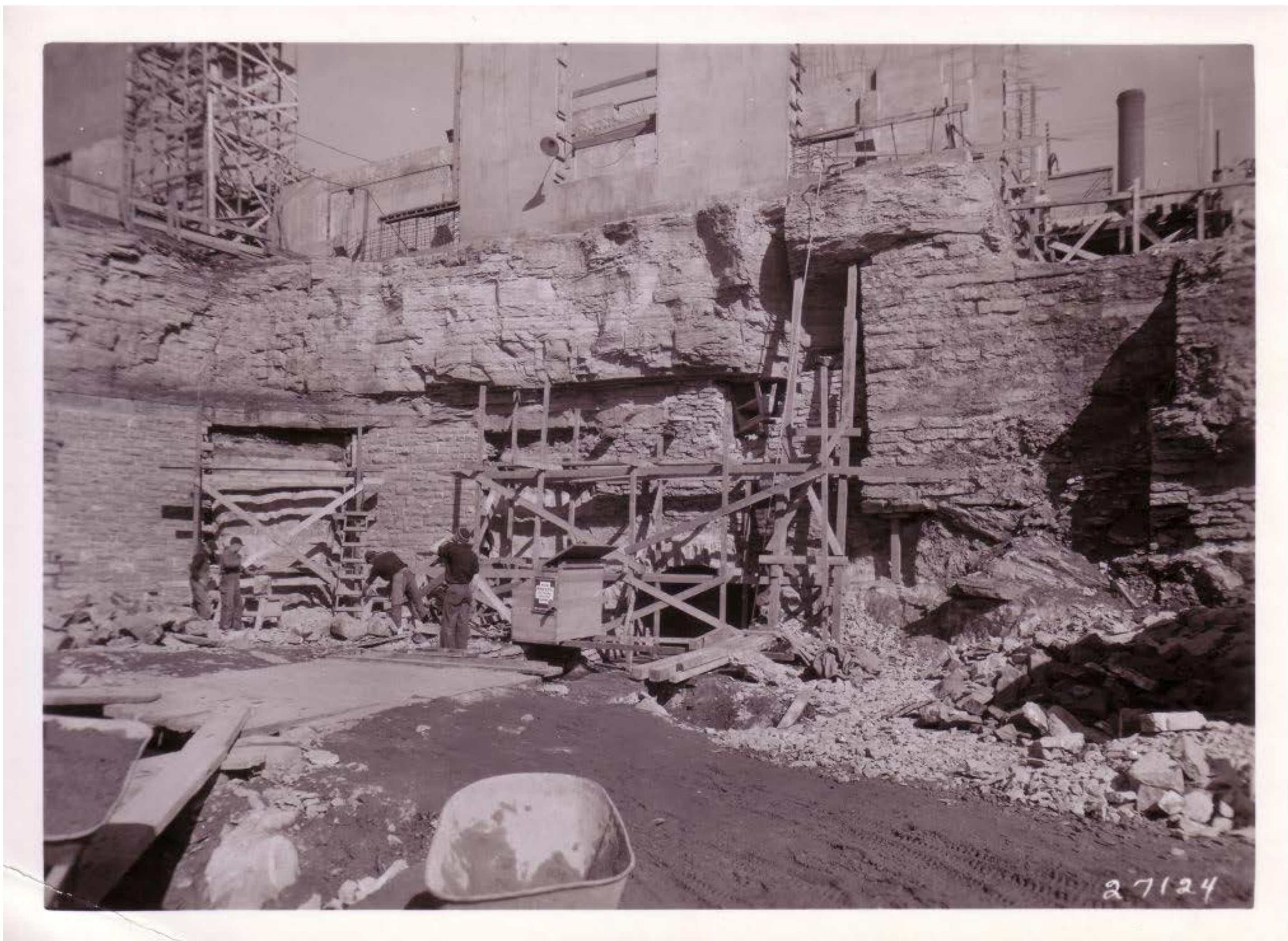
The St. Anthony Falls skyline, with the St. Anthony Falls Laboratory mid-right. Photographer Patrick O'Leary. Image courtesy of SAFL.



Lorenz Straub, SAFL's architect and first director, in his office at the St. Anthony Falls Laboratory. Image courtesy of SAFL.

Laboratory on a River : Idea to Reality

The thought of placing a hydraulic research laboratory at the St. Anthony Falls started as early as 1908. Recognizing the potential value of the natural 50 ft. drop of the St. Anthony Falls, University of Minnesota civil engineering professor F.H. Bass sent a letter to the dean indicating that the site, then the abandoned East Side Pumping Station, could serve the University as "an unexcelled hydraulic laboratory." Aside from some follow-up from that initial letter, that is where the story ended until the 1930s. Then, a new driver entered the scene in the form of civil engineer Lorenz G. Straub.



Construction of the laboratory included excavation into the native Plateville Limestone on site. Image courtesy of SAFL.

SAFL designer and director Lorenz Straub interacting with a physical model of the proposed laboratory. Image courtesy of SAFL.

Dr. Lorenz Straub came to the University of Minnesota in 1930 as an associate professor in the Department of Mathematics and Mechanics. He had received his PhD at the University of Illinois in 1927 and spent the last two years in Europe as a Freeman Traveling Fellow, studying the concept of using laboratory modeling to engineer solutions to river hydraulics problems. His eagerness to embrace experimental research in a laboratory setting reflected a growing national mindset of the time. In 1927, the Mississippi River flooded catastrophically, highlighting the need for refined river control methods. In 1929, the English translation of the German edition of *Hydraulic Laboratory Practice* was released, in which the editor wrote: “Strange to say, in view of the size of our rivers and the importance of the problems they represent in navigation and flood control, there is not yet in America even one laboratory equipped for the study of river problems; and still more strange, the military engineers to whom American river and harbor problems have been given to keep them employed in times of peace, have not yet awakened to the utility of or understanding of research of this kind” (Freeman 1929, 17–18; St. Anthony Falls Laboratory 2014).

SAFL’s Main Channel Flume, which extends the entire length of one floor and can run up to 300 cfs. See sediment transport in this flume in the video included below. Image courtesy of SAFL.

Straub was eager to revive the idea of a hydraulic research laboratory at St. Anthony Falls, but it wasn't until several years later that a viable funding source came in to play. In May 1935, President Roosevelt signed an Executive Order creating the Works Progress Administration (WPA). The program's goal was to implement projects that would employ the maximum number of workers in the shortest time possible. Straub moved quickly, helping orchestrate the legal proceedings between the City of Minneapolis, the University and the Northern States Power (NSP) Company to secure the land and water rights at the site mentioned by Professor Bass 27 years earlier, as well as submitting building drawings for the proposed laboratory. In February 1936, Straub received a letter from the WPA stating that construction could proceed (St. Anthony Falls Laboratory 2014).

It would be two years before laboratory construction was completed, especially given the significant challenges of the construction site itself. The laboratory was carved from the bluff formation at Hennepin Island, with approximately 30,000 cubic yards of bedrock and large boulders excavated on site. Such a large excavation was necessary so the operating floors of the laboratory would be below the level of the river above the falls, so when diverted, the river water would flow through the building without the need of pumps (St. Anthony Falls Laboratory 2014).

The official dedication of the St. Anthony Falls Laboratory occurred on November 17, 1938. The new building showcased an impressive array of flumes, channels, and basins ready for use in experiments and hydraulic research. Straub worked with the U.S. Engineers Office to bring a model study to SAFL whose purpose was to test and determine what effect proposed upper and lower dams and locks at St. Anthony Falls would have on navigation conditions in the Mississippi River. The Mississippi River model, a 1:50 physical model of the Mississippi River from the Hennepin Avenue Bridge to just above the Washington Avenue Bridge, was likely one of the most famous models built at the laboratory. It stayed in place until the mid-1950s (St. Anthony Falls Laboratory 2014).

See video of Transport of sediment by flowing water *from SAFL's Main Channel Flume.*

SAFL's Evolution over Seven Decades

While the new laboratory was an educational facility associated with the University, Straub's vision was that SAFL's legacy would be shaped by its commitment to not only education and basic research, but also applied research, that is, service to the profession. Thus, the laboratory hosted not only students and classes, but welcomed cooperation and partnerships with government and industry. Several federal agencies were drawn to the new laboratory in its first decades, with some agency scientists setting up residence in the laboratory itself, including the Soil Conservation Service (now the Agricultural Research Service), the St. Paul District of the Army Corps of Engineers, and the U.S. Geological Survey. Other partners included the Navy Department, the Minnesota State Department of Highways, Northern States Power Company, and others. In SAFL's first five decades, the majority of SAFL's research income would be from applied research projects. Much of that income would come from the Navy (particularly in the 1950s), the private sector, and other government agencies.

Many of the early research projects at SAFL included physical modeling of hydraulic structures, with Straub attracting local, national, and international projects. He built and tested physical models of the Mangla Dam on the Jhelum River in Pakistan and the Guri Dam in Venezuela. He tested fish ladder and coffer dam designs for the Columbia River system in the Pacific Northwest. Straub became recognized internationally for his ability to diagnose and recommend solutions to hydraulic engineering problems, with one national magazine dubbing him the “River Doctor.” SAFL researchers also conducted basic and applied research in numerous areas of fluid mechanics, including air-water mixture flow, non-Newtonian fluid flow, sediment transport, and boundary layers.

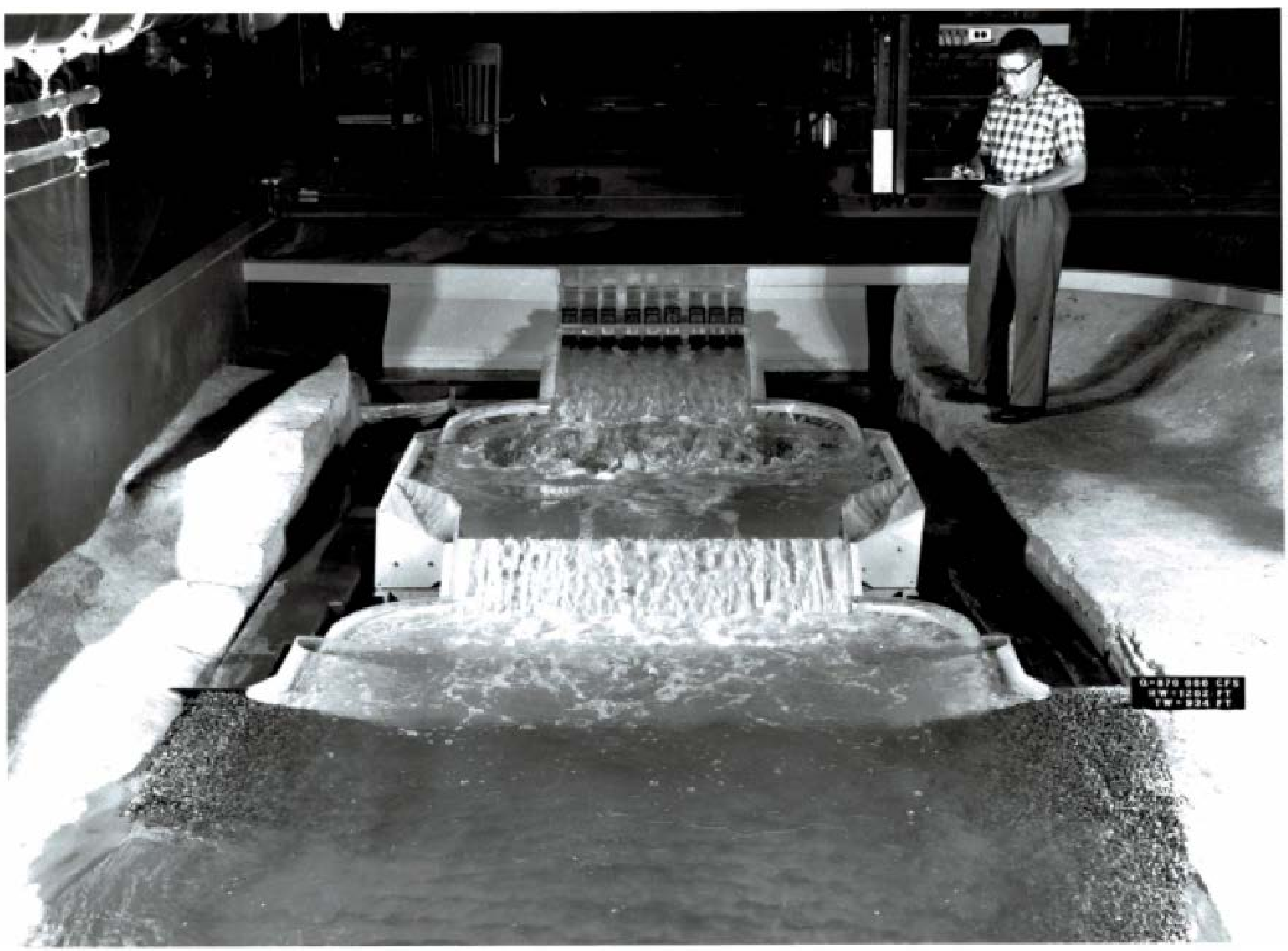
Selection of Historic SAFL Projects

SAFL has hosted over 500 major research projects in its nearly 80 years. Read below to learn more about selected projects.

SAFL researchers take measurements of the Priest Rapids physical model. The dam was constructed on the Columbia River in 1961. Image courtesy of SAFL.

Mangla Dam, West Pakistan

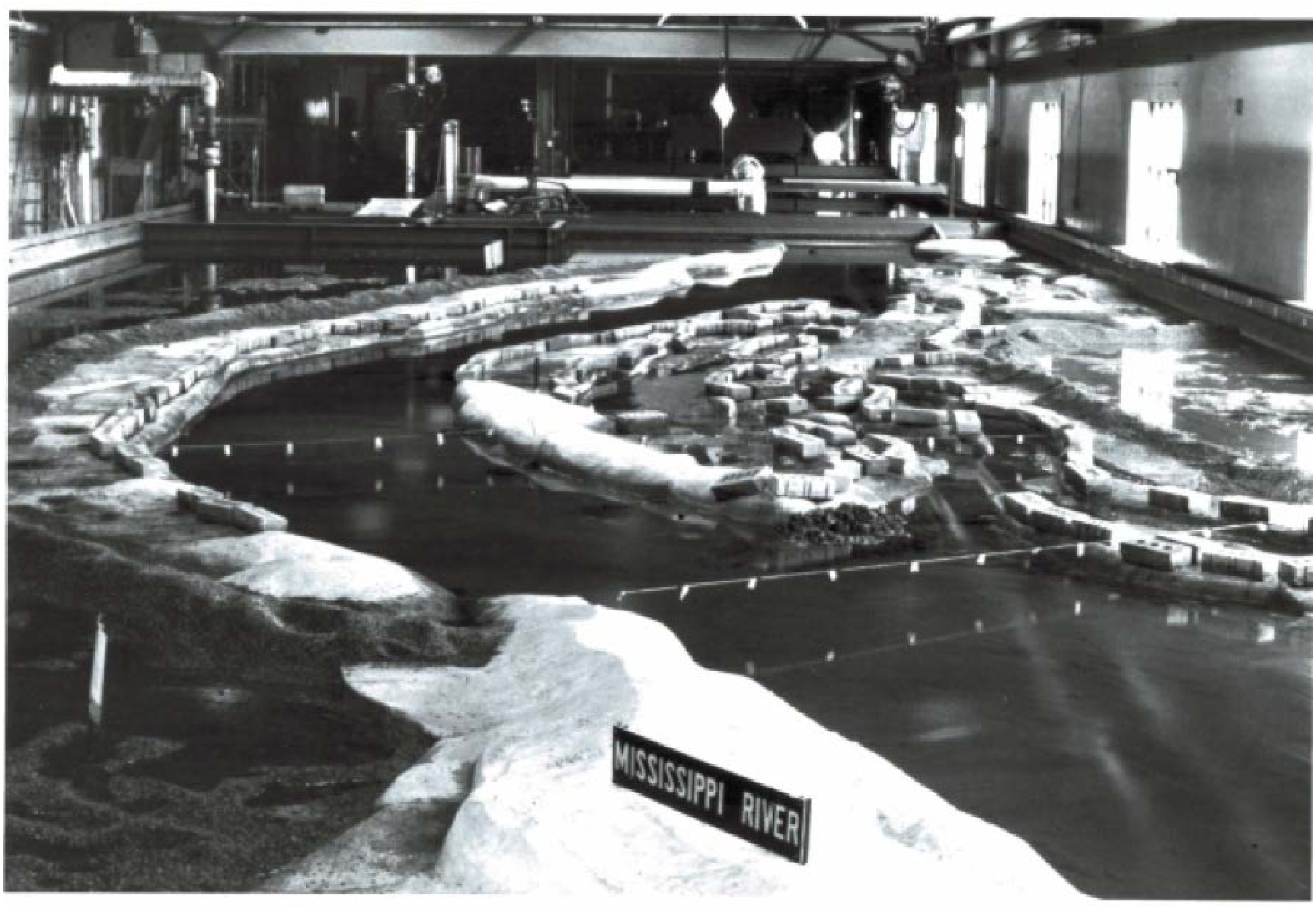
Mangla Dam in West Pakistan on the Jhelum River was designed to provide power and irrigation to the region. This was one of the more extensive and largest hydraulic studies performed at the St. Anthony Falls Laboratory. Initially the spillway was designed to handle 350,000 cfs., but after laboratory and field studies, the final design accommodated one million cfs. Many SAFL personnel contributed to the decade-long project, which began in 1958, and various models and versions of models were tested.



This model of the Mangla Dam shows the basin scheme where the upper basin had been enlarged from its original design to prevent erosion during high flow conditions. Image courtesy of SAFL.

Chippewa-Mississippi River Confluence Model

The Chippewa-Mississippi River Confluence physical model was one of many that utilized the laboratory's large model basin floor. The project, known as the Great River Environmental Action Team, was established to develop ways to reduce erosion and sedimentation in the Upper Mississippi River system. The team was particularly interested in developing an optimum way to maintain a 9 ft. navigable channel without causing harm to the environment. SAFL researchers built a scale model and tested 8 different conditions of the Chippewa and Mississippi Rivers confluence in Phase I and 14 conditions in Phase II. From the model testing, SAFL engineers were able to caution the U.S. Army Corps of Engineers that a dam being built to capture sediment in the Chippewa River might create scouring and deposition shortly after construction. Instead, they recommended a more effective dredging schedule and wing dam designs that resulted in the most desirable channel depth with no bank scouring.



SAFL's Chippewa-Mississippi River Confluence physical model. Image courtesy of SAFL.

Warm Water Discharge Study

A physical model study of warm water discharge from NSP's Allen S. King plant near Stillwater, Minnesota, was carried out to determine its effect on water temperatures in Lake St. Croix. During plant operations, water withdrawn from near the bottom of Lake St. Croix was used as a coolant, then discharged through a channel near the lake's surface. The study was conducted to determine the shape of the cooling water effluent plume. It took into consideration the momentum of the effluent flow (up to 500 cfs.), its buoyancy relative to the ambient receiving water in the lake, and the crossflow of the river. The extent of lake surface area affected by the warm water discharge was determined by computation of the heat transfer from the water into the atmosphere. Conducted in 1964, this was one of the first studies of its kind in the world, with the methodology newly developed at SAFL. Researchers compared the predicted lake surface temperatures with field measurements made after the power plant was built, and found surface areas affected by cooling water and depth of penetration of warm water below the lake's surface were well predicted.

Physical model of the Lake St. Croix. Image courtesy of SAFL.

SAFL after Straub

Straub served as SAFL's director until his death in 1963. One of his former graduate students, Dr. Edward Silberman, professor of civil engineering, was appointed director. Under his leadership and that of others over the coming decades, SAFL's ability to creatively meet the ever-shifting needs of society emerged as one of its greatest strengths. Beginning in the 1960s, SAFL evolved beyond a focus on hard structures imposed on the natural environment to a broader view that emphasizes restoration and sustainable management, working with natural tendencies rather than seeking to ignore or control them. These developments led to much closer ties between engineering and the natural sciences, especially the Earth sciences and ecology.

From 1963 to 1977, under the directorship of Edward Silberman and Alvin Anderson, SAFL focused on intensifying the already robust naval hydrodynamics research and expanding its basic research in such areas as stratified flows, turbulence, and hydrology. Support from the National Science Foundation (NSF) made expansion into these new research areas possible.

Under Director Roger Arndt (1977-93), the laboratory emphasized the integration of education

The SAFL Wind Tunnel is largely used for wind energy research, including optimization of power from different wind farm configurations. Image courtesy of SAFL.

and basic and applied research, including research in hydraulic and river engineering. Several new faculty were appointed, bringing new research efforts in such areas as water resources and energy, environmental and water quality research, and small hydropower development. In 1988, a large-scale wind tunnel, designed to study the boundary layer effects on natural and/or urban environments, was constructed atop SAFL's original structure. Research funding came from such diverse agencies as the U.S. Navy, NSF, the Department of Energy, and the Legislative Commission on Minnesota Resources.

From 1993 to 2005, Directors Gary Parker and Efi Foufoula-Georgiou sought to broaden the participation of other University of Minnesota researchers, adding new faculty with expertise in geology, eco-biological fluid dynamics, and atmospheric boundary layer turbulence. New research areas and faculty expertise catalyzed the transformation of SAFL from the traditional hydraulic engineering research facility to a hub of progressive interdisciplinary fluid mechanics research that can adapt to the pressing environmental needs of the time. These efforts culminated in 2002 with the creation of the National Center for Earth-surface Dynamics (NCED), an NSF Science and Technology Center devoted to quantitative, transdisciplinary study of the surface environment. During its 10-year tenure, NCED comprised engineers, ecologists, Earth scientists, and social scientists.

The Eolos Wind Energy Field Station consists of a fully instrumented 2.5 MW Clipper Liberty wind turbine and 400-ft meteorlogical tower located in Rosemount, Minnesota. Image courtesy of SAFL.

From 2006 through 2015, under the leadership of Director Fotis Sotiropoulos, SAFL continued its expansion into new interdisciplinary research areas emphasizing renewable energy resources (wind, marine hydrokinetic energy, and biofuels), environmental restoration, and biological and cardiovascular fluid mechanics. The SAFL-led University of Minnesota wind energy research consortium, funded by a grant from the U.S. Department of Energy, led to the development of a major new research facility in Rosemount, MN where the 2.5MW EOLOS wind energy research field station was installed. The SAFL Outdoor StreamLab (OSL), SAFL's most publicly visible facility, was built in 2008 on an abandoned flood bypass channel adjacent to the laboratory. Designed as an experimental stream channel and floodplain system, the OSL represents a step between the laboratory and the field where major components (flow and sediment) can be controlled while allowing natural sunlight to foster a more natural ecological system.

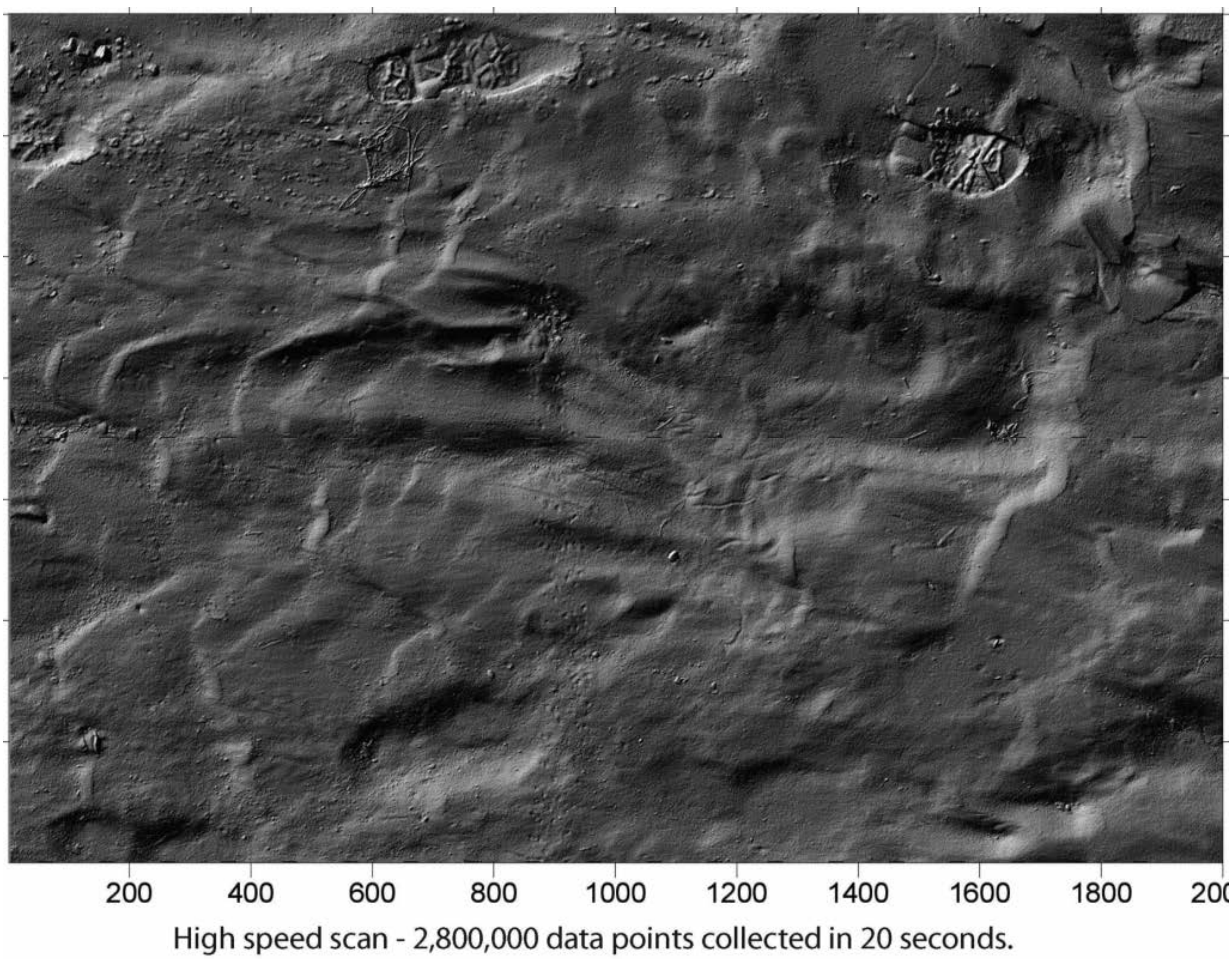
In September 2010, SAFL secured an American Reinvestment Grant from NSF and the University of Minnesota for renovation. The renovation—the first significant renovation since construction in 1938—addressed infrastructure deficiencies and proposed upgrades to key research facilities in the laboratory. The renovation, which took some three years to complete, included basic infrastructure upgrades such as a stair tower and elevator, as well as research facility upgrades like outfitting several SAFL spaces with data

The Outdoor StreamLab (OSL) facility bridges the gap between laboratory and field by allowing control of several parameters (flow, sediment, data collection) while also allowing natural sunlight to drive natural ecological processes. Image courtesy of SAFL.

One of SAFL's data collection carriage systems. Image courtesy of SAFL.

collection carriage systems with 3D surface and sub-aerial scanners capable of taking sub-millimeter resolution measurements.

Since late 2015 Professor Chris Paola, who has been affiliated with SAFL since the early 1980s, has served as interim director. SAFL is currently conducting a search for a new director, who no doubt will continue the tradition of expanding the laboratory's research agenda to address today's societal concerns.



This topographic data, not a photograph, was collected in SAFL's main channel flume using the automated data carriage system. Image courtesy of SAFL.

SAFL Today

Today, SAFL continues to follow its original mission to advance fundamental knowledge in fluid mechanics, benefitting society by implementing such knowledge to develop robust and sustainable engineering solutions to today's environmental problems, and training the next generation of scientists and engineers. The laboratory's vision and mission are well aligned with research trends at the national and state level. Federal and state funding agencies increasingly invest in multi-university, multi-disciplinary research efforts aimed at tackling grand-challenge problems that have the potential to have a direct impact on societal well being (St. Anthony Falls Laboratory 2014).

SAFL research today centers around four major themes:

- Earth surface, water, and life
- Mitigating impacts of global environmental change
- Renewable energy systems
- Biomedical fluid mechanics for personalized health care

All four initiatives are inherently interdisciplinary, involve fluid mechanics as a core expertise, integrate research in the areas where the laboratory has proven strengths and an established record of academic excellence, take advantage of

SAFL Personnel at the Grand Reopening Ceremony in September 2014 after completion of the SAFL Renovation. Image courtesy of SAFL.

the SAFL renovation and our unique laboratory and field-scale facilities, and have the potential to benefit society (St. Anthony Falls Laboratory 2014).

SAFL currently houses 23 permanent research staff, along with 18 faculty members affiliated with departments such as civil, environmental, and geo-engineering, Earth sciences, mechanical engineering, aerospace engineering and mechanics, and ecology, evolution, and behavior. During any given semester, between 40 and 50 students, most of them pursuing graduate degrees, conduct research at SAFL.

Following are a selection of recent river projects that focus around our Earth surface, water, life and renewable energy systems research themes.

Designing Fish-Friendly Culverts

(Contributed by Jessica Kozarek, SAFL Research Associate)

When roads cross small streams and rivers, structures allowing for the passage of water underneath roadways are critical for unimpeded and safe roadway travel. However, when viewed from a fish's perspective, road crossings, and culverts in particular, can alter flow patterns and streambed habitat, creating barriers to movement within a stream network. When stream habitat becomes fragmented, fish have fewer options to manage stressful conditions, and threatened populations face an increased risk of extinction.

One way to address these concerns is to maintain a natural streambed through the culvert to preserve fish and other aquatic organism passage. When designed properly, recessed culverts, where the bottom of the culverts are set below the streambed, allow for flow patterns and habitat characteristics similar to the stream outside of the culvert. However, questions remain about whether the recessed culvert should be filled with sediment or should be allowed to fill in naturally over time to promote the best culvert or stream stability and fish passage capability.

Recent research at SAFL, sponsored by the Minnesota Department of Transportation, looked more closely at this issue by setting up a number of experiments to investigate sediment transport dynamics of recessed culverts in a controlled setting. SAFL researchers used a tilting bed flume to create several 1:8 model streams with three different slopes. Using these models, they tested the effectiveness of two culvert installation methods: one in which the culvert was placed below the streambed but not filled with sediment after installation, and another in which the culvert was filled with sediment after installation. Researchers then used a range of flow scenarios—from baseflow to flood events—to observe the resulting sediment transport dynamics.

Results demonstrated that assuming a recessed culvert will fill with sediment after installation is not appropriate for steep, high-gradient streams and in fact, could lead to scour and channel instabilities upstream of the culvert. Inversely, filling the culvert with sediment as part of the installation process allowed sediment transport through the culvert, maintained natural streambed roughness within the culvert and, most importantly, helped to prevent upstream scour and erosion. Using these observations, a number of design recommendations for recessed culverts were developed for state and local agencies concerned about this issue.

For more information on designing fish-friendly culverts, see the project report.

Experimental set up exploring sediment transport dynamics through culverts. Image courtesy of SAFL.

Sustainable Management of Minnesota Rivers

(Contributed by Jeff Marr, SAFL Associate Director of Facilities and Engineering, and Efi Foufoula-Georgiou, Professor Emeritus of Civil, Environmental, and Geo- Engineering)

SAFL has ongoing research projects focusing on important issues relating to Minnesota's expansive river network. According to the U.S. Environmental Protection Agency (EPA) and the Minnesota Pollution Control Agency (MPCA), the Minnesota River is an impaired system with issues related to high sediment loads, nutrients, and changing hydrology and hydraulics. SAFL has two funded projects underway to support management of this important river basin. The Collaborative for Sediment Source Reduction in the Greater Blue Earth River Basin is a multi-faceted project funded by EPA, MPCA, Minnesota Department of Agriculture, and the Minnesota Agricultural Water Resources Center focused on developing tools for determining the highest value management options to reduce sediment input into the main stem Minnesota River. High levels of sediment in rivers can potentially harm aquatic organisms as well as have a negative impact on recreational use in downstream Lake Pepin. The project seeks to provide tools to help landowners and regulators make informed decisions on how best to mitigate sediment issues on the Minnesota River. Results of the project have culminated in the development of a model that can link sediment delivery to conservation practices. It can estimate the annual cost and sediment load reductions associated with different combinations of conservation practices at a watershed scale. Local, state, and industrial stakeholders, through a user interface, can 'drive' the model to test different management and conservation strategies for use throughout the watershed, and using such data can ideally help build a consensus of where available funds will have the greatest impact in reducing sediment input to the Minnesota River.

A second project centered around the Minnesota River Basin, titled "Climate and human dynamics as amplifiers of natural change," is an NSF Water Sustainability and Climate program project. The effort is focused on identifying areas in the Minnesota River basin that are highly sensitive to human-natural landscape changes. The project identifies "hot spots" in the basin and provides guidance on where best to focus management efforts to avoid the emergence and undesirable effects of these hotspots.

Road Salt and Water Quality

(Contributed by Andy Erickson, SAFL Research Associate)

SAFL researchers in our Stormwater Research group are currently working on two projects related to chloride pollution in Minnesota. The first is examining permeable pavements as an alternative to using salt-based anti-icing and de-icing materials. It is already well known that permeable pavements reduce runoff during storm events and increase shallow groundwater flow, supporting baseflow-fed streams and rivers. During winter months in cold climates, some preliminary studies have shown less ice cover on unsalted permeable pavements compared to conventional asphalt pavements, even when salted. The purpose of the study is to quantify

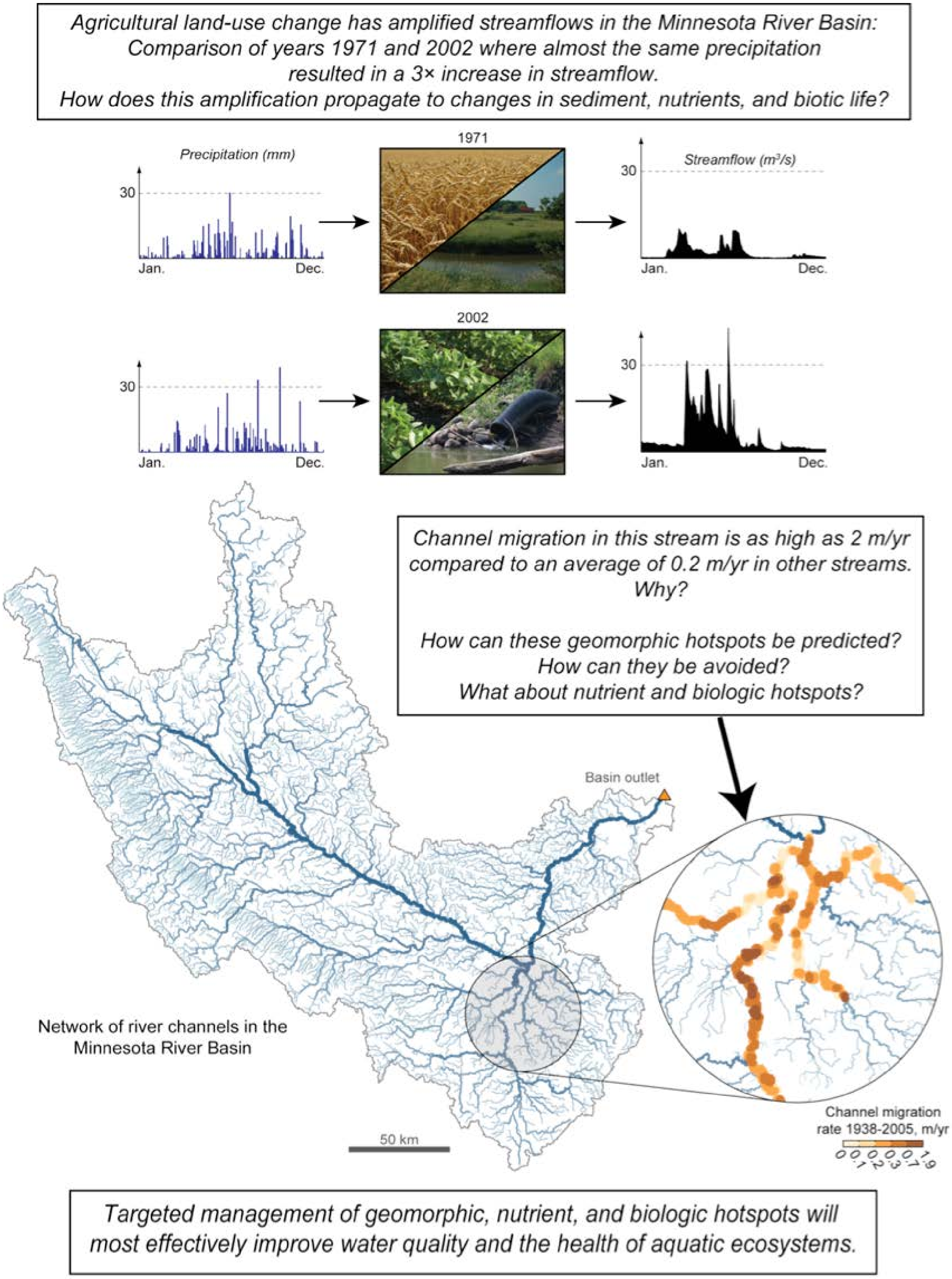


Image courtesy of SAFL.

the amount and duration of bare pavement and better understand the underlying mechanisms. The implications are far-reaching in that residential streets in cold climates could be paved with permeable pavements that do not require salting during winter months, substantially reducing salt pollution to the environment.

A second chloride project seeks to evaluate the movement of chloride through unsaturated soils. Some previous studies have shown lag in chloride transport through soils, which applies to the movement of road salt from the surface to the shallow groundwater as well as chloride from water softening operations. The purpose of this project is to understand the soil properties that affect chloride transport and estimate the long-term residence time of chloride in the soil. With this information, we can better predict the long-term impact of our current road-salt and water softening practices.

A SAFL student cuts into an experimental delta, revealing the stratigraphy of the deposits. Image courtesy of SAFL.

Understanding Deltas and Depositional Systems

(Contributed by Chris Paola, SAFL Faculty and Professor of Earth Sciences)

Some of Earth's most vulnerable and important environments, in terms of human life, infrastructure, and biological productivity, are in coastal lowlands and river deltas. River deltas are, literally and figuratively, the thin end of the wedge of environmental response to rising global sea levels. Their dynamics are strongly influenced by physical, biological, geochemical, and human processes, making them an ideal target for SAFL's multidisciplinary approach. Deltaic systems also create sedimentary deposits that host important reservoirs of hydrocarbons and drinking water, which in turn could provide locations for sequestering greenhouse gases.

SAFL researchers are bringing experimental and theoretical methods to bear on understanding the structure and evolution of these critical coastal systems. A major research effort is underway to develop techniques for replicating the effects of wave, tides, and cohesive sediments on delta morphology and dynamics. This is opening the door to studying the influence of these fundamental processes under controlled conditions, something that has not previously been possible. Initial work using novel sediment mixtures and new ideas about replicating tidal forcing has produced delta landscapes that strikingly resemble those of classic tidal- and wave-dominated deltas from around the world.

In parallel, SAFL researchers are working to develop new theories for predicting delta evolution in response to change. One line of work is the so-called "reduced-complexity" model of delta evolution. While simulating all the details of flow and particle dynamics in a natural delta is still well beyond the reach of even the most powerful supercomputers, by combining "just enough" basic mechanics with rules based on experimental and field observation, we can capture enough of the key processes to reproduce the main elements of delta evolution. Additional work is focusing on the spatial structure of deltaic channel networks, and how this influences vulnerability and resilience, and the sometimes surprising ways in which processes spatially removed (upstream or downstream) from a given point can influence dynamics at that point.

Investigating a Different Type of Hydropower

(Contributed by Michele Guala, SAFL Faculty, and Mirko Musa, SAFL Ph.D. Candidate)

Hydropower is recognized as a clean, renewable energy, but traditional hydropower, typically generated by dams on rivers, can significantly affect the overall flow regime, sediment transport, and ecology of waterways. Thus, new technologies are being explored that hope to minimize our environmental footprint while continuing to provide clean, renewable energy. In-streams turbines, also referred to as Marine Hydrokinetic turbines (MHK) or current energy converters (CEC), are a relatively new type of renewable energy technology that harnesses the flowing water of tidal channels and rivers to produce electrical energy. The operating principle is very similar to the classical wind energy turbines, albeit here water is the driving fluid that spins the turbine rotor. Like any new technology, many research questions need to be answered before incorporating this new technology into our energy portfolio.

SAFL researchers currently are running different flume experiments that seek to understand how these MHK turbines influence, and are influenced by, sediment loads in rivers. Preliminary results suggest that the configuration of MHK turbine arrays have both local and broader effects in their environment. A local effect includes scour and erosion surrounding the turbine support towers (similar to the scour observed at bridge piers) and thus is relevant for the structural stability of individual turbines. An observed broader effect is a spatially alternating erosional-depositional pattern that depends on the area and likely the width occupied by the submerged turbine array. Researchers are currently investigating this latter effect to mitigate it, or to exploit it in development for new river restoration strategies.

MHK model turbines are set in an array in SAFL's main channel for an experimental run. Image courtesy of SAFL.

The Legacy Continues

In 2018, SAFL will celebrate its eightieth anniversary since its dedication in 1938. Indeed, the legacy initiated by Lorenz Straub is more than just a laboratory building and the equipment it contains. The hallmarks of the SAFL culture are collaboration, collegiality, and openness to new ideas, people, and directions. Research foci develop organically from our collective curiosities and expertise but are also informed by the major challenges confronting society, environment, energy, and health. SAFL looks forward to contributing to the continued success of the University of Minnesota, the College of Science and Engineering, the state, and society through fundamental research, research training, and outreach for many decades to come.

More information about ongoing research at the St. Anthony Falls Laboratory is available at www.safl.umn.edu, as well as information on tours, SAFL's eNewsletter and links to social media.

Sections of this article are drawn from the "St. Anthony Falls Laboratory Strategic Plan 2015–2020."

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About the Author

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