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What Is Hydraulic Engineering?

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Abstract: This paper, written to mark ASCE's 150th anniversary, traces the role of hydraulic engineering from early or mid-twentieth-century to the beginning of the twenty-first century. A half-century ago hydraulic engineering was central in building the economies of the United States and many other countries by designing small and large water works. That process entailed a concentrated effort in research that ranged from the minute details of fluid flow to a general study of economics and ecology. Gradually over the last half-century, hydraulic engineering has evolved from a focus on large construction projects to now include the role of conservation and preservation. Although the hydraulic engineer has traditionally had to interface with other disciplines, that aspect of the profession has taken on a new urgency and, fortunately, is supported by exciting new technological developments. He/she must acquire new skills, in addition to retaining and improving the traditional skills, and form close partnerships with such fields as ecology, economics, social science, and humanities.

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Introduction

The answer to the title question will be framed by the experience of the individual reader. Hydraulic engineering is a broad field that ranges from the builder to the academic researcher. Without such a range it would not be the dynamic field that it is and, more importantly, it could not have contributed to society in the positive way that it has over the past century, and it would not continue to be a viable, challenging, and important profession. To illustrate the historical perspective to this question, and in so doing illustrate the evolution of hydraulic engineering, the present work uses one of the more visible activities involving hydraulic engineers—large water projects and especially dams in the United States. The reader, though, should not be misled into neglecting the myriad of other activities in which hydraulic engineers engage, some—individually or in combination—equally important to dams. The huge increase over the past 150 years in understanding of flow processes, especially those that occur in nature, and the associated ability to quantify these processes for analysis, design, and prediction is especially important.

However, the direct answer to what is hydraulic engineering does not lie solely in its history. The profession has always been a leader in the use of the latest technology; thus, technological innovation plays a vital part in the modern practice of hydraulic engineering. Innovations include modern computation, including techniques to make detailed flow processes and their complex interactions with other processes easily understandable. They also include the use of modern electronics for data gathering in the laboratory and the field and a myriad of other tools such as satellite photography, data transmission, global-positioning satellites, geographical data systems, lasers for laboratory and field measurement, radar, lidar, and sonar. Most importantly, they include the hydraulic engineer's interaction with the natural environment and ecology, an interaction that holds great promise and challenge. Indeed, the challenges of the last century, brilliantly solved by the collaboration of academics, small and large private companies, and government action agencies, are being replaced by new demands that will require even more interchange.

That interchange—not a new theme, but one that is beginning to dominate the future of hydraulic engineering—is the primary focus of this paper. First, however, we take a look at where hydraulics has been. A half-century ago the answer to the title question was obvious. The decades at mid-twentieth-century constituted the heydays of hydraulic engineering. It was the big-dam era, the time of large irrigation projects, large power projects, large flood-control projects, large navigation projects—large projects! Strangely, that era was short lived, at least in the United States, because of economic and ecological considerations. It lasted only about a half-century. Where does that leave hydraulic engineering at the beginning of the 21st century? What is hydraulic engineering now in an era of substantially increasing interdisciplinary developments?

A Time of Construction

Fig. 1 shows the history of dam construction in the United States from 1902 to 1987 in five-year periods. Immediately after World War II, dam construction surged, but it tapered off to very little by the late 1980s. Table 1 shows the largest U.S. dam projects, approximately 10 by height of dam and approximately 10 by reservoir size. All the projects on the list were completed between

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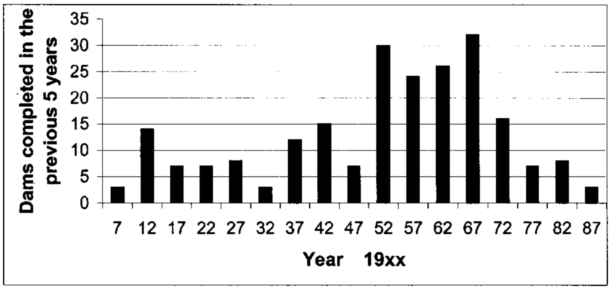

Fig. 1. A summary of dam building in the United States, 1902–1987 (Redrawn from Rhone 1988)

1936 and 1979. It is remarkable that dam building—or at least the largest dams—in the United States occurred in about a half-century.

The prevailing philosophy, both in society and in engineering, in the early and midparts of the century was that we could conquer nature and put it to the use of mankind. In particular, the case for dam building was compelling: dams provided flood control; they provided storage for irrigation and water supply, especially important in the arid west; they provided (what was then) a substantial amount of electrical power; and they provided recreation. The success of Hoover Dam (1936) as one of the nation's monumental construction projects—the largest attempted up to that time in the United States and the world—seemed to prove the point. As Reisner (1986) said, Hoover Dam's ''turbines would power the aircraft industry that helped defeat Hitler, would light up downtown Los Angeles and 100 other cities. Hoover Dam proved it could be done.'' (Appendix I, Economics and War) The total number of dams in the United States grew to 75,000. Hydraulic engineers were building the U.S. economy (with a bit of credit to the structural engineers who designed and built the structural aspects of water resource projects) and, perhaps, we suffered a bit from the ''monument syndrome'' (Hirshleifer et al. 1960).

Of course it was not all dams. Flood control, irrigation, water supply, groundwater, and many other areas of civil engineering were the subjects of hydraulic engineering, and activity in those areas was equally vigorous. Although structural engineering would continue to employ more than any other specialty of civil engineering, hydraulic engineering was the glamour specialty and was surging. The big-dam era is symbolic, but hydraulic engineering in the twentieth century was about much more. The following were some other notable projects, to name a few.

The California Water Projects. Southern California, a region with a large population and little water, began its search for water in 1904 with the Owens Valley Project (completed 1913). After the construction of Hoover Dam and Parker Dam, the Colorado River supplied water to California to supplement that from Owens Valley. In an insatiable search for more, the California State Water Project was begun in 1960 to bring water from Northern California (Oroville Dam on the Feather River) to Southern California (Fig. 2). All of these projects have generated controversy, but they have enabled Southern California to grow and have opened the region, especially the Central Valley, to supply fruits and vegetables that feed the nation.

The Central Arizona Project. Dams along the Salt River, primarily Theodore Roosevelt Dam (1911, the first multipurpose project constructed by the Bureau of Reclamation), supplied water for irrigation and domestic use to the Salt River Valley. The Central Arizona Project (completed in the 1980s) transfers water to the cities of Phoenix and Tucson from the Colorado River. It consists of an aqueduct (336 miles long) from the southern end of Lake Havasu (Parker Dam) and includes 15 pumping plants, 3 tunnels, and a dam with storage reservoir (New Waddell Dam and Lake Pleasant).

The Arkansas River Project. The Arkansas River Navigation System was approved by Congress in 1946 and completed in

Table 1. Largest Dams and Reservoirs in the United States

Dam	River	State	Type	Height (m)	Reservoir Cap ($m^3 \times 10^9$)	Year
Oroville	Feather	Calif.	Earthfill	230	4.30	1968
Hoover	Colorado	Ariz.-Nev.	Arch	221	34.85	1936
Dworshak	North Fork Clearwater	Id.	Gravity	219	4.26	1973
Glen Canyon	Colorado	Ariz.	Arch	216	33.30	1963
New Bullards Bar	North Yuba	Calif.	Arch	194	1.18	1970
New Melones	Stanislaus	Calif.	Earthfill	191	2.96	1979
Swift	Lewis	Wash.	Earthfill	186	0.93	1958
Mossyrock	Cowlitz	Wash.	Arch	185	1.60	1968
Shasta	Sacramento	Calif.	Gravity	183	5.61	1945
New Don Pedro	Tuolumne	Calif.		178	2.5	1971
Hungry Horse	South Fork Flathead	Mont.	Arch	172	4.28	1953
Grand Coulee	Columbia	Wash.-Ore.	Gravity	168	11.79	1942
Ross	Skagit	Wash.	Arch	165	1.90	1949
Fort Peck	Missouri	Mont.	Earthfill	76	22.12	1940
Oahe	Missouri	S.D.	Earthfill	74	27.43	1962
Garrison	Missouri	N.D.	Earthfill	64	27.92	1953
Wolf Creek	Cumberland	Ky.			4.93	1951
Fort Randall	Missouri	S.D.	Earthfill	50	5.70	1953
Flaming Gorge	Green	Utah	Arch	153	4.67	1964
Toleda Bend	Sabine	La-Tex.			5.52	1968
Libby	Columbia	Mont.	Gravity	129	7.17	1973

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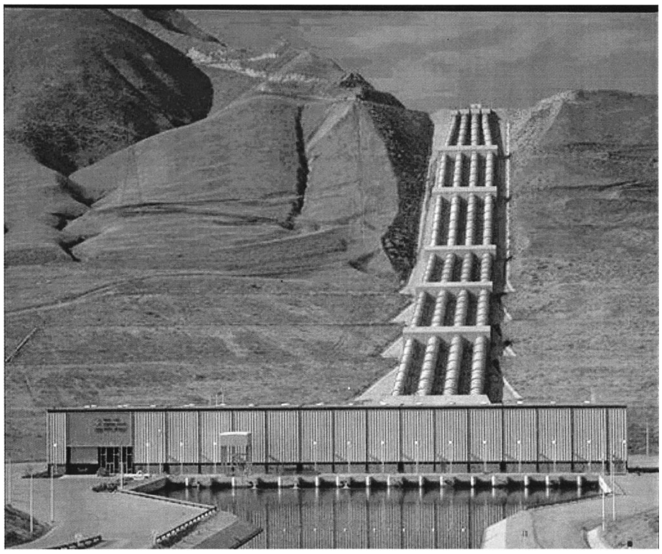

Fig. 2. The Wind Gap pumps. A part of the water delivery system to Southern California, the A. D. Edmonston Pumping Plant lifts water nearly 2,000 feet up the Tehachapi Mountains where it then crosses through a series of tunnels to the Los Angeles Basin. It, along with other projects, enables the cities of Southern California to grow and prosper in an arid climate.

1971. It controls flooding and provides a navigable waterway for shipment of agricultural products, lumber, petroleum, and coal by means of 17 dams and locks along the waterway.

The Mississippi River Navigation and Flood Control Projects. Work on the Mississippi River has been continuing for so long that it seems almost forgotten as a major hydraulic engineering feat. The Mississippi River Commission, created by act of Congress in 1879, is responsible for flood control and navigation along the river (Fig. 3). The main stages of the navigation improvement program included a channel 9-feet deep and 250-feet wide at low water between Cairo, Illinois, and Baton Rouge, Louisiana (authorized in 1896), widening of the channel to 300 feet (1928), and deepening to 12 feet (1944). Channel improvement and maintenance are still under way along with a ship channel 45-feet deep from Baton Rouge to the Gulf of Mexico (authorized 1945). In the upper part of the river, 29 locks and dams have been constructed to create a 9-foot-deep channel to Minneapolis-St. Paul. It has become part of vast inland waterway from the Gulf of Mexico and Florida to Canada, the Great Lakes, and the St. Lawrence Seaway. After the flood of 1927, the Corps of Engineers began the process of levee construction. From Cape Girardeau, Missouri, to the Gulf of Mexico, the Mississippi is encased in levees and sea walls, as is much of the river to the north. The Mississippi projects have enabled the city of New Orleans to exist, have opened the central United States to the economic transportation of goods, and have enabled agricultural production unparalleled in the history of the world.

Fig. 3. The Mississippi River near Muscatine, Iowa. The photo illustrates the barge traffic on the river (''tows,'' although the barges are actually pushed by the tug). The series of pools is a fish hatchery. This site is near the Iowa Institute of Hydraulic Research Mississippi Riverside Environment Research Station, which is intended to study ecology and environmental considerations along the river.

The Tennessee River. In 1933, the Tennessee Valley Authority (TVA) was established for the multiple purposes of flood control, navigation, electrical power, water supply, and, importantly, for the economic development of a previously depressed region. TVA has made the Tennessee one of the most controlled rivers in the world.

This small sample indicates the importance of hydraulic engineering in mid-twentieth-century. All projects mentioned herein are in the United States, but similar activity took place throughout much of the world. Although the construction of big dams has ceased in the United States [Seven Oaks Dam (Southern California, completed in 1999) would not have made the list in Table 1 at 168-m high, but it is of substantial size, and was constructed for flood control], it continues in some parts of the world. These and other projects graphically illustrate the paradigm of controlling nature for the benefit of mankind. There is no question that they have brought great economic benefit to the entire nation and, regionally, to the areas in which they were constructed. Indeed, the first half of the twentieth century was a little Dark Age in the United States marked by the great depression and two world wars. Those who might criticize the engineering accomplishments of that time from a distance have not had to live under such conditions. For example, the TVA has transformed a poor, underdeveloped area of the country into one rich in energy resources and agricultural opportunities. If the title question on this paper had been ''What *was* hydraulic engineering?'' these, along with many other large projects and innumerable small ones, such as municipal water supply and groundwater management, certainly supply the answer.

A Time of Enlightenment

The compelling promise of large water-control projects and other hydraulic works was fulfilled completely. That activity was accompanied by a sort of revolution in knowledge and rational analysis that took place in engineering in the 1950s and 1960s. First, engineering had discovered its scientific basis. In hydraulic engineering, the landmark events were the publication of Rouse's (1938) book *Fluid Mechanics for Hydraulic Engineers* and Vennard's (1940) book *Elementary Fluid Mechanics*. These books and their followers set apart the teaching of hydraulics, a mostly empirical subject, from fluid mechanics, a subject based on mathematical analysis. Other branches of engineering were showing a parallel change. Rational analysis had become popular. This development created an optimism that with the proper mathematical analysis we could solve many nagging problems that were holding back progress.

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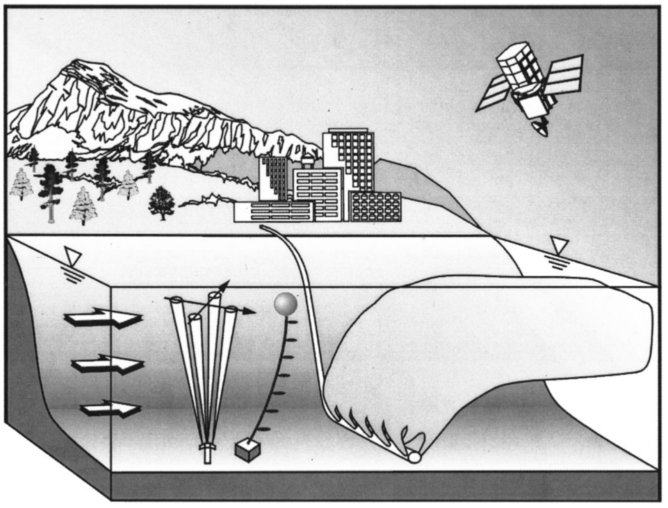

Fig. 4. Plume dynamics. The use of a multitude of sensors for velocity and concentration of substances coupled with satellite data transmission and used in 3D numerical modeling to solve pollution problems in waterways, lakes, and oceans is illustrated. Adapted from Roberts (1999).

Second, the computer became a practical tool for engineers in the latter half of the century. First used as a research tool in the late 1950s, their use spread to the engineering office in the 1960s and 1970s. Although numerical methods had been a sophisticated subject long before automatic computation, it now took on practical importance and held the promise to solve those equations that were presented in elementary and advanced fluid mechanics courses. Now, we believed, we really were on the verge of solving all the practical and relevant hydraulic engineering problems.

The first such solutions were those that we had been taught in the classroom but were laborious. Examples included the steady-state solution of pipe network problems and the calculation of open-channel flow profiles. Finally, hydraulic engineers had gained the ability to solve such problems as unsteady open-channel flow (Isaacson et al. 1954), but we learned from this development that simply plugging the equations into the computer was not an easy process. In fact the solution by Isaacson et al. (1954), the mathematicians, was largely a failure, and we had to await the advancement by Preissmann (1961)–a mathematician working for an engineering consultant, Sogreah—to show the way. The devil was in the details; it was not simply a mathematical exercise but required engineering judgement to determine which of the details were important and which could be ignored.

For the first time, our multidimensional and time-dependent problems seemed within our grasp (Fig. 4). The dimensional approximation (i.e., approximating a fundamentally 3D problem in two dimensions or a 2D problem in one dimension) was not always necessary. These developments led us to believe that it was only a matter of (a short) time before hydraulic engineering became a science almost as rational as physics. The world was filled with meaningful, interesting, and economically important problems, and we were gaining the means to solve them. It was a great time!

Time of New Challenges

If there was a single turning point it was probably the construction of Glen Canyon Dam on the Colorado River in northern Arizona. Environmentalists, primarily the Sierra Club, had criticized the dam since its inception. Glen Canyon is essentially the uppermost part of the Grand Canyon (Appendix, Glen Canyon), one of the jewels in the system of national monuments. To build power dams in the Grand Canyon seemed rather like harnessing the thermal energy of Old Faithful in Yellowstone National Park or using Yosemite and Bridalveil Falls for electrical power. Although such projects would be rejected by society today, it is interesting to recall a long-since forgotten plan proposed at the turn of the twentieth century by the English physicist and hydropower consultant Lord Kelvin (Burton 1992) to turn Niagara Falls into a grand hydropower plant (and, indeed, hydropower is currently being produced at that site).

Other dams have been proposed for the Grand Canyon area. The two most notable are Marble Canyon Dam (abandoned in the 1960s) and Bridge Canyon Dam (sometimes called Hualapai Dam as it is on the Hualapai Indian Reservation. It was officially canceled in 1984 but still shown as a dam site on many Arizona maps). Considerable exploratory work was done on these sites, especially at the Marble Canyon site. There are tunnels deep into the rock and innumerable places where core drilling took place [Figs. 5(a and b)]. Obviously, these dams were serious projects, and construction was almost begun. The Sierra Club takes credit for blocking the construction of these dams (although it once favored Bridge Canyon Dam in a resolution of November 12, 1949). However, economics and the realities of construction probably paid a significant role in the fact that they were never built. Marble Canyon Dam was to be placed in a limestone formation, bringing into question its long-term safety. Access to the dam site is difficult and would have necessitated costly construction of roads. Evaporation from the water-short Colorado River from the lake surface was a negative factor. A strong argument at the time was that hydropower was unnecessary because nuclear energy was to supply abundant electricity, so cheap that we would not have to meter it. (The Sierra Club was initially a promoter of nuclear power, but it has since changed its view.)

Everyone recognized that Lake Powell (behind Glen Canyon Dam) would flood the wild river, covering picturesque rock formations—said by many to be better than the Grand Canyon—and some archeological sites. However, there seemed to be little recognition at the time of the downstream changes. The Colorado River carries a heavy sediment load that is now being retained in Lake Powell. The river through the Grand Canyon has changed from a muddy stream to one that is more or less clear and carries significant sediment from the tributaries and side canyons only during the summer rainy season. The sediment no longer nourishes the beaches in the Grand Canyon and has changed the habitat for fish. Previously, the temperature of the water ranged from near freezing to the mid-seventies (degrees Fahrenheit). Now it is a near-constant 49 °F near Glen Canyon Dam and increases somewhat in the summer to the headwaters of Lake Mead. Flooding occurred on an annual basis; whereas, now the flow is relatively constant (Appendix, Flood) with the result that some of the larger sediment brought in by tributaries is not moved by the main river. The downstream ecology has changed forever, or at least as long as Glen Canyon Dam exists. The endangered natural fish will never be fully restored.

It is not clear, however, that the ecological changes are undesirable. The Colorado is now a cold-water trout stream; the fish seem more desirable. Those who use the river for recreation can now make use of the water (and are not constantly covered by mud in the rapids), which was impossible under former condi-

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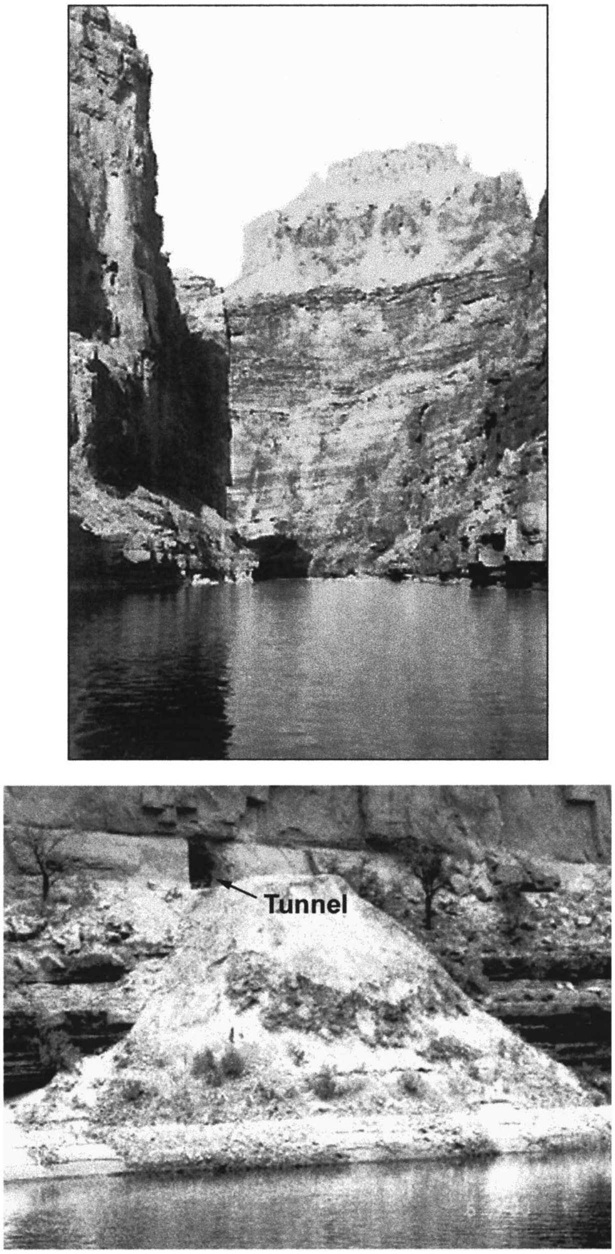

Fig. 5. Marble Canyon. Although not officially part of the Grand Canyon, most people consider it such, and it is in the Grand Canyon National Park: (a) The Colorado River consists of riffles and pools. The pool shown in the photo is natural, not the product of a dam, and reflects the colors of the Redwall limestone. Is this the perfect place for a dam or should it remain in its natural state for the enjoyment of future generations?; (b) Marble Canyon dam site. The hole in the cliff of the upper part of the picture is an exploratory tunnel in the Redwall limestone. The light colored material is tailings from that tunnel. There are several such tunnels on both sides of the river and numerous core drills branch from each tunnel.

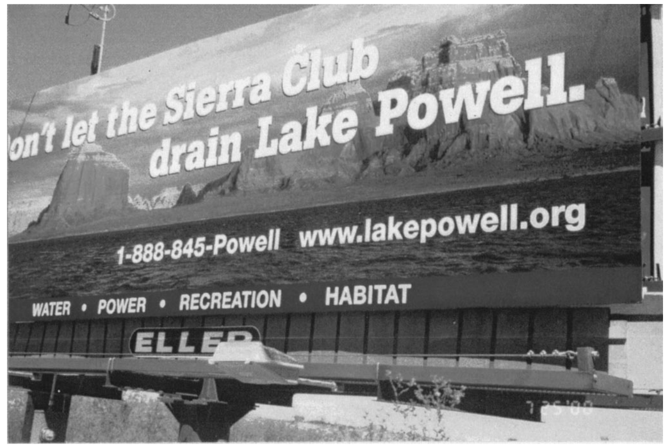

Fig. 6. A billboard that has been put up around Arizona. The Glen Canyon controversy invokes strong emotions on both sides. Many of these billboards have been vandalized, most commonly by painting out the line ''Don't let the Sierra Club'' so that it reads ''drain Lake Powell.''

tions. The issue raises the question: Is a change in ecology always undesirable?

Large dams have been attacked as inefficient, citing, for example, Lake Mead, which loses to evaporation 10% of the flow of the Colorado River, enough to supply Los Angeles. Some who initially favored the construction of Glen Canyon Dam have since changed their minds. Most notable was Barry Goldwater, former senator from Arizona, Republican presidential candidate in 1964, and a leader of the conservative movement in the United States. Senator Goldwater stated that the one vote in the Senate that he regretted was his vote for Glen Canyon Dam. Stewart Udall, three-term congressman from Arizona (first elected in 1954) and 8 years as Secretary of the Interior in the Kennedy and Johnson administrations, went from favoring three dams in the Grand Canyon to two dams to one dam to no dam (Fradkin 1981). Secretary of Interior Bruce Babbitt in the Clinton administration and former governor of Arizona now champions the cause of dam removal (although his efforts have been confined to relatively small dams). It is indeed notable that many who once favored the dam projects as economic pluses, and who ran for office on platforms advocating such projects, have now changed their tune. Secretary Babbitt, especially, has proposed eliminating a large number of dams in the United States and has been campaigning hard—with a symbolic sledgehammer in hand—to that end. Although Secretary Babbitt has stated that he is opposed to the destruction of Glen Canyon Dam, the campaign to remove the dam is in full swing, with the opposition vigorously defending the dam (Fig. 6). It is an emotional issue in the Southwest, with both sides holding demonstrations and generating a large amount of newsprint.

Also controversial is the situation on the Snake and Columbia Rivers where the salmon are endangered in part by the dams. (Fishing is, perhaps, the largest factor in the decrease of salmon, and agricultural pollution plays an important part). Unfortunately, the construction of fish ladders, guide barriers [Figs. 7(a and b)] and transportation of fish over the dams (primarily in the downstream direction because the dams are destructive to the smelt) have not solved the problem. Additionally, hatcheries have not been able to restore the natural cycle of salmon breeding and spawning. [The Corps of Engineers has spent more than $50 million per year on the Columbia River Salmon Program (USACOE 2000)]. Aside from the environmentalists' objections, those dams pit one economic interest against another—those who profit by the dams and lakes against who that profit by the fish and other features of the natural rivers.

The present situation has been the consequence of two factors. First, neither the public, lawmakers, nor the designers and planners of many of the projects appeared to realize the consequences

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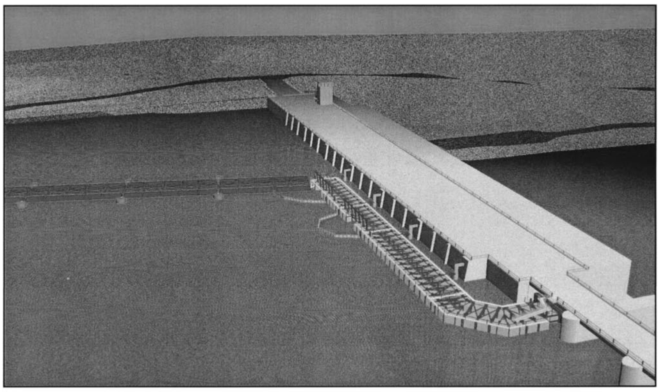
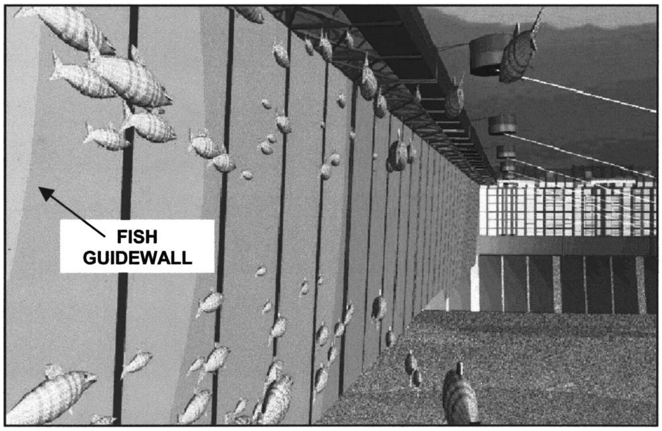


(a)



(b)

Fig. 7. A guide barrier for directing salmon smelt to a by-pass channel around hydropower turbines. The images are from a study by Weber et al. (2001); (a) Although such systems are at least partially successful, the early dams were constructed with no provision for migratory fish: (b) Numerical simulation of fish response to flow conditions along the guide barrier. Numerical codes not only simulate flow fields, they are being developed to simulate fish response to such flow fields.

of the projects. Those who opposed the dams were termed extremists. Benefit-cost studies were questioned at the time by eminent economists, but prodam interests always made sure that they indicated a favorable benefit/cost ratio. Most important was the intense lobbying by politicians of the areas in which the projects were to be built and the optimism expressed by local leaders of the economic benefits of the projects. Second, a change of attitude apparently has occurred among the citizenry. The new attitude is one of conservation of nature rather than conquering nature for our benefit. Loucks et al. (2000) ask, ''What will the desires of future generations be?'' and answer pessimistically, ''Clearly, our guesses about those future desires, even the educated guesses, will be wrong.'' [Despite such abject pessimism, Loucks et al. (2000) go on to discuss how ''sustainable water resource management'' might be accomplished.]

The ''irrefutable'' arguments in favor of dams have not just been set aside; they have been reversed, at least for the moment.

A Time of Reality

The promise of mathematically based solutions to the problems of hydraulic engineering was indeed fulfilled to a great extent, especially through the use of numerical methods. That is not to say that traditional engineering judgement became unimportant. In fact, the role of the engineer became even more crucial when interpreting computational results that might portray poor solutions. Before computer-based computation reached its ultimate conclusion, however, it ran into a serious roadblock, that of scale. Many of the solutions that we want occur at problem scales of a few meters to thousands of kilometers. Unfortunately, such solutions often depend on what occurs at the sub-millimeter scale (Liggett 1996). That fact makes the necessary discretization of equations clearly unachievable, now and in the foreseeable future. The example of long-term (say, 6 month) weather prediction is often used. In that case, the 3D, time-dependent equations would have to describe every blade of grass, every pebble on the beach, and the movement of all animals as well as the large-scale motion of the atmosphere. Not only is there no computer at present or contemplated that could handle such a problem, the task of describing initial and boundary conditions is beyond comprehension. The vast majority of hydraulic engineering problems suffer a similar difficulty. (Numerical analysts can point to considerable advances in computation with turbulence, e.g., large eddy simulation. Such advances will continue and form, perhaps, the most important area of modern fluid mechanics research.)

The result is that although numerical computations have not reached the end of their potential, future advances will depend on the speed of the machines and the power of the algorithms while advancing at a slower pace than once predicted and seemed to be obtainable 40 years ago.

A Time of Quandary

The pessimism expressed by Loucks et al. (2000) about forecasting the wishes of future generations might well be applied to determining the wishes of the present generation. The debate over the production and use of energy is symptomatic, and it is related to hydraulic engineering. Most water projects are either large users or producers (or both) of power. Moreover, hydraulic engineers have been active researchers on alternate sources such as ocean thermal and wave power and wind power. How should society address the problem of sufficient electrical energy?

Renewable sources include wind, direct solar, water, renewable biomass, ocean thermal, and tidal power. As attractive as some of these are, they all—or in combination—have serious difficulties. Wind and direct solar power can only furnish a fraction of the energy that we now use and both require an enormous area of land surface. Water power depends on dams and, even if the public favored more dam construction, economical sites are scarce. Renewable biomass is a form of solar power that also takes much area, has pollution consequences (Appendix, Pollution), and also does not seem capable of producing sufficient power. Ocean power is too widely dispersed to be economic.

Nonrenewable sources have the obvious disadvantage that they cannot be sustained over time. They consist of fossil fuels, nonrenewable biomass, and nuclear energy. The first two have pollution consequences. Nuclear energy is currently regarded as too hazardous in the United States, although much of the world is embracing it as a major source of energy. Breeder reactors, which cannot be built in the United States by law, largely because they can produce weapons-grade plutonium, can go a long way toward making nuclear power renewable. The problem of disposal of waste (largely a false problem in the opinion of the writer) is also greatly mitigated by breeder technology.

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Everyone favors conservation. Indeed the United States does seem to be profligate in use of energy, and could conserve a very large amount without a great change in the standard of living, although many life styles would have to undergo considerable change. However, even drastic conservation measures would only be a blip on the curve of increasing energy use. Assuming, say, a 20% decrease due to conservation, in a few years we would find ourselves in the same dilemma. That is not to say that conservation is not worthwhile, only that it is not a long-term solution.

Indicative of the quandary for hydraulic engineering are the changes occurring to the city of Phoenix. Phoenix recently adopted a flood-control policy in which the small streams (usually dry) would be allowed to flow freely and more or less naturally, instead of past policy in which they were encased in a concrete floodway. Such a change was, of course, applauded by conservationists. But the consequence is that the natural streams require much more space than the concrete floodways, space that could be used for parks or housing. Parks may be compatible with the space, but a restriction on housing decreases density, forcing building further out into the surrounding area and creating more urban sprawl, a current hot-button criticism of many cities. The Corps of Engineers has proposed a similar solution to parts of the Napa River (California) in which flood plains and marshes would be used to convey floods in place of concrete channelization.

There are many cases in which it seems impossible to have our cake and eat it. Do we really want rapid economic development or conservation? preservation of ecology or individual space? pristine forests or recreation? unspoiled national parks or universal access? freedom from traffic and destruction of environment by highways or freedom of individual movement? (many indicators point to a period of deconstruction for highways that may be comparable to the deconstruction of dams), more industry or less pollution? These and many more issues are at the nub of the dilemma of a sustainable economy in general and sustainable (Appendix, Sustainable) water-resource planning in particular. The nature versus growth question is illustrated by a sign in the agriculturally rich Mississippi River flood plain and flyway for migratory birds that asks, ''Food for folk or fowl?''

Thus, the twentieth century, so certain of the path to prosperity at midcentury, has ended in a quandary. A discussion of the question ''Where do we go from here?'' will most likely dominate the first half of the twenty-first century. In an increasingly integrated world, even the goals are not clear. Barrett and Odum (2000) state '' . . . politicians used to talk about 'the greatest good for the greatest numbers' as a goal for society. But this slogan is rarely heard now because society is finding out by experience that the greatest good, in terms of quality of life for the individual, comes when the numbers are not as high as they can possibly be—and when the per capita impacts are not maximized, either.''

A Cornell University ecologist has estimated that the resources of the earth could sustain a population of about 2 billion with a standard of living slightly lower than that of the present-day United States. That number is about one-third of the current population of the earth. The implication is that anything greater than 2 billion will mean a lower average standard of living. If the estimate is anywhere near correct, there are few or no ''developing'' countries; most of the earth's people are destined to spend their lives in poverty, and the pressure on ecosystems will only increase. Indeed, it is difficult to think of a major problem that is not either caused or exacerbated by population pressure. This issue is such a political hot potato with cultural and religious overtones that politicians avoid it. Its impact on every facet of modern life is such that it deserves an open and rational debate, including the choices that are available and their consequences. At present, such a debate apparently takes place mostly in the ecology and economics literature (Arrow et al. 1996; Barrett and Odum 2000). That issue, together with global climate change, will have a large impact on the future of hydraulic engineering as we attempt to supply an increasingly crowded world with water resources and energy. It constitutes a challenge equivalent to any that the profession has faced and, as usual, challenge equals opportunity.

A Time for Consilience and Opportunity

To say that hydraulic engineers must become more a part of a team approach to the solution of modern-day problems is somewhat trite, but it is a fact. Solutions, or at least best shots at solutions, to multifaceted problems lie in rational analysis and good design involving a variety of expertise. If construction required hydraulic expertise, so does preservation and restoration.

The professional responsibilities of the hydraulic engineer demand, in turn, that an effort be made to integrate disciplines involved in water-resource projects. Indeed, life itself does not exist without water, the substance that also gives life to our profession. Wilson (1998) has used the word ''consilience'' (Appendix, Consilience) to express the fact that knowledge in engineering, science, *and* humanities is interconnected. He states '' . . . true reform will aim at the consilience of science with the social sciences and humanities . . . Every college student should be able to answer the following question: What is the relation between science and the humanities, and how is it important for human welfare? Every public intellectual and political leader should be able to answer that question as well'' (Wilson 1998).

By virtue of the many issues they raise, water projects commonly merge engineering, science, humanities, and societal desires. However, integration can be difficult, especially when societal desires evolve and change. Even if it is difficult to predict the desires of the next generation, we have not been very conscientious in studying the impact of what we have been doing. Glen Canyon Dam was completed in 1963, but only in 1982 was the Glen Canyon Environmental Study initiated to determine if an environmental impact statement (EIS) on the operation of the dam was warranted [The National Environmental Policy Act (NEPA) of 1969 required Environmental Impact Statements. Glen Canyon was completed in 1963, several years before NEPA]. Seven years later, in 1989, that committee determined that an EIS was appropriate and such a study was undertaken. Another 7 years went by before the EIS was produced. [Perhaps it is symptomatic that a study to control temperatures downstream of Glen Canyon Dam for the preservation of native and endangered warm water fish has the late date of January, 1999 (USBR 1999).] Perhaps it is only in hindsight to say that the EIS process should have been completed *before* construction began. Thus, the view of Loucks et al. (2000) that planners cannot predict the wishes of future generations missed the point in this case. Planners did not even *know* what future generations were going to get.

It is probably not an exaggeration to say that in the 1960s such studies would have been unwelcome. The prevailing attitude among hydraulic engineers was ''Let's quit studying the project to death and get on with the job.'' That attitude was not without merit. Nonessential investigations and the resulting increases in cost could easily doom a major project and justify the critics' charges of cost overruns and schedule delays. Had many of those projects required present-day justification, much of their eco-

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nomic benefit would have been lost. From the point of view of the year 2001 with the critics campaigning to remove dams, many would say that such studies should have been considered crucial.

A Language Problem

Hydraulic engineers have always worked with nonengineering disciplines (economists, meteorologists, biologist, and others), especially in the planning of large projects. Outstanding examples include the salmon problem in the northwest [Figs. 7(a and b)], ecological studies along the Missouri River, and the operation of Glen Canyon dam. Such cooperation has steadily increased in the latter part of the twentieth century as its necessity has become more apparent. However, the research community has focused primarily on technical progress rather than on ''interdisciplinary studies.'' Interdisciplinary cooperation is not easy and is frequently frustrating.

First, we have to learn a new language—for example, what is ''nature's capital'' as opposed to economic capital (Barrett and Odum 2000) or ''gross natural product'' versus gross national product (Naudascher 1996a)? Even more frustrating is the fact that ecological and economic concepts are difficult to express quantitatively, and generally impossible to analyze using the methods of physics. When we bring in social science and humanities, that difficulty is multiplied many times. But a quantitative understanding of such disciplines is no more difficult than explaining the concepts of fluid mechanics, hydraulics, and hydrology to people uninitiated in hydraulic engineering. Finally, researchers who work on such projects are likely to receive little credit. Papers with no mathematics or only simple formula are considered ''soft'' to fellow engineers, and certainly engineers will have difficulty gaining a foothold in other areas. In research universities, tenure and promotion committees are likely to be suspicious of such interdisciplinary activities. Indeed, such suspicion is well founded and appropriate.

Although we have readily adapted advances in technologically based disciplines—computing, instrumentation, mathematics, numerical methods—into hydraulic engineering, the current challenge is different in that these areas speak the language of engineering and science; they are quantitative. In adapting technology to technological problems, productive and unproductive paths are quickly discovered. In attempting to integrate hydraulic engineering with ecology and social science, it is easy to become bogged down in largely unproductive rhetoric. When the goals are not well defined, the path to those goals cannot be clear.

Liquids in Nature

Hydraulic engineering is the application of fluid mechanics to the liquid earth. Although some applications involve man-made systems (pipe networks, for example), many deal with the complexities of nature. Those latter applications include river engineering; sediment transport; groundwater movement; lake, ocean, and reservoir dynamics (including the complications of stratification); waves; surface flow; and the alteration of natural flows by man, including pollution. Hydraulic engineering is clearly a field for those who love nature and who are comfortable in applying the laws of fluid mechanics for the betterment of mankind while preserving nature. It is a field that has changed in the last half-century, but the challenges were never greater than are those of the present day.

The technical (mechanical) challenges in hydraulic engineering are immense. No one could accurately predict the results of the artificial flood release of Glen Canyon in 1996 toward the objective of partial restoration of nature and natural habitat. Nor is this problem one of traditional hydraulic engineering because ''restoration'' is not simple; it contains multiple implications in the fields of ecology and biology as well as engineering. The immensity of the problems requires the instrumentation, simulation, and communications tools that increasingly are at our disposal (Fig. 4).

A Crossroads

In a real sense hydraulic engineering is at a crossroads. The midcentury challenges were met and largely conquered, albeit with inadequate foresight in some cases. That lack of foresight is only a minor factor in the problems of the twenty first century. In the United States, society has the luxury of debate whether to conquer nature for our economic benefit or to preserve nature for the enjoyment of future generations (and, perhaps, for their economic benefit). Hydraulic engineers can sit on the sidelines and simply do the bidding of the politician or we can influence the debate. Certainly the professional attitude *at the very least* requires us to lay out the alternatives as we know them and to perform the research to know the alternatives and their consequences as best we can.

The words ''water shortage'' are often heard. In the United States there is no permanent water shortage, anywhere (although temporary shortages may exist). The country is bordered by oceans that have an unlimited supply of water. Water is a commodity and, as such, it can be priced according to its supply and demand. With sufficient engineering works we can supply water anywhere, but of course at a price. Traditional hydraulic engineering is only a part of the determination of that price; the other part is the effect on ecology of the source and of the region that receives the water. Outside of the United States permanent water shortages occur in regions where the resources do not exist for its acquisition, either locally or by importation. Naudascher (1996a) argues that in such areas public works projects such as big dams have not helped the really needy. However, they have, without doubt, often contributed to the economy and the general welfare of several nations and to their political stability. Neither blanket condemnation nor blanket acceptance of such projects is a reasonable stance. The displacements of peasants by large dams and their inability to benefit from the irrigation, power, and recreation are well known and documented, but such displacements must be balanced against the destruction and forced relocations caused by flooding. According to Naudascher (1996b), flood control may contribute to impoverishment in that it eliminates the natural fertilization of the land through the deposition of silt and eliminates the flushing of salt. He also points out that these deprivations may actually be counted as benefits because the fertilizer industry increases sales and irrigation, drainage, and desalinization schemes—necessary due to isolation from the river—are added to the gross national product of the nation. Unfortunately, political power often rests in those that see only one side of the problem. Fortunately, the hydraulic engineering literature contains a much more balanced perspective than is common in the popular media.

A Time for Education

At midcentury, few thought that such considerations were the responsibility of the hydraulic engineer. Now it seems that they cannot be ignored if hydraulic engineers are to be professionals. The educational and research burden at midcentury was technical—fluid mechanics, mathematics, and a bit of economics

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along with subjects in hydraulic engineering. Now in addition to the traditional role we must be much broader, studying ecology, biology, resource management, a smattering of systems analysis, and related items plus humanities and social science. Although every engineering curriculum contains these latter two items, they are loosely required with only the vaguest of goals and no thoughts toward the unity of knowledge in the sense of Wilson (1998). In other words, the modern hydraulic engineer must be able to speak ''ecology'' in the broadest sense of the word. We must be team players with a variety of disciplines. To be part of a team, courses in the language and culture of ecology, biology, economics, social studies, and the humanities have to be a part of the education, including the continuing education of hydraulic engineers (Liggett and Ettema 2001). Our universities must do a better job of integrating disciplines—of consilience—than they have up to the present. Courses in these subjects should not be individual and unconnected hurdles on the path to a degree (Ettema 2000).

However, this approach contains its own hazards. ''Environmentalist'' is all too often a buzzword and signifies someone who cares about the environment but knows little science or engineering and is likely to embrace the latest ''green'' fad. One who calls him/herself an environmentalist is frequently regarded as a refugee from academia who cannot make it in science or engineering. Thus, the educational requirements for hydraulic engineers should not be relaxed. *No one should be able to call him/herself a hydraulic engineer until he/she has mastered the science, mathematics, mechanics, and engineering*. When dealing with environmental issues we must speak from a solid background, not repeat the dogma of the Sierra Club or other groups. Although the position of such groups often stems from expert knowledge and is the best that we know at the time, it is too often a knee-jerk reaction of those who seem to believe that everything man-made, especially a large engineering project, is bad.

A New Time of Hydraulic Engineering

The challenges of hydraulic engineering of the last half century remain. They can be stated as familiar questions: How can we better predict and calculate sediment transport? ice effects? open channel hydraulics? water supply for irrigation and municipalities? groundwater flow and groundwater remediation? How can we better link hydraulics, hydrology, and weather forecasting? How can we better characterize turbulence so that it does not defeat our calculations of diffusion, boundary friction, transport, and fluid flow in general? How can we better use computational fluid mechanics to study the complex problems that nature has given the hydraulic engineer? How can we design better and more efficient structures? All these questions and more are crucial not only to the traditional role of hydraulic engineers, but also to our emerging responsibility as a partner in society's decisions for what is best for sustaining human development and environmental well being.

Only if we remain knowledgeable in these matters can we enter the debate as experts on specific questions such as: Should Bridge Canyon Dam be built? Should Glen Canyon Dam be removed? Should the Snake River Dams be removed? Should flood control projects be constructed with higher dikes and levees or should we restore flood plains and marshes for relief? And we should provide expertise on mankind's role in preserving nature while attempting to provide a decent standard of living for the people of an overpopulated earth. Hydraulic engineering must go far beyond the realm of applied fluid mechanics while retaining a base deeply rooted in fluid mechanics. These questions (and those regarding less developed countries, only briefly mentioned herein) can be answered only by the consilience of hydraulic engineering with the humanities and social sciences while being especially careful to maintain the quality and integrity of hydraulic engineering. Such a goal may be as difficult as the characterization of turbulence, but it is as important.

The challenges of the twenty-first century may not contain the same machismo of the twentieth century, but they are certainly as important and even more challenging. It is still a great profession!

Parting Comments

In an attempt to address its title question, this paper considers the role of hydraulic engineering in the development of large water-control projects in the twentieth century. Although the dams associated with those projects are symbolic, highly visible, useful, and sometimes controversial, they are, of course, only a part of hydraulic engineering activities. This paper also is largely about hydraulic engineering in the United States. The development of large water projects, including dams, continues in many other countries and in some cases appears essential to their development. Attitudes and conditions in many countries may differ considerably from those in the United States; therefore, it is not appropriate to judge them in the light of the United States experience. The account given in this work is intended to be broad—and intended to make the point that our profession is becoming broader—in terms of hydraulic engineering's place amidst human endeavors. Obviously, no one answer to the title question is entirely satisfactory. Readers should apply their own perspectives and answers to that question.

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Appendix

Notes

Economics and War. Of course, many other projects contributed to the war effort and the economic development of the west. The United States was especially fortunate to have the huge electrical resources of the Columbia River come on line with the completion of Grand Coulee at the beginning of the war. Power from Grand Coulee and other Columbia River dams supplied the bauxite furnaces that were a cornerstone in aircraft production. The United States may have won the war without Grand Coulee, Hoover, and Bonneville, but it would have been a longer war with more casualties. An extensive (211 pages plus annexes) analysis of the project can be found in Ortolano et al. (2000). They study

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the economics, the projected and actual impacts, what went right and what went wrong, and they identify the winners and losers from the dam construction. The analyses of Ortolano et al. (2000) apply much more broadly than the Grand Coulee project.

Glen Canyon. Glen Canyon is separated from the Grand Canyon by Marble Canyon and is outside of the Grand Canyon Recreational Area. However, it is one long canyon with a wide point near the confluence of the Little Colorado River and low walls in the vicinity of Lee's Ferry and the confluence or the Paria River, a few miles downstream of the dam.

Flood. There was an artificial, 16-day-long ''flood'' in 1996 to mimic part of the natural cycle of the Colorado River. That ''flood'' was small compared to natural floods. The USBR with a great fanfare of national publicity declared the flood a success in restoring beaches and natural habitat to the Grand Canyon. Conversations with boatmen who direct commercial trips through the Canyon indicate that its success was very short lived, perhaps as little as a month and no more than a year. The flood has not been repeated, at least up to the time of this writing (but a smaller, two-day flow of power plant capacity took place in 1997 and a previous testing of reconstructed spillways discharged more water for a longer period of time).

Pollution. Pollution consists of the chemicals and ash produced as biomass is burned and CO_2 is emitted. However, technology can make it a mostly clean process and even net CO_2 emissions might be close to zero when capturing of CO_2 by growth is considered. In the case of some biomass, for example, ethanol from corn, more energy goes into the production than is extracted from the fuel.

Sustainable. The definition of ''sustainable'' is vague. Consider the following paragraph from Barrett and Odum (2000): ''Much has been written in recent years regarding the need to live within a society that sustains its resources for the future, a goal that requires rating plans for the future based on the concept of sustainable development (e.g., Lubchenco et al.1991, Huntley et al.1991, NCR 1991, Heinen 1994, Goodland 1995). A forum on 'Perspectives on Sustainability,' which appeared in Ecological Applications (November 1993), attempted to summarize many of the earlier perspectives surrounding this topic. Unfortunately, considerable confusion remains, especially among the citizenry, as to what is meant by sustainable development. Dictionaries define 'to sustain' as 'to hold,' 'to keep in existence,' 'to support,' 'to endorse without failing or yielding,' 'to maintain,' or 'to supply with necessities or nourishment to prevent from falling below a given threshold of health or vitality.' Given these definitions, the businessperson often views sustainability as sustaining profits based on ever increasing consumption of limited natural resources or sustaining rapid economic growth forever! At the other extreme, the definition in the widely cited Brundtland report (WCED 1987)—namely, that 'sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs' (p. 8)—is so vague as to be impossible to quantify or implement.'' (References not included herein.)

Consilience. From the *Oxford English Dictionary*: ''consilience konsi.liens. [f. next: see -ence.] The fact of 'jumping together' or agreeing; coincidence, concurrence; said of the accordance of two or more inductions drawn from different groups of phenomena.'' Consilience is the title of the book by Wilson (1998) that treats the unity of all knowledge.

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