THE ST. ANTHONY FALLS LABORATORY IN HISTORY

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The laboratory, known until recently as the St. Anthony Falls Hydraulic Laboratory, was designed and built under the direction of a dedicated individual, Lorenz G. Straub. Straub had been a Freeman Fellow and observed several laboratories in Germany during the year of his fellowship. He came to the University in 1930 and promptly set to work to establish his own laboratory. His vision came to fruition through a WPA grant to the University of Minnesota and construction started in 1936. Straub came to be known as the "River Doctor" for his many studies at SAFL on several aspects of river engineering.

The Laboratory building lies on the Falls of St. Anthony in Minneapolis, Minnesota where there is a drop of about 15 meters. Up to 9 m^3/s may be drawn through the building and distributed to the many flumes for experimental research. Laboratory personnel have pursued studies in many areas of river engineering, hydrology and experimental and theoretical fluid mechanics. The legacy left by Straub is more than just a laboratory building and the equipment it contains. His vision of a university laboratory as a leader in the advancement of pioneering methods in water resources engineering as well as being an educational tool lives on. SAFL continues to explore cutting edge research on environmental and geophysical fluid dynamics and apply its knowledge to a variety of water-related engineering problems.

This is a brief account of SAFL's history, present and future written by five of its Directors dating back to 1963.

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INTRODUCTION

This year marks the 65th anniversary of the Laboratory. This paper is intended as a summary of the Laboratory's accomplishments from its beginnings, as seen from a more distant viewpoint than in the references cited, and to recount its current course and possible future roles. A very detailed early history of the St. Anthony Falls Laboratory and its personnel may be found in the book by Mary Marsh, *The St. Anthony Falls Hydraulic Laboratory, the First Fifty Years* (Marsh, 1987).

The Laboratory was designed and built under the direction of a dedicated individual, Lorenz G. Straub. The Laboratory story cannot be told without knowing something about Straub. So, we begin with Straub and follow with the Laboratory history up to the present. We are proud that the preparation of this paper has been a joint effort between the current Director (Foufoula), the newly appointed director (Paola) and three former Directors (Silberman, Arndt and Parker), dating back to 1963.

STRAUB

Lorenz G. Straub (Figure 1), a native of Kansas City, Missouri, obtained degrees, including the Ph.D. in 1927, in Civil Engineering (majoring in structural engineering) from the University of Illinois. In the spring of 1927, the flood of record to that time occurred on the Mississippi River; as a consequence, there was both public and engineering interest in designing river control works. At the same time, John R. Freeman, a prominent and successful hydraulic engineer, endowed a fund to enable American engineers to travel to hydraulic laboratories in Europe where research in river control (and other related topics) was more advanced than in the United States. These traveling fellowships were awarded through three societies - The American Society of Civil Engineers (ASCE), The Boston Society of Civil Engineers, and The American Society of Mechanical Engineers. Rouse (1976) provides more details, but ASCE awarded the first of these to Straub. He spent two years at several German laboratories and traveling in Europe.


Figure 1. Lorenz G. Straub

On his return to the United States in 1929, he was employed by the U.S. Army Corps of Engineers at its Kansas City district office to work on problems in hydraulics and sedimentation of the Missouri River. In early 1930, he was sought out by the University of Minnesota. In the fall of that year he accepted an appointment as Associate Professor of Hydraulic Engineering in the Department of Mathematics and Mechanics!

Marsh, who became Straub's personal secretary in 1955 and retired as Laboratory Administrator in 1981, cites evidence (Marsh, 1987) that Straub's position was created not to just fill a vacancy, but with the intent that the University would build a hydraulic laboratory and form a Department to teach and do research in hydraulic engineering and related areas of fluid mechanics.

Straub, of course, was well qualified for this appointment by his sojourn in Europe and work for the Corps of Engineers. During negotiations leading to his employment, he was shown several reports prepared over a period of many years promoting the use of the falls at St. Anthony for building a laboratory. Marsh (1987) also documents that Straub had already started a design for a laboratory to be built at Kansas City for the Corps of Engineers.

The possibility of building a laboratory was derailed by the depression of that era. In the mean time, Straub taught and did research in an existing small laboratory in the University's Experimental Engineering building. In addition to the undergraduate "Hydraulics" class required of all engineering students, he taught graduate classes titled "Open Channel Flow", "Mechanics of Similitude", and "Mechanics of Sediment Transport". Straub's research was largely on transport in open channels and in porous media and in stability of sand dams. He also found time for some consulting. He encouraged several of his graduate students to undertake experimental theses in the then more modern areas of fluid mechanics like viscous flow in channels. In fact, all his graduate students were expected to take the few courses that were available in the mathematics curriculum dealing with hydrodynamic theory and practice using the books by Lamb (1932) and Prandtl and Tietjens (1934).

Finally, in 1935, the federal government created the Works Progress Administration (WPA) to reemploy the millions of idle workers in the country. The Dean of the College of Engineering immediately commissioned Straub to investigate the possibility of using that program to build a laboratory at St. Anthony Falls. Through many tribulations, the St. Anthony Falls Hydraulic Laboratory was built and dedicated on November 17, 1938, but Straub was not officially named its Director until the spring of 1942.

Straub designed the laboratory and all the equipment that went into it at the time; he fought many battles with WPA and with the University over the amount of money he required; he faced labor strife; even his health suffered (he was a diabetic). Following dedication of the Laboratory, Straub continued his teaching, research, and consulting; he also struggled, with some success, to bring in sponsored experimental research to support the Laboratory. He encouraged one of his doctoral students to undertake experiments on surface air entrainment in high velocity flume flow. This continued as an important research area well into the 1950's and resulted in publication of a prize-winning paper (Straub and Anderson, 1958). Another student of that period, John S. McNown who obtained his Ph.D. in 1942, later wrote a very perceptive article about Straub (McNown, 1992).

However, before a fully meaningful program could be established at the Laboratory, Straub and most of his assistants were called to participate in civilian activities related to World War II. Straub went to New York City to serve on the National Defense Research Committee. He did not return until January of 1945, although he made occasional visits.

Straub returned to the University after prolonged negotiations with the administration as to his and the Laboratory's status. He had offers from other universities, and he used these as leverage. He wanted an almost autonomous Laboratory and European type "chair" within what had become the "Institute of Technology". He finally agreed to become head of a newly created Department of Civil and Hydraulic Engineering and to the title, Professor of Civil Engineering and Director of the St. Anthony Falls Hydraulic Laboratory. He also brought to the Laboratory three of his former graduate students (Alvin

G. Anderson, John F. Ripken, and Edward Silberman) to lead the research program and to do much of the teaching, all under his close supervision. No research could be undertaken, no courses could be taught, and no outside technical activities could be undertaken, without his approval.

Figure 2. St. Anthony Falls

Straub carried on an intensive consulting practice after his return, in addition to doing some teaching and administering the research program at the Laboratory and running the Civil and Hydraulic Engineering Department. He reimbursed the University for 25 percent of his salary to permit the consulting work, but that work brought in many hydraulic model studies that supported the general Laboratory budget handsomely. He became recognized internationally for his ability to diagnose and recommend solutions to hydraulic engineering problems and was dubbed the "River Doctor" by a national magazine.

Finally, his diabetes and intense work regime caught up with him and a graduate student found him dead at his desk early Monday morning, October 28, 1963.

Two memorials exist in his name at the Laboratory. First, there is the Lorenz G. Straub Memorial Library. Second, an endowment fund was established by contributions from his numerous colleagues and industrial contacts. This has been devoted to supporting the Lorenz G. Straub award. The award is made annually to the author of an outstanding Ph.D. thesis in hydraulics or a closely related area.

STRAUB'S LABORATORY (1938-1963)

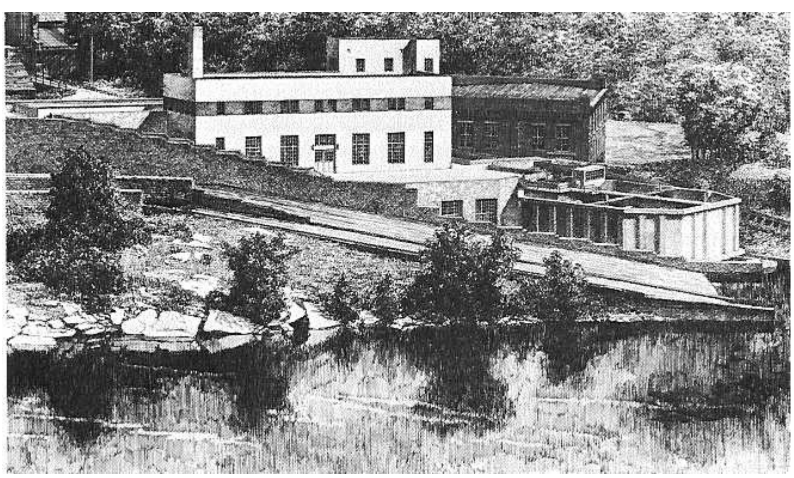

Figure 3. Artist's Sketch of the Laboratory, 1937

St. Anthony Falls on the Mississippi River (Figure 2) was first suggested as a laboratory site in 1908. The head of Civil Engineering at the time wrote to the Dean of the College of Engineering that the city of Minneapolis water supply plant located on Hennepin Island at the Falls had been abandoned a few years earlier (following a typhoid epidemic) and that this would be an excellent place to develop a hydraulic laboratory (Figure 3) for the Department. It was noted that there was 50 feet (15 meters) of hydraulic head and that water rights would be acquired with the site, which was located just two miles from the University's Engineering building. Nothing was produced by this letter or by several studies and reports during the following years until the hiring of Straub in 1930. Most of the early reports emphasized that a laboratory would be used to study pumps and turbines, and that support could be expected from manufacturers of those machines as well as from a potential hydropower industry in Minnesota. Also noted was the potential for developing and calibrating instruments and making river models.

The geologic structure at the laboratory site consisted of an earth and boulder overburden, a layer of fairly sound Platteville limestone about 20 feet thick which was exposed at the river bluff, and under that, the friable St. Peter sandstone. The main experimental floor of the building was dug into the limestone so that it would lie about 20 feet below the river level on the upstream side of the falls. The Laboratory is well described by Straub in the following paragraphs copied from Marsh (1987).

> "The laboratory may be divided into essentially five units, the main experimental laboratory, the hydraulic machinery laboratory, the turbine testing laboratory, the large-scale volumetric measuring tanks, and the administration and lecture rooms."

> "The main experimental laboratory is approximately 300 feet long and 45 feet wide. It is two stories high and contains three large channels extending the entire length of the structure. One is an overhead flume 8 ft wide and 9 feet deep, connected directly to the headwater above the falls, and is provided with numerous off-takes to supply water for the various experimental projects. The others are low-level channels below the level of the main floor. Of these, one is a wasteway and the other an experimental flume arranged for a wide variety of experiments. It is 9 feet wide and 6 feet deep, and is supplied directly from the upper pool of the river through a pressure tunnel. Enough head is available to put water through the flume at the rate of about 35 cubic feet per second for shallow depths. A towing car will make it possible to pull current meters, model ships, and the like through the flume with the water either at rest or in motion."

> "The hydraulic machinery laboratory also has a clear height of two stories and is 34 feet wide and 125 feet long. It will be provided with an overhead crane. At one end of this laboratory there is a penstock shaft about 20 feet square and 30 feet deep below the machinery testing floor; the shaft provides a means of bringing the water from the overhead channel to the turbine testing laboratory, the floor of which is about 46 feet below the headwater pool."

> "The turbine testing laboratory adjoins the hydraulic machinery laboratory, but at a lower level. It is of irregular shape in plan, two sides

being formed by the limestone ledge of St. Anthony Falls. The turbine laboratory is approximately 60 feet long and 75 feet wide. A tailrace channel traverses the length of the laboratory beginning in the penstock shaft and extending to the tailwater pool below St. Anthony Falls."

"The volumetric measuring basins are constructed with their bottom just above the tailwater pool. They are so located that the flow from all parts of the laboratory except the turbine-testing laboratory can be measured. A central control house is arranged to operate large cylindrical valves in a diverter system for the tanks, also in the tanks themselves. Recording and indicator gages will be located in the control house. The valves are laid out to operate pneumatically. The measuring system is designed to handle a continuous flow up to 300 cubic feet per second. It is intended to use this discharge measuring arrangement for checking measurements on large scale experiments and for calibrating water measuring devices to be used in connection with the turbine testing laboratory."

"Administration and lecture rooms are provided in a superstructure above the hydraulic machinery laboratory. A unique feature here is a demonstration lecture room so arranged that large quantities of water could be readily handled in various types of demonstrational experiments. Below the lecture platform is the main overhead supply flume for the laboratories while above the lecture platform is a head-control room containing a constant level reservoir. At one side of the lecture platform is a stairwell and pipe shaft providing access to the laboratory below and the control room above; at the other side, an apparatus room is arranged for housing the various pieces of demonstrational equipment."

"Access to the laboratory is by means of a roadway which bridges over the head race to an adjoining power plant and also over the roof of the main experimental laboratory down a ramp to the main level about 20 feet above the headwater pool."

It might be mentioned that the penstock, described above, which brings water to the turbine-testing laboratory was the original shaft for the Minneapolis water supply. Also, all of the flow structures described above were modeled in the Experimental Engineering laboratory space assigned to Straub.

Figure 4. Original Mississippi River Model

A few of the things Straub planned did not materialize, but much was added to the Laboratory under his direction during his tenure. Both Ripken and C. Edward Bowers, also a retired professor, were his principal assistants in the design of both the building additions and major items of equipment.

As to the building structure, several internal floors were added, sometimes as mezzanines, reducing two-story spaces to single stories; an elevator was installed connecting the original upper floors and the turbine room using the stairwell at the downstream end of the building and excavating below that to the lowest level; and, just before his death, a new floor was completed above the roof of the main experimental laboratory and adjacent to the administrative floor. One end of this new structure was used to house the Lorenz G. Straub Memorial Library.

Straub learned in early 1938, before the Laboratory was completed, that the St. Paul District Office of the Corps of Engineers intended to perform a model study in connection with extending navigation on the Mississippi River so as to create an upper harbor in Minneapolis above the Falls. The District Office maintained a sub-office at the Iowa Institute of Hydraulic Research with personnel who regularly performed river model studies. Straub fought a battle, which extended to the halls of Congress and eventually forced the Iowa personnel to come to St. Anthony Falls to build the model! Straub then faced another battle to convince the University to provide money to build a floor where the model (Figure 4) could be placed. He managed to do this, too. The new floor covered the entire main experimental hall, dividing its height in two, and when the model was completed, it covered most of that floor. This space was named the River Model Floor and has served to this date as the location for a great number of other models.

At this point, something needs to be said about financing. In his original agreement with the University to return as Head of Civil Engineering and Director of the Laboratory in 1945, Straub extracted several commitments from the University administration (through the Dean of the Institute of Technology). A technician, maintenance man, and part time secretary serving the Laboratory were to be carried on the Civil Engineering Department payroll, and he was authorized to establish an independent revolving fund at the Laboratory, funded using receipts from indirect costs on research projects and from reversions on the salaries of academic staff members who worked on research during the school year and thereby had a portion of their salaries paid by the projects. At least twice during his tenure, Straub had to battle the administration to maintain this agreement. Thus, the Laboratory was nominally "self-supporting" so that building additions and new major equipment were readily financed.

Several major items of equipment were added under Straub's direction, associated with Laboratory research programs. A large tilting flume replaced the original one used in the air entrainment research, already mentioned (Straub and Anderson, 1958) (and was later dismantled). Research on several aspects of cavitation resulted in construction of a six-inch water tunnel (Straub et al., 1955) (which was originally designed as a model for a sixty-inch tunnel for the David Taylor Model Basin of the U.S. Department of the Navy), a ten-inch free jet gravity-flow water tunnel (Silberman and Ripken, 1959), later supplemented with a two-dimensional test section, and the development of a towing carriage for the nine-foot wide main channel in the experimental laboratory (Straub and Bowers, 1956). Both a mechanical and a pneumatic wave maker and beaches of various types were designed for this channel to support research in the wave making process itself, as well as to test structures (both rigid and erodible) in waves. The channel and towing carriage could then be used to test ship models, hydrofoils, and other watercraft in waves. Considerable effort was given to instrument development for use in these facilities; John M. Killen, a research fellow now retired, was trusted to lead this effort.

Straub built river models and river structure models (dam sections of earth, rock, and concrete, similar spillway sections, gates of many types, fish ladders, coffer dams, open and closed water conduits) wherever space could be found in the building. This is the main reason mezzanines were constructed in all of the original two-story parts of the building. Numerous other areas of research, both basic and applied, were addressed: air-water mixture flow, including acoustics, hydrofoil development, non-Newtonian fluid flow, and boundary layers. The Laboratory list of publications (through 1963) may be examined to obtain a more complete picture of the program during that time.

The transfer of the Mississippi River model to St. Anthony Falls eventually resulted in the transfer of the entire Corps sub-office to the Laboratory where it remained long after Straub's death. Another federal research group was also established at the Laboratory about this time and, again, required intense negotiations by Straub. This was the research arm of the Soil Conservation Service, which later became the Agricultural Research Service (ARS) whose long time head at the Laboratory was Fred W. Blaisdell. This office, too, remained until well after Straub's death. Later, the Federal Interagency Sedimentation Project was also established at the Laboratory with personnel from the U. S. Geological Survey as well as from the sub-office of the Corps of Engineers.

Straub established a series of publications for the Laboratory (SAFL, 1981). There were Project Reports, limited distribution publications giving complete details of each project reported upon and intended for the sponsor and as a permanent record; there were Technical Papers in two categories, A and B, the former being reprints from peer-reviewed publications and papers presented at conferences and elsewhere and the latter which were published only by the Laboratory after review within the Laboratory, describing research not published or presented elsewhere. There were Circulars dealing with general information about the Laboratory, and there were motion pictures. Every publication bore Straub's name, at least to state that he was Director of the Laboratory. Straub did not encourage publication outside the Laboratory. These categories are still in use, save for the Technical Paper series B.

THE LABORATORY AFTER STRAUB (1963-1999)

On the evening of Straub's death, Edward Silberman was called by the Dean of the Institute of Technology and asked to take the position of acting Director of the Laboratory. Subsequently, he became Director without further formal action. He resigned that position on June 30, 1974 and was replaced by Alvin G. Anderson. Anderson died in office after exactly one year. John F. Ripken then became acting Director while a search committee sought a new Director. Roger E. A. Arndt was selected for the position and took office in January 1977. Arndt was the first Director who was not a student of Straub; but he had a connection to the Laboratory - he was the third recipient of the Lorenz G. Straub award, in 1968. Following Arndt, Gary Parker assumed the Directorship in 1995. Parker had been a student of Anderson and was thus a second-generation student of Straub. Finally, in 1999, a new Director, Efi Foufoula-Georgiou, who had no previous connections with the

Laboratory, was selected to replace Parker and is the current Director. A newly appointed director, Chris Paola (currently, the co-Director), will assume responsibility in September 2003. Paola, who is a faculty in the Department of Geology and Geophysics, will be the first director who is not a faculty of the Department of Civil Engineering. This is a vivid demonstration of the natural broadening of the Laboratory's breadth over the past decade to areas of geophysical fluid dynamics and earth surface processes. This evolution will be discussed in a later section.

During Silberman's tenure as Director, the Laboratory program was aimed at intensifying the already robust naval hydrodynamic research (cavitation, hydrofoil development, underwater noise, and the like); obtaining more National Science Foundation (NSF) support for basic research in the areas already supported by the Navy and in new research in stratified flows, turbulence, and hydrology; and maintaining the river and hydraulic structure modeling work at which Straub had been so successful. An unsuccessful attempt was made to begin a program in wind engineering (a wind engineering facility was later built under Arndt's directorship).

In a brief time, the modeling work, which brought considerably more indirect cost reimbursement to the Laboratory than was obtainable from government agencies, fell off considerably. After a few years, support by U.S. Navy research agencies was also reduced by acts of Congress. Furthermore, Silberman was unable to maintain the agreements Straub was able to extract. The civil service positions in the Civil Engineering budget were dropped right after Straub's death. Faculty salary reversions ceased within two years. By 1969, when a number of staff people had to be discharged, the Dean of the Institute of Technology attempted to arrange a sale of the Laboratory to a private research corporation. Fortunately, just at this time, the President of the University returned from a trip to several South American Universities. Within days of his return, he called Silberman to arrange a visit to the Laboratory and stated that the reason for his visit was to observe for himself what many of his hosts on the trip had told him about that "wonderful installation at St. Anthony Falls." The proposed sale ended there. Subsequent adjustments had to be made so that the University obtained some of the indirect costs, but financial problems were alleviated.

Added to the Laboratory during Silberman's tenure was the Buoyant-Body Test Facility, a prominent vertical 60-inch pipe structure rising from the turbine laboratory floor through its roof and then outside past the machinery laboratory and administrative floor to above the building roof (Killen, 1974). Another addition was a large, high-speed water tunnel (SAFL, Circular 5) installed on a mezzanine floor in the turbine laboratory. And, this being the start of the mini-computer age, a stand-alone computer was purchased so that punch cards would no longer have to be carried to the campus for less demanding tasks. But there were no building modifications.

Silberman was more successful in maintaining the academic structure Straub had created. During the 1950's, what became the Department of Aerospace Engineering and Mechanics established its own fluid mechanics courses. Within weeks of Straub's death, the department head requested that the Dean immediately transfer all fluid mechanics courses to his Department. Mediation resulted in preserving the status quo and led, eventually, to complete cooperation between faculty members of the two groups as well as with those in Mechanical Engineering, Chemical Engineering, and Mathematics.

In addition to administering the Laboratory and teaching courses in fluid mechanics, Silberman became interested in Water Resources Management and later introduced a course with that title. When Congress passed the Water Resources Research Act of 1964, creating Water Resources Research Centers in each State, Silberman attempted to have the University build a new floor over the administrative level of the Laboratory so that the Minnesota Water Resources Center could be housed there. He was not successful in this. But the activity created by the Act resulted in the formation of the American Water Resources Association, which Silberman joined as a charter member. In 1969, he became President of the Association and in 1974, at the end of his tenure as Director, the Association moved its headquarters to the Laboratory (to remain until 1982).

Silberman resigned from the Directorship following an amicable disagreement with the head of the Department of Civil Engineering over the assignment of faculty to the Laboratory. It had been agreed in advance that Dr. Alvin G. Anderson would become Director on July 1, 1974. No search was conducted among possible candidates because of limited financial resources to fund the position. Anderson had completed his Ph.D. dissertation in 1950 under Silberman's guidance.

One of the obvious changes Anderson set in motion almost immediately was to stress research in more traditional Civil Engineering areas, especially sediment transport and erosion, at the cost of reduced support for naval hydrodynamics. This was apparent in support for travel to organizational conferences. In fact, Anderson died in trying to reestablish a prominent place for the Laboratory in the International Association for Hydraulic Research, an organization which Straub had help to found and of which Straub had been President. Anderson was en route to the biennial congress of that organization at his death on July 1, 1975.

Anderson had little time to make a large mark on the Laboratory building or equipment, but he is best remembered for the graduate students he counseled. After his death, family, colleagues, and former students established a memorial fund in his name and this has been used to fund the Alvin G. Anderson Award. The Award is made to a graduate student at the Laboratory working in Anderson's major field of interest, sediment transport, or a related area. The first award was made in 1976 to S. Dhamotharan, who is now a Senior Vice President at URS Corporation.

On Anderson's death, Silberman declined an offer to be an interim Director while a search was conducted for a new Director. Professor John F. Ripken took on this task and guided the Laboratory as much as was possible on the course Straub had set and Silberman had tried to follow. Ripken was personally interested in several aspects of cavitation research and published regularly on this subject. He left no special mark during his Directorship, but his name was associated with the Laboratory in important respects from the original building design through the date of his retirement in 1979. He now lives in retirement in Minneapolis.

Dr. Roger E. A. Arndt was named as the new Director near the end of 1976. Arndt came to the Laboratory on a part time basis in January 1977 and assumed full time duties that summer. He came to the position with a different background and a different perspective. Although educated as a civil engineer with graduate work at MIT under Daily (SM) and Ippen (PhD) his industrial background and prior academic post at the Pennsylvania State University were in aerospace engineering.

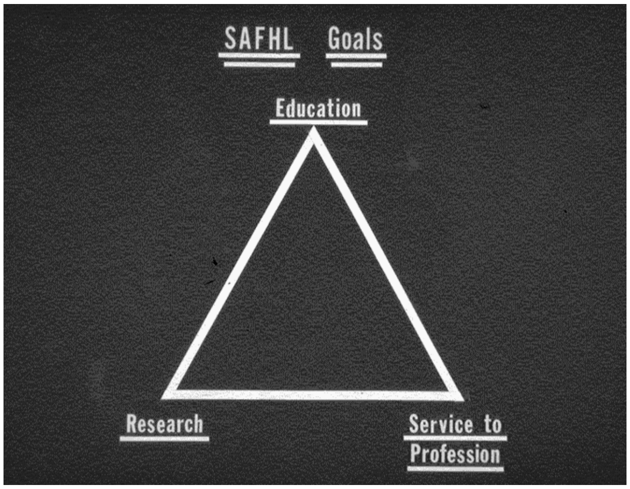

Figure 5. SAFL Goals

Arndt's first objective was to revitalize the fundamental research program and to increase graduate student participation in the operation of the laboratory. He felt that the time was ripe to base both the fundamental *and* applied work on a firm foundation of fluid mechanics. As shown in an early presentation, his view of the laboratory was one of an integrated program of education, fundamental research and service to the profession (Figure 5). It was expected that students would benefit from involvement in both basic research where grounding in fundamental principles would be received and, where feasible, participating in applied research where real world problems are solved within time and budget constraints. The basic program would benefit from the identification of relevant problems for future research during the course of an applied study. The applied work would in turn benefit from the use of the latest experimental and computational methodology developed in the basic program. The vision was that the integration of the three objectives would benefit greatly from this synergism. Education, research, and applications are all integral parts of a major research university.

To commemorate the 40th anniversary of the laboratory, Arndt and Marsh organized the Symposium on Fluid Mechanics in Water Resources Engineering, which was held in April 1979 (Arndt and Marsh, 1981). The Symposium addressed fluids mechanics research in water resources engineering, both as to the state-of-the-art and the future directions of fluid mechanics. This symposium served as a road map for further development of the laboratory. Following the symposium, the Laboratory underwent substantial change. The Laboratory had` built its reputation on the use of hydraulic models for solution of a variety of hydraulic and river engineering problems, the development of specialized instrumentation, and naval hydrodynamics research. This activity was expanded to include topics such as computer simulation of water quality dynamics, thermal pollution, aeration, fluid transients, slurry transport, acoustic radiation from bubbly flows, cavitation, hydropower, ice formation, surface and groundwater hydrology, and the design of major research facilities.

The new hydro-turbine research facility and the new boundary layer wind tunnel, both of which are unique installations, considerably enhanced the Laboratory's capability in experimental research. Computer simulation of everything from physico-chemical processes in rivers and lakes to flow through the turning vanes of a $150,000,000 water tunnel became almost routine, mostly under the direction of Charles Song, now an Emeritus Professor. The Laboratory's new linkage with the University's Supercomputer Institute provided the opportunity to meet the challenges during this period of rapid expansion.

Much of the expansion was based on several new opportunities that presented themselves during this period. The energy crisis of the late 1970's fostered an interest in small hydropower, both on the Federal and State level. The Legislative Commission for Minnesota Resources (LCMR) began to recognize the University and SAFHL as a significant resource for appropriate research in water resources and energy. The US Navy saw the need for considerably expanded research in naval hydrodynamics, hydroacoustics and cavitation while the National Science Foundation became interested in developing a program of fundamental research to complement a growing activity of applied wind engineering being carried out at other laboratories.

Probably the most significant opportunity was the appointment of several new faculty, following the appointment of Heinz Stefan in 1967. The new faculty were Cesar Farell in 1978, Gary Parker and John Gulliver in 1980, Peter Kitanidis in 1984, and Efi Foufoula-Georgiou in 1989. Farell brought expertise in wind engineering and fluid mechanics. Parker was key to revitalizing research in river mechanics and fluvial hydraulics and in developing a coordinated effort in both fundamental and applied activities in this area. Gulliver brought a new perspective to environmental research and was key to adding *engineering solutions* as part of the water quality research program. He also played an active role in all phases of hydropower research, and was instrumental in developing stronger ties with the environmental faculty with the Civil Engineering Department. Kitanidis (who was hired to replace Edward Bowers in the area of hydrology) remained at Minnesota only briefly and left to assume a faculty position at Stanford. Efi Foufoula-Georgiou, who developed an active research program in space-time rainfall modeling, geomorphology and scaling in hydrologic processes utilizing a suite of sophisticated mathematical tools, replaced him. She is the current director of the laboratory.

In response to these opportunities, the laboratory started a large program in small hydropower development that built on its previous experience in the development of very large hydropower schemes around the world. The program included a very successful series of professional development courses for hydropower practitioners and developers (Gulliver and Arndt, 1991), major participation in the development of Minnesota's hydropower potential, research on resource assessment, hydroturbine dynamics, aeration and water quality as well as physical modeling and field studies of several small schemes in Minnesota. The laboratory was also in partnership with the City of Minneapolis, the Minnesota Historical Society and Northern States Power Company in the development of a hydropower museum. The need for enhanced research facilities led to the building of the Independent Turbine Test Facility under the sponsorship of the hydropower industry, the US Department of Energy and the LCMR.

At the same time, the US Navy identified the need for a new facility for propeller research with an increased emphasis on hydroacoustics. The laboratory was selected to be responsible for the hydrodynamic design of the Large Cavitation Channel (LCC), which is now the world's largest water tunnel. This was a large project and permitted the laboratory to expand into the field of computational fluid dynamics as a supplement to the extensive experimental research that was required. This led to further work for the German government to develop a similar, albeit smaller (1/2 scale) facility. At the same time the US Office of Naval Research made a significant grant to the laboratory for hydroacoustic research. Faculty from the Departments of Electrical Engineering and Aerospace Engineering and Mechanics collaborated in this research. This latter opportunity fostered much stronger ties with other academic units at the University. In fact, Arndt was appointed Chairman of the Fluid Mechanics Program in 1981, helping to strengthen the laboratory's ties with other fluid mechanics faculty, and foster active research collaboration with Aerospace Engineering and Mechanics, Mechanical Engineering, and Chemical Engineering

A large wind tunnel was designed and built under sponsorship of the NSF. Initially this facility was under-utilized, but now serves as an integral component of a recently developed program in boundary-layer atmospheric turbulence. Support from the LCMR was significant during this period (averaging roughly one-third of the budget for several years). This allowed for significant research in water quality, global warming, engineering solutions to water resources problems, hydrology and a host of other environmental research of critical importance to the State.

In spite of significant growth during the 1980 decade, the laboratory was again under scrutiny by the University. A faculty committee appointed by newly inaugurated President Keller recommended closure along with other major units such as the Colleges of Dentistry and Veterinary Medicine as part of the University's "commitment to focus." This was viewed as a serious threat by all at the laboratory and consumed a good deal of time for the director, faculty, staff and students. A serious erosion of research sponsorship occurred, especially from commercial interests, out of fear that laboratory closure would adversely affect time sensitive projects.

In response to this threat, an external review committee was appointed in 1989. The committee was chaired by Professor Benjamin Liu, Professor of Mechanical Engineering and Director of the Particle Technology Center, University of Minnesota with Norman Brooks, Professor of Environmental and Civil Engineering at the California Institute of Technology, John Cassidy, Chief Engineer, Bechtel Civil and Minerals, Inc., Bob Hansen, Director of the LCMR, Helmer Johnson, Chief, Geotechnical, Hydraulic & Hydrologic Engineering Branch, St. Paul District, US Army Corps of Engineers, Bob Lillestrand, Control Data Corporation and R.S. McGinnis, General Manager, Research, Northern States Power Company. They produced a report that stated, "The current program and long-range goals of the SAFHL are basically very sound in the context of today's funding opportunities and future societal needs. There have been significant evolutionary changes in Lab policy under Dr. Arndt's direction and they should continue."

This report and the receipt of the *Outstanding Water Achievement* Award from the American Water Resources Association greatly encouraged all at the laboratory. However, it took several years to completely recover from the fallout from the proposed closure. Arndt decided at this point to step down (in September 1993) and take a three-year leave of absence to be the director of the Fluid and Particle Processes Program at the National Science Foundation. He returned to SAFL in 1996 to reinvigorate a very active research program in cavitation and hydrodynamics which continues to date. He also provided to the succeeding directors, an invaluable source of information in regard to Laboratory management.

The Directorship of St. Anthony Falls Laboratory remained vacant for the period September 1993 to February, 1995. The Head of the Department of Civil Engineering, Steven Crouch, filled in as Acting Director of the Laboratory during this period. In spite of his many departmental duties, Crouch acted vigorously to familiarize himself with management issues and propose improvements.

In so far as no faculty position was vacant at the Laboratory at the time, it was necessary to seek a new Director from the existing faculty. The clear favorite of all parties was Heinz Stefan, who had served as Associate Director under Roger Arndt. Crouch actively recruited Stefan for the Directorship, but after several months of negotiations Stefan declined the position and the search was unsuccessfully terminated. With no obvious candidate for Director, Crouch named a Steering Committee to manage the Laboratory. The members were Heinz Stefan, Gary Parker and Rick Voigt. Stefan and Parker were (and remain) tenured faculty members, and Voigt was a research fellow managing applied research at the time. Parker served as the committee head. The Steering Committee commenced operation in July of 1993, continuing to February, 1995.

The period of governance by the Steering Committee constituted a holding pattern. The Laboratory's infrastructure was aging and its central revolving budget had dipped into the red. There was an element of demoralization among the faculty and staff, who were uncertain about the future of the Laboratory. The Steering Committee attended to maintenance and repairs on an as-needed basis. A method was sought to encourage researchers to redouble their efforts to bring in overhead-bearing projects, so improving the finances of the Laboratory. This was implemented in terms of a devolution of a portion of the overhead earned to the individual principal investigators, to be used as each investigator saw fit.

The budget of the Laboratory improved modestly but perceptibly over time, allowing for a few initiatives. A fund was designated for the purchase of new books for the Lorenz G. Straub Memorial Library at SAFL, with input specifically solicited from the graduate students. An annual "Hostage Exchange" program of invited speakers was organized with SAFL's sister institution, the Iowa Institute for Hydraulic Research. Planning was begun on a Local Area Network, and efforts on minor repairs to infrastructure were redoubled. During this same period, however, an inspection of the electrical wiring, which dated from 1938, revealed numerous code violations.

After several months of negotiation, Steven Crouch appointed Gary Parker to formally take over the Directorship of SAFL from February, 1995, for a term to extend until June, 1998. Crouch is owed a debt of thanks for his services beyond the call of duty in overseeing SAFL in the "interregnal" period between Arndt and Parker. Parker negotiated for and got a "setup package" to allow for a start on an infrastructure upgrade. The package included a) rewiring to bring the Laboratory up to code, b) replacement of the existing inadequate lighting on all experimental floors to fluorescent lighting, c) replacement of the crane and forklift, essential pieces of equipment for a laboratory with a three-dimensional structure, d) repairs to the gate house, e) implementation of the Local Area Network and f) the purchase of "cargo," i.e. a number of pieces of office and experimental equipment. This "setup package" awarded by Francis Kulacki, then Dean of the Institute of Technology, provided a needed lift to Laboratory morale.

Parker commenced the Directorship with the goal of widening the participation of other University of Minnesota Researchers in SAFL. It was during this period that overtures were first made to Vaughan Voller, a faculty member in Civil Engineering, to formally join SAFL. Voller eventually agreed to do so, and his numerical skills remain of great benefit to the Laboratory. Chris Paola, a professor in the Department of Geology and Geophysics, had long maintained a close relationship with SAFL since his appointment in 1983. In the period 1991 – 1993 Paola and Parker worked jointly on an applied project concerning the performance of the tailings basin of the Hibbing Taconite Mine in northern Minnesota. The tailings basin could be modeled as an alluvial fan-delta, a topic in which Paola had a long-standing interest. In the course of the project, Paola proposed the idea of a unique experimental facility, one that could be used to study the morphodynamics of depositional basins, drainage basins and continental margins undergoing tectonic subsidence or uplift. Paola and Parker prepared a proposal to the Academic Research Infrastructure program of the National Science Foundation in order to build this facility, later dubbed the XES (eXperimental EarthScape) facility, a.k.a "Jurassic Tank." Concurrent with Parker's negotiations with Dean Kulacki in regard to the Directorship, Paola and Parker obtained a generous commitment from him to contribute $250,000 in matching funds for the proposal. The proposal was funded, and the XES facility remains one of the mainstays of active research at SAFL. Featured in *Science* (Stokstad, 2000), it is the first system ever built for doing controlled experiments on the formation of large-scale stratigraphic patterns, which develop through the interplay of tectonic subsidence and sedimentation. A plan-view and the mechanism for operation of this basin are illustrated in Figure 6.

In recognition of the growing diversity of laboratory activities beyond hydraulics, the laboratory was renamed during Professor Parker's tenure, from St. Anthony Falls Hydraulic Laboratory to *St. Anthony Falls Laboratory*: *Engineering, Environmental and Geophysical Fluid Dynamics*. In short, it is simply called St. Anthony Falls Laboratory (SAFL).

In June 1999, Gary Parker stepped down as Director of SAFL, and Efi Foufoula-Georgiou was appointed by Dean Ted Davis as the new Director.

THE LABORATORY TODAY (1999-2003)

Efi Foufoula started her Directorship at a lucky time at which a much-needed rejuvenation of SAFL's intellectual power took place. Two new faculty members were added to the Laboratory in 1999 to replace the retired faculty, Professors Charles Song and Cesar Farell. The two new faculty, Miki Hondzo and Fernando Porté-Agel, brought new expertise and new energy that was felt throughout the Lab. Miki Hondzo brought expertise in ecobiological fluid dynamics (the interaction of water with biota), algae formation and biochemical processes in lakes, rivers and the coastal ocean. Fernando Porté-Agel brought expertise in atmospheric boundary layer turbulence, land-atmosphere interactions, field experimentation and large-eddy simulation modeling of boundary layer flows. Both developed very quickly outstanding research programs of national recognition (both received the "CAREER" award given annually to the most promising young scientists by the National Science Foundation). Hondzo developed a new Water Quality Laboratory (also called EcoFluids Laboratory), which features state-of-the-art equipment for biochemical analysis. Porté-Agel rejuvenated SAFL's wind-tunnel experimental facility and adapted it for atmospheric boundary layer research.

As the diversity of research expertise within SAFL's faculty saw a sudden growth, Foufoula's first priority was to harness this diversity and promote its uniqueness. Now, faculty could address questions on turbulence, water quality, hydrometeorology, biochemistry, fluvial geomorphology, sedimentology and atmospheric transport, all in the

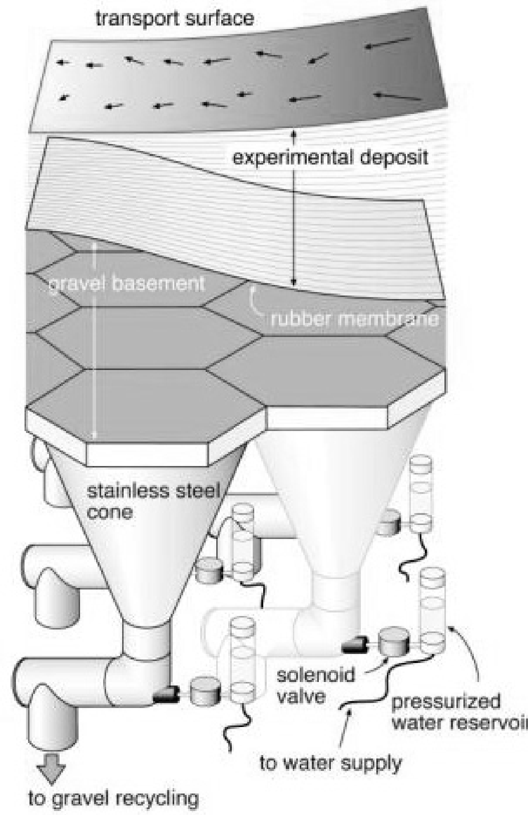

Figure 6. eXperimental EarthScape (XES) facility

same laboratory and via a unique combination of experimental, computational and theoretical approaches.

Pat Swanson (senior editor, now retired) created the first SAFL web-site (www.safl.umn.edu), which tried to reflect both the uniqueness of each "scientific group" within SAFL, but also the synergy among these groups. Figure 7 illustrates the 10 research areas of SAFL and the group leader in each of these areas, all of them centered around the unifying theme of Environmental and Geophysical Fluid Dynamics. These areas are:

- Chemical Fate & Transport in the Environment (Gulliver)
- Hydrologic Processes and Multiscale Dynamics (Foufoula-Georgiou)
- Earthscape Processes (Paola)
- Computational Modeling of Transport Processes (Voller)
- Land-Atmosphere Interaction Measurements & Simulations (Porté-Agel)
- Environmental & Biochemical Systems (Hondzo)
- Fluvial & Oceanic Sediment Transport and Morphology (Parker)
- Cavitation & Bubbly Flows (Arndt)
- Lake & River Water Quality Dynamics (Stefan)
- Computational Fluid Dynamics & Applications (Song)

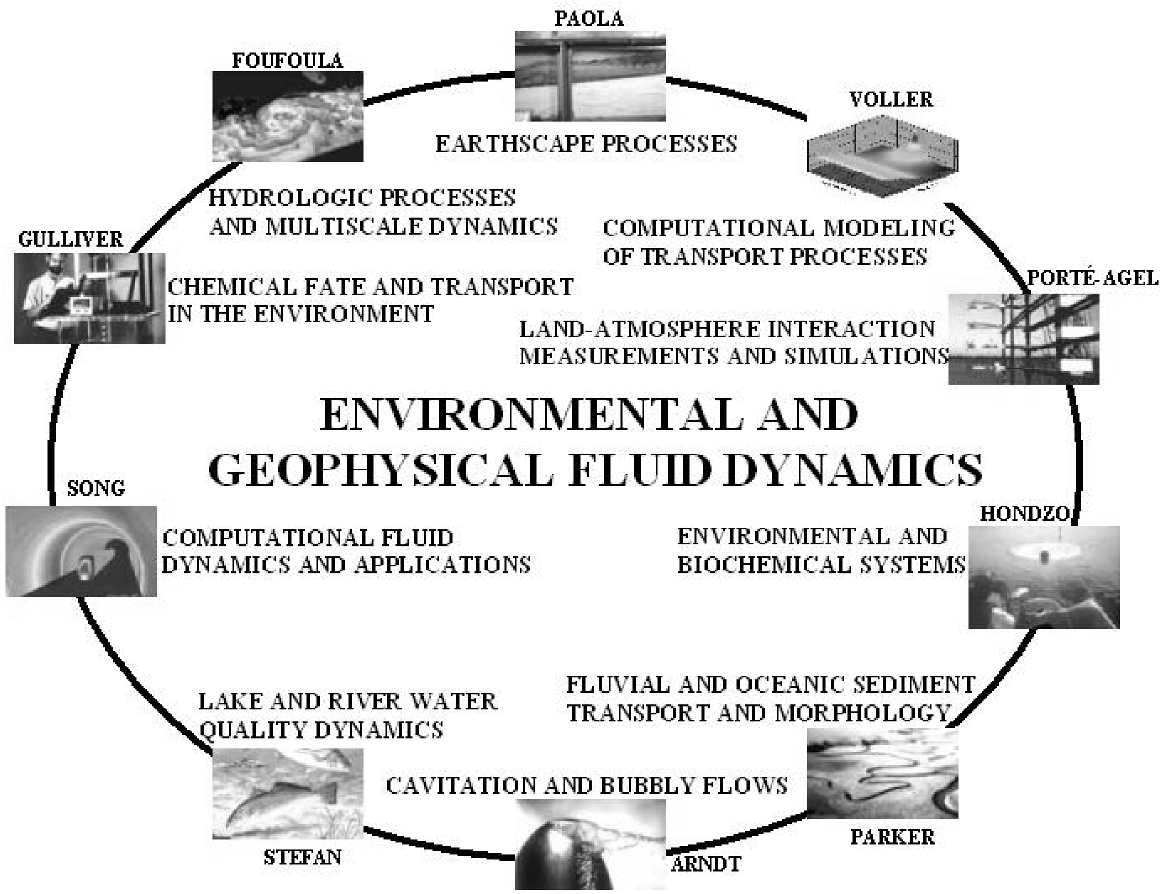

Figure 7. Basic Research at SAFL

SAFL's mission was revised to read:

> "*Our goal is to advance the knowledge and understanding of environmental hydraulics, turbulence, earthscape evolution and climate, ecosystem dynamics via innovative experimental, theoretical and computational research. As a group, we are committed to transferring that knowledge to the engineering community and to the public through applied research and outreach activities*."

SAFL has by no means turned its back on traditional applied-engineering projects. In 1999, a new Associate Director for Applied Research was hired (John Thene) who emphasized quality and cutting-edge technology in the applied projects. Nevertheless, the number of classical model studies the laboratory has performed in recent years has declined for several reasons including a world-wide decline of new hydraulic structures (EOS, 2003), increased use of computational methods in hydraulic design and improvement in the modeling capabilities in developing countries where most major new water projects are taking place. (Many of the present leaders of these projects were trained in labs like SAFL.) SAFL's applied projects within recent years have been very diverse, and have tended to be individually somewhat smaller than in the lab's early years. Some of the more significant ones have dealt with protection measures for bridge piers; drop shaft improvements for the city of San Antonio; visualization of storm-water systems for the city of Milwaukee; and measurement of loss coefficients in pipe fittings for the American Society of Heating, Refrigerating and Air-Conditioning Engineers. We also have a new program in applied research for the oil industry. This involves developing better ways of predicting the geometry of potential oil reservoirs.

SAFL's unique expertise and experimental, numerical and theoretical approaches to water and earth surface processes led to a successful proposal to the National Science Foundation for a new Science and Technology Center named "National Center for Earth-surface Dynamics" (NCED). NCED's (www.nced.umn.edu) mission is "to identify and quantify the major physical, biological and chemical processes that shape the Earth's surface .… work towards a holistic approach in which information and understanding from sedimentary geology, geomorphology, engineering, oceanography, hydrology, biology and geochemistry are seamlessly integrated into a consistent, quantitative understanding of Earth-surface dynamics." The hallmark of NCED, as for all Science and Technology Centers, is integrative, multidisciplinary research with clear benefits for society. NCED involves the Departments of Civil Engineering, Geology & Geophysics, and Ecology, Evolution and Behavior at the University of Minnesota, as well as research colleagues from the University of California at Berkeley, Massachusetts Institute of Technology, Princeton University, and Fond du Lac Tribal and Community College. In addition, a strong partnership was formed with the Science Museum of Minnesota on a range of educational programs including a unique series of outdoor, hands-on exhibits on surface processes and engineering. All those who work in laboratories like SAFL understand the fascination of flowing fluids and sediment. The Science Museum partnership will bring some of the fascination of surface dynamics to the public along with the engineering challenges they pose, in a direct and engaging way.

SAFL today is a far cry from the struggling facility that was threatened with closure in the 1980s. Our greatest problem today is insufficient space to house our growing staff and visitors, and the projects they bring. In large part this is because SAFL has continued to develop new ways of applying its core strengths in experimental and theoretical fluid and sediment dynamics. SAFL's success in this regard reflects two mutually beneficial trends. The first is development of a more 'holistic' approach in Civil engineering, in which engineering solutions are more closely integrated with natural conditions and processes. The second trend is a growing appreciation of the role of fluid processes in non-engineering fields such as biology and the Earth sciences. This coincides with an increasingly quantitative, analytical approach in these fields that leads to a greater role for carefully controlled experiments.

SAFL today houses eleven faculty members (a new faculty member not shown in Figure 7 was added this year: Lesley Perg from the Department of Geology and Geophysics who brings expertise in biogeomorphology), approximately 60 graduate students and postdoctoral researchers, 20 undergraduate students and 10 full-time technical staff and research engineers and several support staff. The faculty bring about $1.5 million in research funds annually (mainly from NSF, ONR, NASA, NOAA) and, starting this year, another $2.5 million from the newly established NSF center. Federal funds comprise 85% of the total funds, and the rest comes from state and commercial projects. The revenue created from the overhead of these research grants forms the annual operating budget of the Laboratory. This provides for salary of the support and administrative staff of SAFL and partial support of technical staff and engineers. It also provides for repair and expansion of the lab's experimental facilities and for investing in new initiatives.

The year 2003 has seen major remodeling of the aging building partly due to the new NSF center and partly due to the University's recognition of SAFL as a unique center to promote and cherish in the years to come. SAFL has been completely rewired with new power and digital transmission lines, it has been connected to the main campus with fiber optics, it has been completely re-roofed, and has seen moderate furnishing improvements, especially in the graduate student offices. There is a constant effort to provide the best research and educational experience to our graduate students, and we are grateful to our alumni for supporting the "Graduate Student Fund" created in 1996 for that purpose. More than 400 students have received degrees and numerous undergraduate students have been trained at the Laboratory, and more than 100 visiting scholars and post-doctoral fellows from all over the world have spent up to two years in active collaboration with our faculty and research staff. Also, more than 400 middle and high school students are given tours of the Lab annually to develop an appreciation of water resources and career opportunities. In a typical year, roughly 10 M.S. and Ph.D. students graduate from the laboratory's programs with degrees in Civil, Mechanical and Aerospace Engineering, or in Geology and Geophysics.

THE FUTURE

What are the major water challenges in the 21st Century? What science is needed to address these challenges? These two questions have formed the focus of many recent studies by the National Research Council and the National Academies (NRC, 2001a; 2001b). All studies point to the fact that in the face of increasing water demand and other stresses (capital shortages, increasing concerns for the environment, experience of extreme hydrologic conditions), we have to rethink the traditional approaches to water management and take an integrated view of the water cycle and its interaction with the environment. Water is the main transporting medium for organic carbon and major nutrients that influence terrestrial vegetation processes and aquatic ecosystems at all spatial and temporal scales. These in turn influence the quality, quantity and transport pathways of water, forming a closed cycle of water and bio-ecological interactions. Understanding this cycle holds the key to our ability to make predictions that are essential for efficient water resource planning and management. Theoretical, numerical, and experimental research is needed to achieve this understanding, and SAFL is at the forefront of this research.

One way of understanding the cycle of water bio-ecological interactions is by studying the past. How has the water interacted with the earth surface over the past million years to deposit the sediments and create the tremendous variability in landscape we see today? This is an active area of research at SAFL and a big component of the "National Center for Earth-Surface Dynamics" at SAFL. The uniqueness of SAFL for such research was recently highlighted in an NSF vision document (NSF, 1999):

> *At present there exist only a few major experimental facilities for the study of Earth surface processes. It is important that these facilities be maintained, and that access to them be open to the entire community on a competitive basis…This (St. Anthony Falls) Laboratory has provided*

through their own work and that of others a significant experimental basis for the understanding of many fluvial and now submarine processes.

We expect that experimental facilities will continue to be central to SAFL's mission, but our focus is on understanding processes, and not on using a particular kind of tool. The experimental facilities will be applied along with computational and other theoretical research, laboratory analysis, and field work. We expect to continue supplementing our "classical" experimental equipment with new facilities such as our Ecofluids Laboratory. The Ecofluids lab also illustrates the increasing role that biological fluid processes will play in SAFL's future. Finally, experiments, field work, and analysis are always most powerful when done in conjunction with theoretical analysis and modeling. Our theoretical research will continue to make use of in-house computing strength, backed by the considerable resources of the University of Minnesota Digital Technology Center and the Minnesota Supercomputing Institute.

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