From wind to water

Studying hulls in high seas or the rain in your face, researchers in Iowa probe the complex flow of the world.

By Cornelia F. Mutel

For tens of thousands of years, salmon have been weaving their way from the Pacific Ocean up the rivers of the Pacific Northwest to lay their eggs near the headwaters and then die. For about half a century, the U.S. Army Corps of Engineers and public utility districts have been building dams that, as a side effect, block passage of the egg-bloated salmon and that of their offspring, or "smolts." And for nearly two decades, scientists like Larry Weber have been attempting to restore the salmon's ability to reproduce as they are genetically programmed to do.

"It's not a simple engineering problem," Weber said, fiddling with a small-scale model of a system he designed to get smolts safely past a dam's hydroelectric turbines into the free-flowing river below. "We need to use studies of fish ecology and behavior, because even the best-engineered bypasses are often stymied by the eccentricities of fish behavior."

For this reason, live fish are sometimes fed through the small-scale models of bypass systems. Their patterns of movement are carefully recorded, sometimes with surprising results. "Once we thought we had the perfect bypass," Weber said, "until we put fish into the model and found them congregating in corners of a square bypass pipe where the current was weak, trying to swim back upstream. We quickly replaced a square bypass pipe with a round one and the problem was solved."

In the last few years, the Institute of Hydraulic Research at the University of Iowa has developed a numerical code that accurately predicts the three-dimensional flow of water over the variable bed of a dam's forebay and into a hydropower plant's intakes. In addition, fisheries biologists working independently have identified basic behavioral patterns of salmonids.

For example, smolts are known to avoid areas of rapid water acceleration and high turbulence, and they prefer to change direction laterally rather than vertically. Weber, a research engineer at the institute, is working with U.S. Army Corps of Engineers ecologist John Nestler in an attempt to integrate fish tracking data and river hydrodynamics in a totally unexplored manner. The two researchers are working to merge the knowledge of water flow and fish behavior into a single computational fluid dynamics code that will better predict the fish-related effects of proposed changes in a given hydropower operation.
This is but one of many ways in which engineers at the Iowa Institute of Hydraulic Research use state-of-the-art research techniques and equipment to provide solutions to practical water-related problems. This has been going on since 1920, when the University of Iowa's Hydraulics Laboratory opened its doors with a straightforward goal in mind: to provide the nation with its first industry-sponsored turbine-testing laboratory west of the Mississippi River.

The goal was rapidly displaced by a diversity of other projects, and within a few years the laboratory (with a full-time research staff of one) was off to a multifaceted career of testing road culverts, gauging current meters, investigating characteristics of river flow over weirs, and describing scour around bridge piers. The course was set.

In the 80 intervening years, the institute, which today incorporates the Hydraulics Laboratory and six additional research annexes in Iowa City, has modeled new locks and dams for the Mississippi River, developed classroom and laboratory curricula that fuse fluid mechanics and hydraulics, monitored the flow of water from the skies to and through the earth and its water channels, and helped define fundamental properties of turbulent flow. In the last decade, it has developed numerical models to supplement data from traditional physical models and field efforts.

In short, the institute has investigated many of the initiatives that today are incorporated in the annals of 20th-century hydraulic engineering and fluid mechanics research. By doing so, it has been a prototype for hydraulic engineering academic institutes around the globe.

Since 1982, the institute has received contracts from the U.S. Army Corps of Engineers and several electric power utilities to seek methods that will decrease the impact on migrating salmon of the numerous gigantic dams dotting the Columbia and Snake Rivers. For most of its studies, the institute has depended on field observations combined with small-scale models of the dams and of potential fish bypass structures (such as pipes that carry the fish around a dam's turbines). Although models may be only a hundredth the size of the structures they represent, the models themselves can still be gigantic. The institute's 1:52 model of the forebay of the Wanapum Dam, for example, holds 120,000 gallons of water, and yet is sufficiently detailed to incorporate exact variations in the river's topography.

Weber is providing a three-dimensional hydrodynamic field to Nestler, who also receives biological information of real fish moving through the flow. Nestler determines the parameters the fish respond to through multivariate regression. The trick lies in assuring that the movements of a single fish can be generalized to represent behavioral responses of actual fish populations moving through the dam. This will be determined by overlaying numerous actual fish trajectories (determined through radio telemetry and hydroacoustics) with the calculated three-dimensional hydrodynamics field.

It's not an easy process. Even putting the hydroacoustics sensors into the water is extremely complicated. The sensors, which must be fixed to a stationary structure (the dam face or river bottom), are mounted as deep as a hundred feet under the water by divers. Doing so is an annual effort, because divers collect the sensors following the three-month fish migration season. However, the effort is worthwhile when one considers the high costs and complexity of physically modeling large-scale structural modifications to guide migrating salmon.

Once CFD models that merge water's flow with fish behavior patterns are perfected, the effects of flow characteristics at countless points can be measured rapidly and economically, and design decisions can be made accordingly. The code thus promises to become a formidable planning tool that will save power utilities major amounts of both time and money.

SOLVING FLUID FLOW PROBLEMS

Fluid flow around ships presents similarly complex problems to fluids engineers. The complexities of turbulent flow around a ship's hull, incident ocean waves, bow spray, and cavitation and bubbly foam replace those of irregular riverbed geometries and fish behavior. Yet here, too, the challenge is for more efficient and less expensive designs, in this case to assure that ships costing billions of dollars will operate as desired.

For more than a half-century, the institute has been assisting the U.S. Navy in its design and testing of defense ships. In recent years, efforts to develop valid numerical codes for predicting the flow of fluid from bow to stern have been funded by the Office of Naval Research, which accounts for approximately a fifth of the institute's funding. These codes, which require the fastest, most sophisticated com-
Physics-based simulation would make it possible to design a ship's structure to suit its purpose precisely, rapidly, and relatively inexpensively.

Validating the codes as they are developed is crucial to their success. The institute has built a tool to assist with the process: a towing tank equipped with the only towed (as opposed to stationary) particle image velocimetry, or PIV, system in the world. The system was created by the Danish firm, Dantec Measurement Technology. “This is a modern experimental tool for modern flow-field measurements,” said Joe Longo, a postdoctoral associate in charge of the towing tank research. Longo is working on the ship hydrodynamics team led by professor Fred Stern.

According to Longo, a carriage moves along tracks that run the entire length of the 100-meter-long towing tank. A ship model is attached to the carriage, along with the partly submerged PIV, which uses a pulsed laser to produce a sheet of light that reflects off seed particles, silver-coated glass hollow spheres around 15 microns in diameter, immersed in the flow field. The PIV system provides mean and turbulent velocity data rapidly and relatively nonintrusively, over a two-dimensional plane.

The PIV system and other towing tank instrumentation are set up to record such standard data for validating CFD codes as the ship model's resistance, wave pattern elevations, and mean and turbulent velocities of the fluid in the boundary layer and wake.

Two features distinguish the current batch of experiments. The ship model, unlike those tested in the past, is a 1:46 scale model of a typical U.S. Navy fleet ship, which includes a sonar dome, propeller shafts and struts, and a transom stern. And this model, for the first time, is being dragged through waves (an unsteady flow problem) rather than through a flat free surface (a steady flow problem). The waves are generated by a plunger-type wavemaker capable of creating them with precise amplitudes and lengths.

“We create the profile of the waves we want on a computer that feeds the information directly into the wavemaker,” Longo explained.

For any of the unsteady-flow experiments, a land-based data-acquisition system communicates with the moving data-acquisition system aboard the drive carriage while measuring the incident waves. Thus, the two data-acquisition systems are melded into a single synchronously moving complex.

At present, only regular or sine waves are being tested. Even though these experiments represent a grossly simplified situation, they are a major step toward modeling a ship operating in a realistic environment that contains waves and currents of constantly varying velocities, sizes, and directions.

The institute’s current simulation code, CFDSHIP-Iowa, which predicts the flow about a ship moving through a calm sea, is now being verified and validated as part of an Office of Naval Research program to demonstrate the applicability of CFD to radical new ship designs. The code is also being extended to study unsteady maneuvering and seakeeping, or the stability of a ship in waves. The new towing tank data are being collected to validate next-generation simulations, which will predict the flow of water around an actual ship moving through a sea of regular waves.

**Assessing Moisture Flow in Air**

Iowa researchers are investigating the flow of moisture through the air as well as over land and through the sea. “We don’t even know how accurate weather radar is,” said Witold Krajewski, senior member of an active group of hydrometeorologists. “We think that radar rainfall estimates are correct to within a factor of two. Our efforts focus on quantifying the uncertainty associated with rainfall observations, and also on contributing to new techniques that will refine the accuracy of weather predictions.” These techniques, if successful, will allow greatly improved estimates of the quantity of precipitation falling in a specific location.

Many of the estimation inaccuracies stem from assumptions about basic characteristics of rainfall (such as the size, shape, and velocity of falling raindrops). Greater knowledge about these traits would result in better assumptions, which in turn would lead to better precipitation estimates. To this end, Krajewski and other hydro-
sensitive and precise sensors, each with its own capabilities. Iowa also has the Mobile Rainfall Observatory, a compact trailer that makes it possible to transport these sensors around the globe.

In addition to standard rain gauges and wind instruments, the mobile laboratory carries a vertically pointing Doppler radar and a video disdrometer, designed and built by Joanneum Research in Austria, and one of only three of its kind in the United States. The Doppler radar dish, which looks straight up into the sky (as opposed to typical radar that scans from side to side), records a vertical profile of falling rain with extremely high resolution, at 10-meter intervals. The disdrometer uses two video cameras to record the shape and size distribution of individual raindrops. This information feeds into calculations of the volume and rate of falling rain and other important radar parameters. Together, these highly sensitive instruments paint a detailed picture of storm systems.

Professor Bill Eichinger is now working to add another instrument to the researchers’ array, a laser-based radar, or lidar, which sends out a pulse of energy that is reflected by raindrops. Eichinger hopes that the traits of the returned pulse will make it possible to create detailed high-resolution maps of rain falling within a few kilometers’ distance. This will allow the study of the effects of the Earth’s surface, such as wind and surface roughness (hills, buildings, trees, and the like), on the variability of precipitation.

MEASURING TROPICAL RAINFALL

In addition to being instrumental in refining U.S. weather predictions, the mobile observatory is tied into an international effort called TRMM (for “Tropical Rainfall Measurement Mission”), funded jointly by NASA and the Japanese space agency, NASDA. This mission is attempting to evaluate precipitation over the Earth’s tropical belt, which receives about two-thirds of the planet’s total rainfall. Improved rainfall measurements are crucial to understanding the weather in the tropics, and will feed into our understanding of larger climate patterns, including those that govern our temperate region.

The world’s air circulation patterns, and thus climate, are strongly influenced by the intense atmospheric energy exchanges associated with tropical rains. Because rainfall data are used as a proxy for atmospheric energy budgets, a factor crucially important to global climate models, TRMM investigations ultimately will be significant in validating these complex numerical models and thus in improving the accuracy of climate change predictions.

Since traditional rainfall measurement techniques are difficult to use in dense tropical forests and over oceans, TRMM is attempting to procure accurate rainfall measurements via satellite. University of Iowa graduate students have taken parts of the mobile laboratory down the Amazon and flown them to the Marshall Islands in the Pacific Ocean, where they have collected ground-based rainfall data that are being used to validate the accuracy of satellite data. These trips add additional trials to the data-collection process: spending days repairing and realigning the optics of instruments that have been badly shaken up during rough truck rides, transporting instruments on World War II troop boats to distant atolls, working through the night on ground that comes to life with hermit crabs searching for food, and placing critical instruments in air-conditioned doghouses to assure that they function in tropical climates.

The institute functions as a research laboratory in an academic setting. Most researchers at the institute are professors at the University of Iowa’s College of Engineering. Many students—more than half in recent years—are from foreign countries, and many of them return to their homelands once their education is complete. Through them, the institute’s ideas and methods are spread abroad. But what about efforts and procedures in other countries? How can U.S. students be imbued with an understanding of the divergent approaches to water resources and management that are practiced around the globe?

With this in mind, in 1998 the institute started a course called International Perspectives in Water Resources Planning. For two weeks each year this course takes a dozen or so students, along with one or two faculty members, to a region of the world where water problems and solutions are enmeshed in social, political, economic, and environmental situations far different from those in the United States. Through pre-travel seminars and lots of local contact at the visit sites, students gain a sense of the complexity of conditions that shape water resource projects today.

“I didn’t know that such gigantic dams were being built any more,” said one student after touring large reservoirs under construction in Taiwan this past May. “I’ll be working as a consultant in an international engineering firm. I need to learn U.S. water resources history, so I can help avoid repeating the mistakes we made 50 years ago.”

The International Perspectives program is intended to prepare the next generation of hydraulicians to attack problems with water’s abundance, scarcity, and flow that are becoming increasingly global in nature.