Our Hydraulic Engineering Profession

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Abstract: This 2015 Hunter Rouse Hydraulic Engineering Lecture reflects on the synergy between facts/knowledge and imagination/creativity. Our hydraulic engineering profession deals primarily with hard facts, and the complementarity between theory and practice is emphasized. We nevertheless have to face an increasing number of "soft" facts introduced by the stochastic variability of field observations linked to turbulence and climate change. A triangular relationship between observations, physics, and mathematics is highlighted to guide future research initiatives. In recent decades, tremendous developments in computer modeling of surface runoff from watersheds have been achieved. Physically based computer models should replace the remaining black boxes of our field. Experimental research should be pursued to continue to gain physical understanding. Answers to questions from the audience lead to a promising outlook for the future challenges in hydraulic engineering. **DOI:** 10.1061/(ASCE)HY.1943-7900.0001267.

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Introduction

Preparing this article gave me reason to ponder what could be written that has not already been stated in past Hunter Rouse Lectures. For decades, the lecture became the anticipated annual gathering of our profession, nothing short of a ritual that could be counted in units: the 29th HR Lecture, the 30th . . . ! My concern was whether it is important to stimulate our imagination about something new and exciting, or should we should look back at our collective achievements and reflect on our core knowledge?

Two distinct concepts arise:

- The structure of this annual lecture provides a unique moment for reflection on things we already know; the concept of a professional huddle comes to mind where our core values can be defined from the review of past accomplishments: can a rigid foundation in hydraulic engineering be solely based on facts and knowledge?
- Fluid individual creativity and the power of imagination are released by innovative solutions to the complex problems of our generation; is there a need for professional inspiration and enthusiasm generated by commemorating the great achievements of our predecessors?

While navigating between the two concepts, I found it worthwhile to separate: (1) facts and knowledge from (2) imagination and creativity. The difference in sports is very clear. The goal posts separate knowledge from creativity. The players can develop the most creative schemes to get the ball behind the goal posts. When this is achieved, points are counted in a clerical fashion and in equal measure whether the goal was the result of a brilliant play or a lucky bounce. Are things different in science? When Einstein said that imagination is more important than knowledge, he favored the second part, but is this true for all professions? His very innovative theory of relativity only became possible after the remarkable Michelson-Morley experiment demonstrated that the speed of light is independent of direction. This experimental "hard" fact allowed creative imagination to take place. In some fields, things can get disparaging when people imagine the facts (e.g., the holocaust did not exist . . .) and attempt to draw conclusions in line with personal beliefs.

Let us ponder for a moment these two concepts in regard to hydraulic engineering. The reality in our field is that hard facts are sometimes difficult to obtain. For instance, the case of incipient motion of gravels under water remains elusive. Getting exact values of parameters describing the threshold of particle motion can be extremely difficult to extract given the turbulent nature of the flow and the random propagation of eddies. Should we talk about incipient motion as a "soft" fact in this case because of the stochastic nature of the process? In a broader sense, can anyone collect "hard" facts from stochastic processes? Another good example that our hydrology colleagues face on a daily basis is climate change. Can we accurately measure sea level rise at the level of approximately 1 millimeter per year when water levels vary daily by several meters according to wind, waves, and tides? Is global warming a "hard" fact or a "soft" fact? When does a "soft" fact become a "hard" fact? The issues of turbulence in hydraulics and climate change in hydrology do have a serious impact on the science of our profession.

This paper emphasizes the need to value both knowledge and creativity. Four subjects under abbreviated headlines are discussed: (1) My H&H Dream . . . ; (2) By the Year 2000 . . . ; (3) We all know . . . ; and (4) Where did the water go? This will be followed by a brief discussion on the essential elements of hydraulic engineering and then answers to questions from the audience.

My H&H Dream . . .

Hydrology and hydraulics are abbreviated as H&H. Over the years, I have had numerous opportunities to discuss the past, present, and future of H&H with Prof. Jose Salas, my friend and colleague at Colorado State University (CSU). Around a dinner table holding double-shot cappuccinos, we have pondered which of the *H*s stands for Heaven and which is closer to Hell.

My H&H dream started as a student at Laval University in the 70s when it was −30°C outside our library, which was kept warm by an IBM 360. Graduate students at Laval learned numerous linear techniques in hydrology such as instantaneous unit hydrographs.

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These black boxes were linearized for mathematical convenience. One day, our hydrology teacher introduced the idea of physically based modeling. He introduced a watershed model with 23 parameters, and the immediate comment was "Oh yes, it looks nice, but where are we going to find that many parameters on any watershed?" Well, this new concept fascinated me, and I poured countless hours into discretizing the 5,830 km^2 Chaudière Watershed at a 2-km grid. It was tedious to record the highest/lowest elevations for each pixel. The soil types were digitized from soil maps, and a land use code was developed from forest maps. Of course, no GIS existed back then, but new exciting times emerged when 72 kB of computer space on APL became available for watershed modeling. This sparked creative imagination, and detailed maps for topography and soil erosion losses from the universal soil loss equation (USLE) could be developed as shown in Fig. 1. It was just a prelude to an adaptation of the USLE to Canadian rivers, where 70% of the total annual sediment load is observed during snowmelt (Julien 1983).

When I joined CSU in 1983, the world of computing drifted toward personal computers. The pressure toward tenure was real, and my colleagues reminded me that nothing could be done without a VAX. Somehow stubborn, I believed that personal computers would eventually become fast enough for physically based hydraulic calculations on entire watersheds. With several graduate students (Richardson and Julien 1994; Saghafian et al. 1995; Ogden et al. 1995), we dropped the peeks and pokes, XTs and ATs, and welcomed the new PC 286-386s. At that time, we could start to look into dynamic codes to calculate infiltration rates from an explicit solution to the Green and Ampt equation. Surface flow could be calculated with Manning's formula based on the surface roughness coefficient. However, the algorithms for surface runoff calculations were very unstable at first, as we tried all sorts of numerical schemes based on the method of characteristics. Inspired by the work of David Woolhiser on a cascade of planes, I resorted to a simple explicit formulation of the two-dimensional (2D) diffusive wave formulation of the Saint-Venant equations which was unconditionally stable, but the price to pay was a short time step. At first, the model was too slow, but we capitalized on the fact that computers were accurate and developing rapidly. Thus, I persevered in thinking that one day we may be able to use grid sizes fine enough for our calculations. The gamble paid off, and our CASC-2D model was describing a 2D cascade of planes flowing into a 1D main channel. By the late 1980s, we were sharing our results and source code with colleagues at the Waterways Experiment Station. Both Billy Johnson and Jeff Jorgeson joined us for their doctoral work (Johnson et al. 2000; Jorgeson and Julien 2005). The next step was sediment transport and radars, which we figured out rather quickly. We then thoroughly tested the model with 15 minimum flow and sediment measurements at Goodwin Creek, Mississippi, during summer rainstorms (Rojas et al. 2008).

Around 2000, the EPA had a superfund site at California Gulch, near Leadville, Colorado, and we intended to include the effects of heavy metals in our simulations. We became interested in the toxicity from dissolved, adsorbed and particulate phases of Zn, Cu, and Cd. With a great command of environmental problems in Wisconsin, Mark Velleux joined us, and he coupled CASC2D-SED with WASP5. This was quite a difficult task because the output from the first model would not interface well with the second. Mark and John England from Reclamation rewrote the entire code, which we renamed *TREX* (two-dimensional runoff erosion and export. The model deals with water, sediment, and heavy metals (Velleux et al. 2006; England et al. 2007). I showed a TREX movie from California Gulch during my lecture, but for this article let me simply refer to Fig. 2, where the flow depth on a 30-km^2 watershed around the city of Leadville is calculated for a 100-year storm.

At a 30-m resolution, the model calculates higher surface runoff rates from urban areas and much lower rates from forested areas. The infiltration rate depends on soil characteristics. On this pervious watershed, the upland areas dry out promptly as rainfall ceases and the runoff concentrates in the lower areas. The flash flood rapidly develops and overtops the main channel to spread onto the floodplain. Overbank flooding lingers for quite some time, and the water either returns to the main channel or infiltrates the floodplain areas (Julien and Halgren 2014).

This approach encapsulates my H&H dream because it bridges the gap between statistical hydrology (rainfall at a given return period) and hydraulics with flow depths and velocities. As you

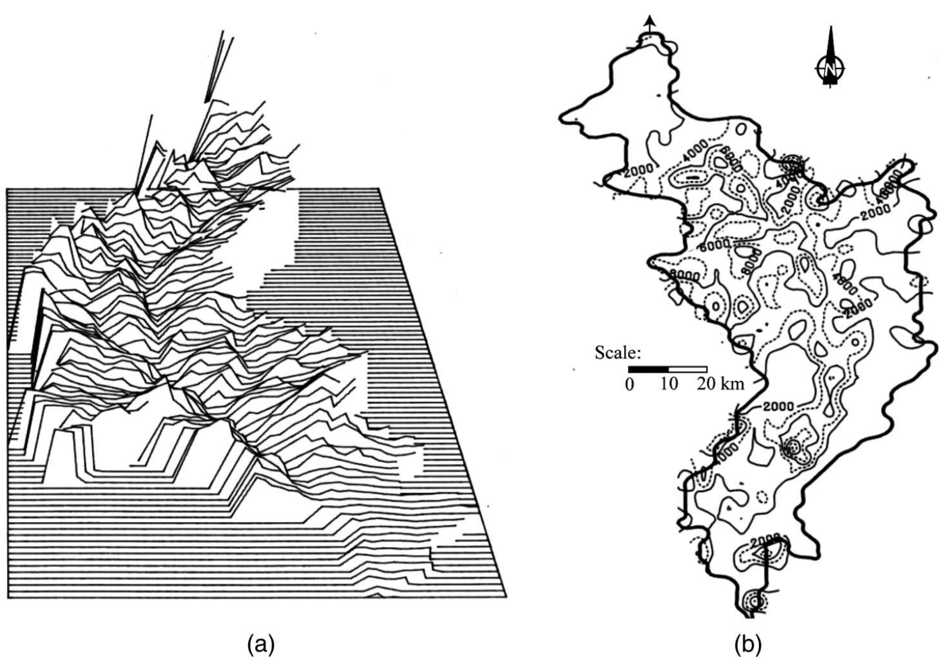

Fig. 1. Chaudière watershed: (a) topography; (b) upland erosion losses (adapted from Julien 1979)

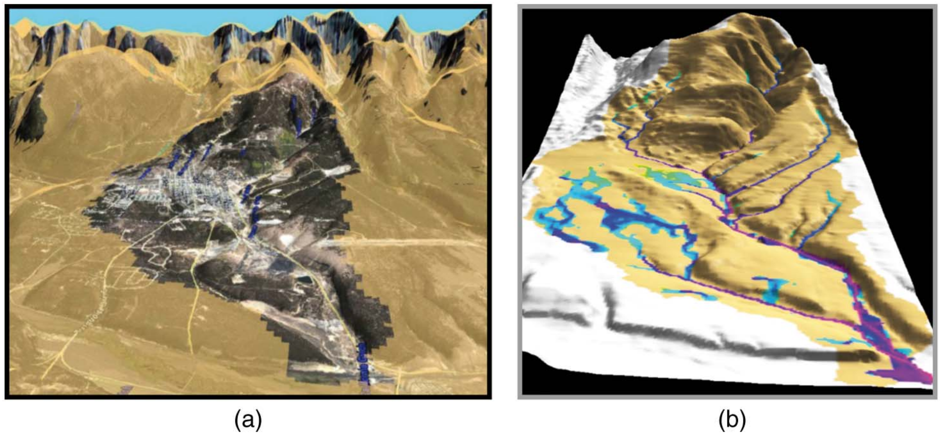

Fig. 2. Flow depth from *TREX* at California Gulch, Colorado, during 100-year storm

can see, this model offers detailed quantitative information on distributed surface runoff. Fig. 2(b) also illustrates the nonlinearity of runoff processes, including converging/diverging surface flows and the complex connectivity between the main channel and its floodplain. The simulation results present a completely different way to look at hydrology from what I learned as a student. For some time, there were lingering thoughts that models like this were closer to Hell whereas measurements were treated with heavenly praise. Nowadays, there is no doubt that the combination of physically based computer models like TREX with field measurements results in extremely powerful tools for hydraulic engineers.

By the Year 2000 . . .

In the 1990s, some keynote speakers at renowned international conferences gloated about revelations such as "By year 2000, all hydraulic problems will be solved with computers . . . " Although we carried out extensive experimental research at the CSU Hydraulics Laboratory, this statement raised major concerns among faculty members of my generation. In hindsight, the impact of computer modeling has been real, but still there are problems we cannot solve without the use of our large Hydraulics Laboratory.

For instance, the problem of incipient motion of a submerged sediment particle illustrates the need for physical modeling. From the force diagram on a particle, the ratio of the drag force to the submerged weight defines the dimensionless Shields parameter. Incidentally, DuBoys had defined this parameter long before Albert Shields was born. Nevertheless, to investigate bed-load particle velocity, a simple set of plates with uniform granular roughness was set up in our laboratory. The plates were placed in a flume under steady uniform flow and we would roll gravels, marbles, and bearings of different sizes, angularity, and density [Fig. 3(a)]. The measurements were repeated 10–15 times to define averages and standard deviations. On the weekends, we would even venture some particle races, and it was not that simple to find the fastest particle for all conditions. Large spheres were best on smooth plates, but one had to be careful selecting the fastest particle on rough surfaces. Very large particles would not start rolling but smaller ones would often get stuck.

Nowadays, we teach our engineering students that the Shields parameter τ_{*ds} for gravels at incipient motion typically ranges from 0.03 to 0.06, which our experiments confirmed. At a Shields parameter equal to 0.01, conventional wisdom dictates that a particle would not move (Julien 2002, 2010). However, for a particle of size d_s much larger than the plate roughness k_s, this is amazingly not what we observed in the laboratory [Fig. 3(b)]. Particles did move at values of the Shields parameter as low as 0.0008—a value much lower than predicted by the Shields diagram. Obviously, the need for physical modeling is still relevant today. Experimental

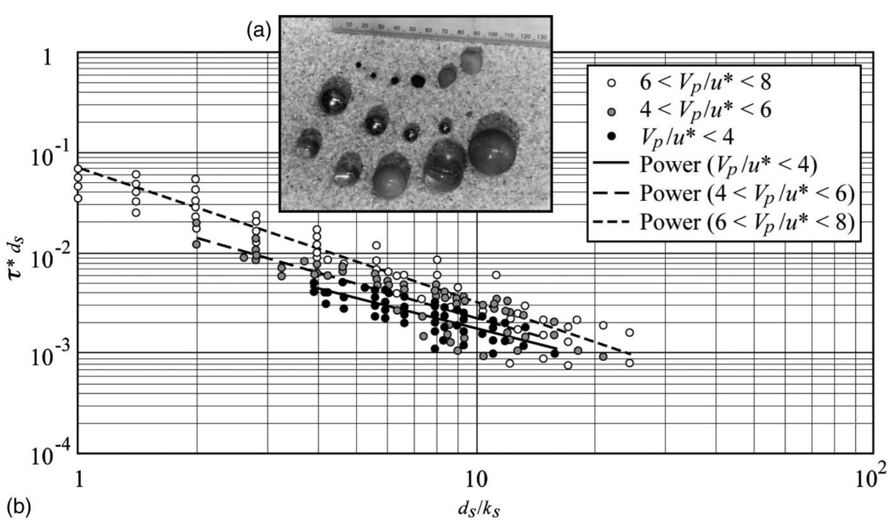

Fig. 3. Laboratory experiments on bed-load particle velocity [(a) reprinted from Julien and Bounvilay 2013, © ASCE]

research can provide information that cannot be obtained by the exclusive use of textbooks and computer models.

We All Know . . .

We all know that the maximum velocity in open channels is usually observed below the free surface. This velocity dip phenomenon has appeared in hydraulic engineering textbooks as far back as the 1950s in Chow's *Open-Channel Hydraulics* (Chow 1959). However, this observation is quite disturbing because the reason for observing a negative velocity gradient near the free surface is very difficult to understand. Is there a nonzero shear stress at the free surface? Well, the Prandtl and von Karman logarithmic velocity profile was applied to open channels by Keulegan as far back as the 1930s. Accordingly, velocity always increases with depth. In the 1950s, Coles developed a wake-flow function that is always positive. The wake-flow function became quite popular in the 1980s when Neil Coleman at the National Sedimentation Laboratory used it successfully in a set of careful flume experiments. Unfortunately, the log-wake model does not solve the issue of a maximum velocity below the free surface. Junke Guo and I looked at this problem with a new perspective based on secondary flows. Secondary flows are quite complex but compatible with wake-flow functions. We developed a modified log-wake model after including boundary conditions in the differential equation. The result shown in Fig. 4 is in very good agreement with both small-scale laboratory and field measurements on the Mississippi River (Guo and Julien 2008). Is it appropriate to ask what took so long to solve this problem?

Our hydraulic engineering profession is filled with a number of observations that remain poorly understood at this time. We should cherish the opportunity to have a fresh look at these problems. This example highlights the fact that field measurements alone can only bring us so far. Several new developments can emerge from the complementarity between theory and practice. We should be guided by our ability to develop new understanding that is theoretically sound and yet in tune with laboratory and field observations. These results have a better chance to serve a purpose in engineering practice.

Where Did the Water Go?

We hear about climate change, but is this real? One day, my friend Drew Baird at Reclamation showed me a photo of a sediment plug on the Rio Grande in New Mexico. The river was filled with sediment but the water was completely gone. We normally have situations where water is all over the place and we have to find out where the sediment is going to go. In this case, we were facing the exact opposite: sediment all over the place and asking ourselves, "Where did the water go?" The fundamental question is this: Do we know how sediment plugs form? Many would be tempted to start first with setting up a computer model to try to solve this problem. At some point, it has been proposed to program all the known physically based equations and ask the computer to tell us which ones fit the data. ... Let us be careful here. Before getting into computations, we first need to understand the physics of our problem. As long as we do not have a clear concept of what is mechanically happening, we should refrain from calculating anything! As much as I enjoy and fully appreciate numerical models, there is no miracle model. So how are we able to understand the mechanics of this problem?

Before any calculation, physical understanding should emerge from a phase of observation. As a kid, my son had a great expression for this process: "Dad, just watch and learn!" This catchphrase can take a while to gain traction, but it is the necessary first step. For the complex case under discussion, the Rio Grande at the plug site was braided in 1996 and was a single-thread channel in 2006. As we seek physical understanding about rivers, fluvial geomorphology is often very helpful but not always. Clearly, a braided channel barely transports its excessive sediment load compared with a single-thread channel. This reach of the Rio Grande obviously became more efficient from 1996 to 2006, so why would a plug form in 2008?

Sedimentation is a hydraulic engineering problem caused by backwater effects. Sharp river bends and bridge contractions can choke the flow and induce backwater. This turns out to be the correct starting point! Indeed, the bed material and flow conditions combine to a high Rouse number with high near-bed sediment concentration. Clear water spills onto the overbanks, resulting in a sediment overload in the main channel. Yes! It is only with this physical insight that we can now start looking for a model that can simulate backwater effects with Rouse concentration profiles. None exist, but we can develop our own or modify an existing model to simulate this process. In summary, this discussion emphasizes the need for observations leading to physical understanding before starting any numerical model.

Essential Elements

The previously mentioned examples point toward the description of "essential elements" that helped me gain a better understanding of hydraulic engineering processes over the years. In Fig. 5(a), the complementarity of theory and practice is sketched like the yin and yang of hydraulic engineering. New theories should be developed to solve practical problems with sound engineering practice grounded in solid theoretical understanding. The velocity dip

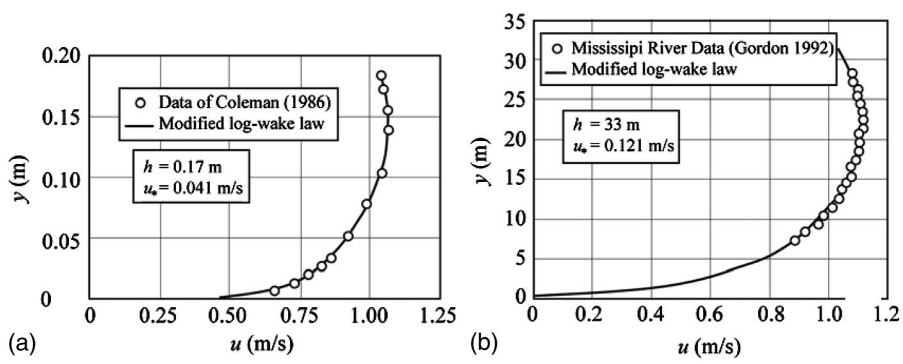

Fig. 4. Modified log-wake velocity profile (a) in a flume and (b) in the Mississippi River

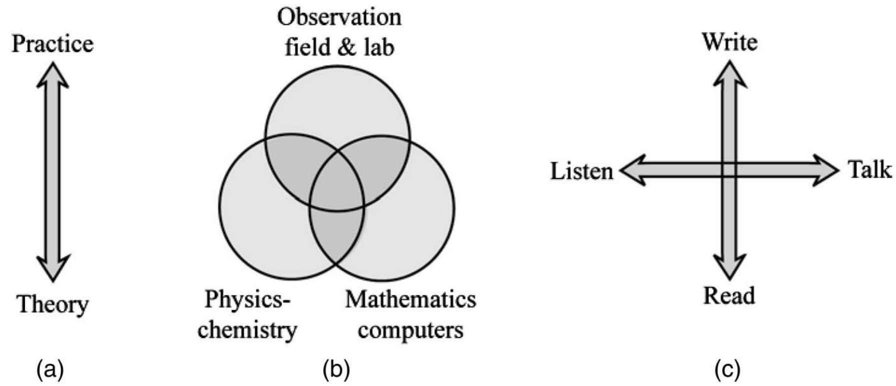

Fig. 5. Essential elements of hydraulic engineering: (a) theory and practice; (b) triangular components; (c) communication

phenomenon is a good example of this powerful complementarity. The value of theoretical models in solving problems that cannot be observed is greatly diminished.

Although engineering practice may be our ultimate goal, there is an essential need to understand the underlying mechanics. Fig. 5(b) shows a three-way sketch with observation above physics and mathematics. The sediment plug of the Rio Grande discussed earlier is a good example of this three-way interaction. It is interesting that the field of observation spans both field measurements and laboratory experiments. It involves our own senses as much as our sensors. For instance, some people have tremendous memories for events and names. At the close of meeting with many new people, someone can remember who is who and all that has been said. Over the years, I have found that observational skills can be developed at work as much as when playing games and music. The circle of physical understanding relates to any cognitive relationship between observations. It is not limited to physics and can include chemistry, biology, and so forth. The last circle of mathematics involves all calculations and includes logic and computers. Arithmetic deals with equal units whereas geometry deals with unequal sides and angles. Nowadays, our engineering classes can readily expand mathematical skills to include Bessel, Neumann, and complementary error functions. These functions, now available on spreadsheets, can solve interesting wave propagation and diffusion problems.

It is essential to master all three elements of Fig. 5(b) to solve hydraulic engineering problems. Detailed computer models with physically based equations (e.g., *TREX* in Fig. 2) become really powerful when calibrated with field observations. Although it is possible to link mathematical models directly with laboratory/field observations, extreme caution should be exercised when models are without any physical understanding. For instance, the use of a family of methods including regression analysis and neural networks can lead to incorrect interpretation. Let me simply illustrate. Over a long period of time, data can be collected about stage and discharge in a river. A plot of discharge as a power function of river stage can be developed with high correlation. Nevertheless, it would be erroneous to infer very high discharges if the river is turned into a deep reservoir. The relation is mathematically sound and based on observations, but the reader notes the lack of physical understanding regarding backwater effects.

Fig. 5(c) emphasizes the importance of communication in hydraulic engineering. This is particularly true in the classroom, and all elements from Fig. 5 are integrated in this last example. When asked to give a lecture about non-Newtonian fluids, I usually bring a bottle of clear hand sanitizer to class, which I shake and use first before passing it around to the students. Students are usually very suspicious of being handed anything but paper from their teacher. Many students pass the bottle straight on to their neighbor with a "no-thanks" glare. When a student asks, "Did you see the bubbles in the gel?" I respond, "Ah thank you!" with my best smile. This prized moment is the dedicated teacher's reward: someone understands!! Yes, of course, bubbles got trapped in the gel and did not return to the surface, even after a very long time. How can this be? Well, the yield strength has not been exceeded, preventing deformation of the fluid. If it were only for high viscosity, the bubbles would move very slowly but would not remain captive inside the gel. Based on our observations, physical reasoning emerges before a mathematical treatment. Nowadays, a formula can define the maximum bubble diameter captured in non-Newtonian fluids (Julien 2010). Rather than starting at the board with a bundle of non-Newtonian equations, the communication with students started from an observation that turned into physical understanding before the mathematical treatment of the problem.

Questions and Answers

Keeping time for questions generated interest in at least part of this lecture.

Q. What are the promising research areas in hydraulic engineering?

A: Well, this is a million-dollar question. I'd say that the future belongs to the young participants in the audience. They will embrace the latest technology to solve the complex engineering problems of our times. However, to be more specific about your question, let me suggest five promising research areas.

First, one of the greatest global challenges before us is to mitigate natural disasters (Julien 2015a) and provide drinking water to all on Earth. Our involvement is needed to educate and collaborate with the new generation of water experts around the globe. Although it is still possible to have flooding and water quality problems here at home, the challenges abroad are considerably greater (e.g., Julien et al. 2010). Clean water issues in the United States may be refined beyond pesticides and fertilizers to include pharmaceuticals and taste-odor problems.

Second, there is a need to continue developments in environmental hydraulics. This broad area includes aquatic habitats for endangered species (e.g., Leon et al. 2009); riparian and hyporheic zones with macroinvertebrates; and interaction with changes in hydrology, hydraulics, and anthropogenic activities, including urbanization, sand/gravel mining, water quality, nitrates and phosphates, acid mine drainage, radio nuclides, and the like.

Third, the role of reservoirs and their conjunctive use as a source of clean water, including flood control, irrigation and water supply, hydropower, and environmental needs will remain an active research area in the face of decreasing storage capacity from sedimentation (e.g., Shin and Julien 2011). Our new millennium has emphasized dam removal, and recent droughts offer a unique opportunity to recalibrate the pros and cons of reservoirs.

Fourth, we should replace black-box models with physically based models (e.g., Shah-Fairbank et al. 2011). There is no point in using models that do not make physical sense. We also need to introduce uncertainty, climatic variability, and stochastic processes into hydraulic models.

Fifth and not least, we need to better understand turbulence and more specifically the fluid-sediment interaction (e.g., An and Julien 2014). There is also a need for better physical and mathematical understanding of incipient motion, bed forms, ripples, and dunes. For instance, the "rose petal" shape of some ripples reveals a well-organized turbulent fluid-sediment interaction.

We still have a lot of work to do and the future will be exciting.

Q. What are your thoughts about climate change?

A: This is a great question, which I briefly broached in the presentation on sediment plugs. Reclamation and the Corps of Engineers are very concerned about climate change. In April 2015, Governor Jerry Brown announced a 25% water use reduction in California. At that time, Oroville Lake was already quite low and we could sense the economic impact of the announcement. Without snow on the ground, a reservoir that is normally half-full turned out to be half-empty. It goes without saying that we take the role of reservoirs for granted. Simply stated, the drought in California would have been a lot worst without reservoirs.

Global warming impacts the balance between the accumulation of rain and snow. A snowpack serves as a system integrator where frozen moisture accumulates over large spatial areas for several months and melts more or less at the same time each year. This brings a lot of stability to our ecosystems. In contrast, rainfall patterns from thunderstorms can be viewed as differential elements where precipitation falls in large amounts within short periods of time over relatively small spatial areas. Accordingly, the change from snowmelt to rainfall results in sequences of floods and droughts, localized flashfloods, extended stress on vegetation, forest infestation (e.g., pine beetle), and forest fires, as we have seen in Colorado and California. One hurdle in terms of public opinion stems from the "soft" fact aspect of stochastic climate variabilities. It is difficult to ascertain the effect of climate change with and without the greenhouse effect. However, some hard facts regarding global warming remain: higher sea surface temperatures induce stronger hurricanes, and this can have devastating effects. We can therefore expect an increase in the frequency and magnitude of hurricanes (and typhoons in the Pacific; see Park et al. 2008; Ji et al. 2011) as a result of global warming. The sea level rise has been measured at approximately 1–2 mm per year in San Francisco, and at a much higher rate in the Mississippi River delta. In April 2015, my presentation at the World Water Forum in Korea focused on the prospective effects of climate change on rivers and water resources (Julien 2015b).

Q. What keeps you going in your professional life?

A: This is an amazing question and a more personal one. Frankly, I did not reflect much about this, but can gladly share some personal insight. My early enthusiasm dates back to my student years in Québec. I enjoyed parallel studies in classical music at the conservatory and civil engineering at Laval University. Marcel Frenette was my distinguished mentor and former President of the Canadian Society for Civil Engineering. In 1973, he gave me my first opportunity for summer work on an international team at the Matamek River Research Station. We measured hundreds of velocity profiles and collected many sediment samples. Our field work assisted salmon biologists from other Canadian universities and the Woods Hole Oceanographic Institution. I am also deeply grateful to professors Verrette, Soucy, Ouellet, Michel, and other who stimulated my early academic career while teaching at Laval University in 1979.

My CSU colleagues and particularly Professors Richardson, Abt, and Salas provided support and friendship over the decades. When I joined CSU, D. B. Simons and H. Rouse quickly became role models. Daryl's dynamic and entrepreneurial spirit is still alive at the Engineering Research Center (ERC) (Bhowmik et al. 2008). Disciplined and rigorous, Hunter Rouse was the ultimate perfectionist. He would lecture every day for eight weeks and the weekends were always too short to study all we needed to know for the Monday quizzes. His summer class required drawing flow nets below a sluice gate. After defining potential and streamlines, perfect circles had to fit within each cell. My nice work with a HB pencil was not good enough in the eye of Dr. Rouse because the lines were too thick. My work had to be redone with a 2H pencil. I found tremendous inspiration in his fluid mechanics books, which explain very complex problems with amazingly terse simplicity.

In 1984, I met my wife Helga who supported me throughout my entire career at CSU. It is clear that without her support, I would not have delivered this lecture. Nowadays, Helga and our son Patrick remain my main source of motivation. Helga enjoys reminding me in the morning: "Oh No! Not Again! You just look like an engineer." A statement to which I simply reply: "Yes, this is what I am: a hydraulic engineer." Thank you for your attention!

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