KANSAS GEOLOGICAL SURVEY
OPEN-FILE REPORT 2000-51

Water and Energy, the Basis of Human Society:
Are They Globally Sustainable Through the 21st Century
October 8-11, 2000
Arbor Day Farm, Nebraska City, NE

Pre-Conference Papers

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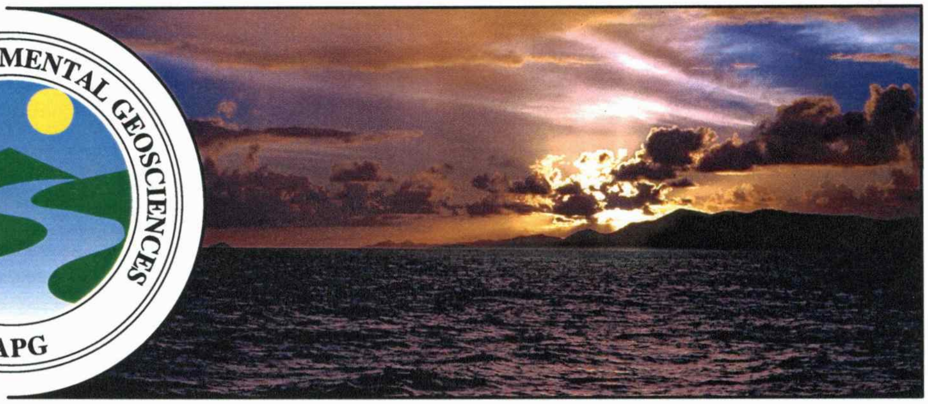
Kansas Geological Survey
1930 Constant Avenue
University of Kansas
Lawrence, KS 66047-3726



Water and Energy, the Basis of Human Society:
Are They Globally Sustainable Through the 21st Century?

Conference Agenda

Sunday, October 8, 2000

4:00pm — Room check-in (Registration desk-lobby)
Meeting Registration (Terrace Rm)

5:30pm — Reception (The Overlook-weather permitting)

6:45pm — Dinner (Terrace Rm.)

7:30pm — Introductions and comments

7:45pm — Keynote: Victor Yannacone: Environmental Attorney
Ethics of Sustainability

9:00-11pm Hospitality Room open (Marcotte Rm.)

Monday, October 9, 2000

Breakfast: 7:00am - 8:00am (Restaurant)

8:00am — Opening Plenary Session
Self-introductions, statements of concern and interest.
Convener's statement of sustainability agenda, geologic roles, outcomes.

8:45am — Keynote: Marlan Downey, President, AAPG
Will Technology Save Our Affluent Society Scenario?

Discussion and questions

9:30am — Break

9:45am — Keynote: Dr. Jack Edwards, University of Colorado
Twenty First Century Energy-Transition from Fossil Fuels to Renewable, Non-Polluting Energy Sources

Discussion and Questions

10:45am Keynote: Dr. Gerald Groenewold, University of North Dakota
Tides and Trends in the World's Electric Power Industry

Discussion and questions

11:45am Lunch (Restaurant)

1:00pm Keynote: Dr. Walter Youngquist, Consultant
Alternative Energy Sources

Discussion and questions

2:00pm Organize breakout groups

2:10 - 3:00 Breakouts on energy sustainability.

3:00pm Plenary session: Presentation of breakout statements and comments about energy sustainability

4:00pm Speaker panel discussion/comments about breakouts and conclusions on energy sustainability.

5:00pm adjourn to Hospitality Room (Marcotte Rm.)

6:00pm Dinner (Restaurant)

7:30pm Presentation: ***What Should We Do Next On The Moon and Then Mars and Why?*** by Hon. Harrison "Jack" Schmitt, Geologist-Astronaut, former U.S. Senator from New Mexico.

Adjourn to Hospitality Room (Marcotte Rm.) open until 11pm

Tuesday, October 10

Breakfast: 7:00am - 8:00am (Restaurant)

8:00am Keynote - **Dr. William Alley**, USGS
Some Reflections On The Sustainability Of Water Resources

Discussion and questions

8:45am Keynote: Dr. Charles Kreitler, Consultant
A Pragmatic Perspective Toward Water Resource Sustainability

Discussion and questions

9:30am Break

9:45am Keynote: Dr.James Triplett, Pittsburg State University
Water Sustainability and Ecology

Discussion and Questions

10:30am Keynote: Dr. Thomas Scott, Deputy State Geologist of Florida
Water Sustainability:Geological Perspectives On The Everglades And Water Supply Problem

Discussion and questions

11:30am Breakouts on water sustainability. Continue through lunch

12:00pm Lunch (Steinhart Rm.)

1:00pm Plenary session presentation: Lee Gerhard, Kansas Geological Survey

The Kansas Water Management Model

1:30pm Presentation of statements and comments about water sustainability

2:15pm Panel discussion/comments about breakouts and conclusions on water sustainability.

3:15pm Time to hike, walk, see the farm country, or shop the Pendleton Factory Outlet Store. (Organizing committee meets)

5:00pm Hospitality Room open (Marcotte Rm.)

6:30pm Dinner (Steinhart Rm.)

7:15pm Presentation: Dr. Sam Adams, Editor-in-Chief, Geotimes; and Consultant Geologist

(Topic TBA)

8:00pm Hospitality Room (Marcotte Rm.) open until 11:00

Wednesday, October 11, 2000

7:00am Breakfast (Restaurant)

8:30am Plenary Session - Organizing committee: designing the conference conclusions.

What are the accepted or expectable geological constraints on **energy** sustainability? How do the constraints compare to expected needs? What are the suggested solutions to the differences, if any? How can the scientific community best argue its case? Where should leadership come from?

(Listing, then ordering) (Organizing Committee)

10:00am Plenary Session - Organizing committee: designing the conference conclusions.

What are the accepted or expectable geological constraints on **water** sustainability? How do the constraints compare to expected needs? What are the suggested solutions to the differences, if any? How can the scientific community best argue its case? Where should the leadership come from?

(Listing, then ordering) (Organizing Committee)

11:30am Keynote: Dr.Tim Weiskel

12:00pm Check out of rooms

Lunch (Restaurant) and farewells.

Samuel Adams
Past President, AGI
POB 697
Lincoln, NH 03251

Dr. William Alley
U.S. Geological Survey
411 National Center
Reston, VA 20192

Gerry Calhoun
New Paradigm Exploration, Inc.
114 Prospect Hill
Nashville, TN 37205

Marlan Downey
President, AAPG
5902 Yardley Court
Dallas, Texas 75248

Dr. Jack Edwards
University of Colorado
Dept. of Geology
Campus Box 399
Boulder, CO. 80309-0399

Dr. Gerald Groenewold, Dir.
University of North Dakota
POB 9018
Grand Forks, ND 58202

Priscilla Grew
Dept. of Geosciences
301 Bessey Hall
University of Nebraska-Lincoln
Lincoln, NE 68588

Lee C. Gerhard
Principal Geologist
Kansas Geological Survey
University of Kansas
1930 Constant Avenue
Lawrence, Ks. 66047

Rep. Carl Dean Holmes
KS House of Representatives
125 District
POB 2288
Liberal, Ks. 67905

Travis L. Hudson
American Geological Institute
1432 Fox Hollow Road
Sequim, WA 98382

Dr. Charles Kreitler
LBG-Guyton Associates
1101 S. Capitol of Texas Highway
Suite B-220
Austin, TX 78746

Dr. Jane C. S. Long, Dean
Mackay School of Mines
University of Nevada-Reno
Mail Stop 168
Reno, Nevada

Dr. Pat Leahy
Chief Geologist, USGS
U.S. Geol. Survey Nat. Ctr.
12201 Sunrise Valley Dr.
Reston, VA 22092

Rep. Laura McClure
KS House of Representatives
119th District
202 S. 4th St.
Osborne, Ks. 67473

Monte Naylor
Diversified Operation Corp.
15000 W. 6th Ave.
Suite 102
Golden, CO. 80401

Ronald A. Nelson
BP Amoco
200 Westlake Park Blvd.
Houston, TX 77079

A. R. Palmer
Institute for Cambrian Studies
445 N. Cedarbrook Rd.
Boulder, CO 80304-0417

Hon. Harrison "Jack" Schmitt
POB 90730
Albuquerque, NM 87199

Dr. Thomas M. Scott
Florida Geological Survey
Assist. State Geologist
903 West Tennessee St.
Tallahassee, FL 32304

Everett Sondreal
Energy & Environmental Res. Ctr.
University of North Dakota
POB 9018
Grand Forks, ND 58202

Marios Sophocleous
Kansas Geological Survey
University of Kansas
1930 Constant Avenue
Lawrence, Ks. 66047

Stephen Testa
Testa Environmental Corp.
19814 Jesu Maria Rd.
Mokelumne Hill, CA. 95245

Dr. James Triplett
Chairman, Dept. of Biology
Pittsburg State University
Pittsburg, KS 66762

Sidney Warner
Warner Ranches, L.P.
POB 309
Cimarron, KS. 67835

Tim Weiskel
Harvard Seminar on
Environmental Values
Harvard Divinity School
45 Francis Avenue
Cambridge, MA 02138

Carol A. Yannacone
58 Rose Avenue
Patchogue, NY 11772

Mr. Victor J. Yannacone, Jr.
Yannacone & Yannacone, P.C.
39 Baker Street
P.O. Drawer 109
Patchogue, NY 11772

Dr. Walter Youngquist
POB 5501
Eugene, OR 97405

TABLE OF CONTENTS

WILL TECHNOLOGY SAVE OUR AFFLUENT SOCIETY SCENARIO?

Marlan W. Downey
President, American Association of Petroleum Geologists

Perhaps I can give you the answer at the start ...Technology, alone, can't solve all our energy problems. Technology can only solve those problems that are curable by Science.

When Need comes begging to Science, Technology does the heavy lifting.

Technology can improve the mileage on small cars to 100 miles per gallon; Technology can not make people want to buy and drive small cars that get great mileage. Taxation policy makes people want to have small, high mileage cars. In the United Kingdom, gasoline prices are about $4.30 a gallon; such costs will get your attention if you drive an SUV.

Much of my discussion will focus on the marvelous things technology can do for us, but we need to remember that many of the worlds energy problems may demand non-technical solutions.

Implicit in all our discussions is the concept that we desire to retain the characteristics of affluence, that we want a future with comfort and safety. We will choose to live in an Affluent Society Scenario. Living in caves, and eating carrion, is a scenario requiring only trivial energy needs.

We will hear from other speakers about the supplies of "conventional" hydrocarbon energy that some believe may be unequal to meet the future demand envisioned.

I have no basis for disagreeing with anyones thoughtful forecasts, ... except that all such forecasts,... have been wrong.

Such forecasts have always been wrong because they have been unable to estimate future demand, and they usually have underestimated the role of technology in increasing supplies. Demand for some types of energy will decrease. Technology does not merely add hidden resources of hydrocarbons; it creates low cost energy from thought-to-be-high-cost hydrocarbon deposits.

I see at least four technological assists to providing large quantities of hydrocarbons in the next two decades

A) Heavy Oils and Tar Sands
   In the Orinoco Tar Sand area of Venezuela, there are known to be one trillion barrels of heavy oil. Recent technology has demonstrated that the oil can be produced to the surface for about $1.60 a barrel, at rates of several thousand barrels per day. Only the Middle East fields have lower "lifting costs". This heavy oil, as produced at the wellbore, is of low value and is

difficult to transport and use, but it can be readily upgraded to conventional oil, and produced in great quantities for market,...if a stable long-term market price of $20.00 can be expected.

B) Enhanced Recovery, Known Fields
Modern Gulf of Mexico fields are expected to recover over 40% of the oil in place. Most of the fields of the world have been managed less intensively, and recovery factors of 15% are more common. Even in the USA, many regions have recovered only a small fraction of the known oil. Charles Mankin of the Oklahoma Geological Survey has pointed out that only 13% of the oil in Oklahoma oil fields has been produced, after nearly 100 years of effort.

C) "Tight" Gas
Enormous deposits of methane are held in reservoirs that are too "tight" to allow production of the methane at commercial rates. With current gas prices nearly treble those of the recent past, even wells that produce methane slowly are commercially valuable. Advances in fracturing such "tight" reservoirs to speed up the flow of gas to the bore hole has greatly increased productivity of many "tight" gas reservoirs. These "tight" gas reservoirs are commonly associated with gas source rocks, have pore space fully charged with methane, with the only movable fluid being methane. The lack of free water levels mean that the gas accumulations can extend over vast areas, unconfined by local structure. In one such "tight" gas play, Anadarko, alone, is running 26 drilling rigs and completing Bossier sand wells averaging 3BCFG per well from 80 acres in eastern Texas.

D) Gas Hydrates
Keith Kvenvolden of the United States Geological Survey has concluded that there is more methane in solid form, as gas hydrate, than the energy equivalent of ALL the petroleum, ALL the methane gas, and ALL the coal known in the world. Can we recover and use any of it in a commercially efficient manner? Not today,...but I will not put any limits on what Technology can do, on demand.

I've talked about the role of technology in lowering cost, in making valuable resources out of "occurrences", in increasing useful supplies. I'd like to move on to a vision of the changing role of hydrocarbons in our energy future.

Some say we are at the end of the Petroleum Age, as we may be running out of petroleum. Perhaps,... but for those of us old enough to remember...we didn't leave the Stone Age because we ran out of stones. If we leave the Petroleum Age, it won't be because we ran out of petroleum, but because we may decide we want something better than petroleum for our future energy base.

What might be the components of the future energy base of the United States? How will these components change with time and consumer demand?

One thing looks assured; there will remain a large demand for petroleum-based fuels for at least a half century. Petroleum-based fuels have a very high energy density in a small volume; a modest weight of gasoline contains a great amount of energy. There are about 212 million vehicles in the USA; only about 1 million run on alternate fuels.[1] Since vehicles must carry their energy supply with them, if they want to use "low energy" fuels, they must carry larger volumes of fuel in larger containers. Even the best of the alternative fuels has substantial problems. Methane, in natural gas, is a wonderful, clean burning fuel in engines, but...compressed gas has about one third the energy of gasoline, and, therefore, requires three times the tankage volume required for gasoline. And, widespread use of natural gas for automobiles would require completely new gas stations, with treble the underground tankage, to store and dispense the methane.

As we consider the future energy needs of our affluent society, it may be instructive to look at the history of energy use.

From the dawn of history, energy demands were provided by burning wood and the harnessing of human and animal strength. With the invention of the steam engine for pumping water out of mines in the middle of the 18th century, we began to see a supplanting of the need for horse power and man power, and a great desire for cordwood for fuel for steam engines.

By the middle of the 19th century, with wood providing 80% of the worlds fuel,[2] the need for a higher density of energy to supply heat to steam engines caused the development of the coal mining industry. Indeed, the early steam driven ocean freighters could not carry enough cordwood in their bunkers to make it across the Atlantic. We entered the Age of Coal,...but not because we ran out of wood. For 100 years, coal provided hydrocarbon energy to power steam engines, heat homes, and smelt iron.

We left the Age of Coal in the early part of the 20th century; not because we ran out of coal,... but because we needed a better source of energy. In 1915, Winston Churchill, First Lord of the Admiralty, convinced the British government to take a large stake in the Anglo-Persian oil company to provide the British Navy with oil for their new fuel oil driven battleships. It was pointed out that the Navy gained 78% in fuel power and saved 30% in bunker space, besides freeing up many sailors for fighting duties.[3]

Coal remains an important and necessary part of our energy future, but it now best fills a narrow and specific role as fuel for electric power generating plants.

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[1]Assinus Muses, August 2000, Oxford Energy Forum

[2]Biomass and Bioenergy, May 2000, Ralph Overend, Oxford Energy Forum

[3]The Prize, 1991, Samuel Yergin, Simon and Schuster

The Age of Coal was succeeded by the Petroleum Age. Our lives have been part of the Petroleum Age, and when we exit the Petroleum Age, it will be because we've asked technology to supply us with a better form of energy,...not because we run out of petroleum hydrocarbons.

And what will that "better" energy source be? It is interesting to look at the changes in composition of fuel over the past 300 years. There has been a remarkably regular progression in desire from consumers away from fuels with high carbon and low hydrogen content towards fuels with low carbon and high hydrogen contents. Wood and Coal have relatively high carbon contents and contain modest amounts of hydrogen. Petroleum has more hydrogen, roughly twice as many hydrogen atoms as carbon. Methane (natural gas) has four times as many hydrogen atoms as carbon atoms.

Does this regular progression of demand for more hydrogen in our fuels suggest a particular future? I think it does; I think we are entering into the Methane Age, and the Methane Age may lead us by the hand into a Hydrogen Age.

A Methane Age may describe the next 50 years, as methane becomes the basic energy source, supported and assisted by petroleum, by coal, and by nuclear. As fuel cells gradually supplant the internal combustion engine, methane and hydrogen become the desired fuels. It has been suggested[4] that a massive shift to methane may drop petroleum consumption by 2020 to only 55 MMBOPD from our current usage of 77 MMBOPD.

Any worries about running out of methane tomorrow? We've discussed the enormous amount contained in "tight gas", and in gas hydrates,...amounts that may exceed all known conventional hydrocarbons. And, do you remember where your grandfather got the gas for his lamps sixty years ago? It was MADE! Until about 1950, most of the methane gas in the world was produced in each city; it was produced by blowing steam on red-hot coke. The steam (H2O) reacted with the carbon to give methane (CH4) and carbon monoxide (CO). The "old lamplighter" of a century ago was lighting methane gas that was made locally. Think we can handle century-old technology? Think we are running out of water and carbon? We stopped making our methane gas this way,... because technology gave us a cheaper and better method.

If we follow our historical trend, it suggests that our affluent society will want much of its energy from pure hydrogen in 50 to 100 years. Should that frighten and concern us? Of course not.

Two widely different approaches for unlimited hydrogen production are being suggested; one involves local generation of hydrogen by green algal culture in shallow pans exposed to the sun. Recent experiments reported in Science[5] described a yield of 3ml of hydrogen per hour per liter

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[4]The Color of Oil,1999, Mike Economides and Ron Oligney, Round Top Publishing

[5]Power from Pond Scum, Science, March 2000

of solution. With modest improvements, a square pool 7 meters on a side should yield enough hydrogen each day to run a fuel cell powered car. Of course, it will help to live in a sunny State.

A second approach involves using electricity generated during off-peak hours by nuclear power generators, producing hydrogen by simple electrolysis of water. Nuclear plants can be built to operate cheaply, safely, and with minimum effect on the environment. They can provide huge amounts of environmentally safe electricity for our Affluent Society Scenario. This is technology that can save our A.S.S.

And the role of solar and renewable energy? "Cheerful self-delusion about new solar and renewable energy since 1970 has yet to produce a single quad of the more than 90 quadrillion BTU's the USA will consume in 2000."[6]

But, remember, technology can only solve technical problems; technology can't make the ignorant intelligent, or transform fanatics.

Can technology save our Affluent Society Scenario? You bet'cher A.S.S.

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[6]Letter to Editor, May 2000, Jesse Ausubell, The Industrial Physicist

TWENTY FIRST CENTURY ENERGY

TRANSITION FROM FOSSIL FUELS TO RENEWABLE , NON-POLLUTING ENERGY SOURCES

J. D. Edwards
Geology Department
University of Colorado
Boulder, CO 80309

ABSTRACT

The world must prepare for the transition to renewable non-polluting energy sources to ensure the continuous flow of energy to the world's increasing population and expanding economies. World oil supply will meet demand until the peak plateau of world oil production is reached which is estimated to be between the years of 2010 and 2030. Ultimate oil recovery will range from a conservative 2750 GBO (billion barrels oil) or an optimistic 3670 GBO (billion barrels oil). Declining production after peak oil production occurs will cause a global energy gap to develop because energy demand will continue to grow. This energy gap can be avoided by forward planning. Energy conservation, improved energy efficiency, expanded production of unconventional oil and conversion of natural gas to liquids will help extend the time of peak world oil production. The long-term solution to world energy supply is the transition from fossil fuels to renewable, non-polluting energy sources. These include, solar, nuclear, hydroelectric, geothermal, wind, biomass and hydrogen. Hydrogen, solar and nuclear will become major power sources in the 21st century.

INTRODUCTION

The purpose of this paper is to inform the petroleum industry, governments and the general public of the risks, challenges and opportunities that will occur as peak world oil production is approached in the first quarter of the 21st century. The transition to renewable energy sources is inevitable because fossil fuels, which now supply 86% of world energy, are exhaustible resources. Oil production, which now supplies 40% of the world's energy, will begin to decline when peak production occurs. World energy demand will continue to increase. Producing and marketing competitively priced, convenient, readily available renewable energy supplies will become profitable during the first quarter of the 21st century. Energy sources in this paper are described as petroleum liquids which include conventional oil, unconventional oil, natural gas liquids, oil equivalent of conversion of natural gas to liquid and oil equivalent of coal, hydroelectric, nuclear and all renewable energies.

DRIVING FORCES OF INCREASING WORLD ENERGY DEMAND

Population growth, expanding industrialization and improving life styles, principally in developing countries, are the causes of continued increase in world energy demand. World population passed 6 billion in October 1999. During the 20th century, global population has tripled. Improvements in agricultural production, medicine, education and communication have caused decreases in both mortality and fertility rates. However, the present population of two billion under the age of 25, mainly in developing countries, even with decreasing fertility rates, guaranties continued population growth at least to the middle of the 21st century. The world's present annual population growth rate is 1.4%, which adds 80 million per year. The population growth rate among the four billion people in the developing world is 1.7%. World population will probably reach 8 billion by 2025 and could reach 9 billion by 2050 (Population Reference Bureau 1999; United Nations, 1999). World population could peak at or below 10 billion by 2100.

Most industrial growth and 98% of population growth is expected to occur in developing countries. This growth will increase the competition for natural resources, particularly energy.

Developed countries produce 1/3 and the developing countries produce 2/3 of the world's oil. Developed countries use 2/3 but developing countries use only 1/3 of world oil. Annual per capita oil consumption in developing countries is 1.9 barrels, while the average in developed countries is 14.3 barrels per year. Annual per capita oil consumption in the United States is 25 barrels. World oil production is estimated to continue to increase during the first quarter of the 21st century at a rate of 1.5 %. If this rate persists, world demand for oil will increase from 24 GBO in 1999 to about 38 GBO in 2030, which is 104 MBOPD.

World Oil During the1990's

World conventional oil reserves remained above 1000 GBO since 1993, peaked at 1163 GBO in 1997 and were 1016 GBO in January 2000. However, 300 GBO are suspect as political reserves booked by OPEC, principally in the Middle East, during 1987-1989 to support their production quotas. These reserves may be real but include probable and speculative oil from future discoveries and development. Cumulative world oil production reached 836 GBO in January 2000 (Figure 1).

During the 1990's, major oil and gas discoveries have been made most notably in deep offshore waters of the U.S. Gulf Coast, Angola, Brazil and in the Caspian Sea. Significant additional oil and gas reserves have been discovered on the Northwest Australian Shelf and in Indonesia, China, Iran, Iraq, Saudi Arabia, Egypt, Algeria, Nigeria, the North Sea, Alaska, Canada, Columbia, Venezuela, Peru and Brazil.

New technologies have been successfully applied. These include rapid computer software data analysis, 3D and 4D seismic, extended reach and underbalanced horizontal wells, new drilling tools and production platforms, new logging and completion methods, seismic sequence stratigraphy, petroleum systems analysis and detailed reservoir compartmentalization studies. Application of these techniques have improved success rates for wildcats and development wells and have added reserves in old fields. Deep-water discoveries in new areas, particularly in major deltas, will undoubtedly be found. No new giant oil provinces have been found since the North Sea and offshore Mexico in the 1960's when world discovery volumes peaked. Super giant field discoveries (> 5 GBO), have declined. However, world reserves have increased by almost 50 GBO by recent discoveries in Saudi Arabia, Iran and Iraq, each over 10 GBO.

During 1998 and 1999 the petroleum industry was forced to deal with excess oil supply and low prices. Companies downsized, restructured, merged, and cut budgets. Reserve replacement declined for many companies because of declining production in old fields, sale of marginal production, plugging of stripper wells, record low drilling rates, and low discovery rates. Oil prices recovered during 1999, due to production cuts by OPEC, Norway and Mexico. The rise of crude oil prices to historical highs in 2000 has resulted from increasing world demand and limited excess productive capacity. Future crude oil price will probably remain above $25 per barrel with OPEC attempting to balance supply with demand. Huge capital investments will be required to develop increasing [productive capacity.

UNITED STATES OIL DURING THE 1990'S

United States annual crude oil production from 1990 to 2000 decreased from 2.7 to 2.1 GBO, while annual natural gas liquids (NGL) production remained flat at about 0. 8 GBO. During this decade total United States liquid production decreased from 3.4 GBO to 2.9 GBO (Figure 2). Imports of crude oil and products, on the other hand, have increased from 2.9 GBO to 4.1 GBO per year during this decade. United States oil consumption increased from 6.35 to 7 GBO per year from 1990 to 2000 (Figure 2). In the past ten years United States reserves of crude oil and NGL declined from 34 GBO to 29 GBO (Figure 3). Reserve growth in existing fields has become the dominant component of reserve additions in the United States.

WORLD ULTIMATE LIQUID PRODUCTION

World ultimate liquid recovery is estimated to be 3670 GBO (Table 1, Case A) The ultimate could be only a 2750 GBO according to Campbell (1998) and Laherrere (1999) (Table 1, Case B). The ultimate liquid recovery of Case A consists of 836 GBO cumulative crude oil production, 100 GBO cumulative NGL production, 1016 GBO crude oil reserves, 100 GBNGL reserves, 583 GBO future oil discoveries and oil field growth, 100 GBNGL future discoveries and field growth, 570 GBO of unconventional oil, and 365 GBO from gas to liquid (GTL) conversion. GTL conversion is estimated optimistically at 20% of world gas reserves. Mean values of undiscovered oil and gas are used (USGS, 1994). Unconventional oil resources include 270 GBO of Eastern Venezuelan heavy oil and 300 GBO of Western Canadian tar sand oil (Kahn, 1998; Meyer and DeWitt, 1990). Notice that neither liquid from oil shale nor coal to liquid conversion is counted.

If the projection of 3670 GBO ultimate production (Table 1, Case A) and the 1.5% demand growth rate are correct, the peak plateau of conventional oil productive capacity will be reached from 2010 to 2020 at about 31 GBO per year, which is 85 million BOPD (Figure 4). Total oil productive capacity by adding unconventional oil will reach 38 GBO per year from 2020 to 2030 which is about 104 million BOPD. If the world ultimate is only 2750 GBO (Table 1, Case B), peak production will occur in 2010 at 30 GBO per year which is 82 million BOPD (Cambell, 1998; Laherere, 1999).

UNITED STATES ULTIMATE LIQUID PRODUCTION

United States ultimate liquid petroleum production is estimated to be 455 GBO (Table 2). This consists of cumulative crude oil production, 180 GBO; cumulative LNG production, 36 GBO; crude oil reserves, 21 GBO; NGL reserves, 8 GBO; crude oil discoveries and field growth, 140 GBO; NGL discoveries, and field growth, 30 GBO. An optimistic 40 GBO from gas to liquid (GTL) conversion is included (Table 2). United States oil production in 2030 could still be 3 GBO per year but demand by then could be 9 GBO if the growth in demand persists at 1.5%. Imports of 6 GBO per year would then be required (Figure 5).

PEAK PLATEAU OF WORLD LIQUID PRODUCTION

Oil is the most valuable and most used fuel in the world today. Oil provides 40% of world and United States energy supply. Oil with its high energy density, ease of transport and storage, today has no comprehensive substitute. The world will remain critically dependent on oil well into the 21st century. Why should there be concern about peak world oil production? The problem is not if, but when, peak world oil productive capacity will occur. There is a strong probability that peak world oil production will be reached during the first quarter of the 21st century. Peak oil production will probably be reached between 2010 and 2030 (Table 3). The peak plateau of oil production would be suppressed and occur earlier if the future discovery rate is low or capital is not available to develop new productive capacity. A gap in energy supply could then develop.

The seventeen authors on Table 3 have made estimates of ultimate economically recoverable oil, and the year of peak oil production. These calculations have been made repeatedly in the past and will continue to be made in the future. Past projections have been too low and too short. The scenarios presented here may also be inaccurate, but have credibility based upon reasonable present day estimates of oil reserves, future oil discoveries and demand growth. Even with the addition of one trillion barrels of oil reserves above 3670 GBO, peak oil production would be extended for only about ten years (Bartlett, 2000).

Oil and gas reserves will be generated from new discoveries, improved recovery technologies and huge unconventional resources, the limits of which are unknown. These include bitumen, heavy oil, oil sands, coal bed methane, deep basin gas, biomass, and possibly oil shales and gas hydrates.

Oil will be more expensive as supplies diminish. Oil will be available throughout the 21st century and into the 22nd century for highest value uses such as petrochemicals and air transportation.

Some authors believe that there is no threat of an oil shortage in the foreseeable future. Price rises will generate new oil production. They believe that market forces, new technologies and adequate resources will insure the growth of supply to meet rising demand (Fisher, 1991; Alelman and Lynch, 1997; Linden, 1998; McCabe, 1998; Lynch, 1999). Riva in 1999 presented a balanced discussion of the differing opinions of economists and geologists concerning ultimate oil reserves.

FOSSIL FUEL CHALLENGES

Fossil fuels are exhaustible resources. The amount of oil, gas and coal that nature has formed during the past 500 million years is huge and unknown. All the oil and gas that exists in the earth will never be totally extracted just as the last ton of coal in deep, thin seams will never be mined. The total amount of oil ultimately produced will depend upon the validity of present reserves, recovery efficiency from existing fields, quantities and qualities of future discoveries, new technologies, competition from alternate energy sources and energy demand and price changes over time.

During the second half of the 21st century both oil and gas production will decline. Oil and gas will be produced from lean, remote, deep and expensive resources to extend production into the 22nd century. These bottom of the barrel reserves will be used for the highest value products (petrochemicals). None of the renewable energy sources, except biomass, can provide these unique products.

Fossil fuels produce 86% of world energy but are facing political and environmental constraints because of their polluting emissions. The energy industry must meet the clean fuel challenge. Competitive renewable non-polluting energy sources will ultimately replace fossil fuels. As this transition away from fossil fuels occurs, the potential problem of carbon dioxide emissions causing global climate change will be alleviated. The price of oil will rise as the approach of peak oil production is recognized. Peak liquid petroleum production can be extended by increased use of natural gas, gas to liquid conversion and expanded coal production. Increased oil production will come from Eastern Venezuelan heavy oil deposits, estimated to contain 270 GBO recoverable from an in-place resource of 1200 GBO and Western Canadian tar sands, estimated to have 300 GBO recoverable from an in place resource of 1686 GBO (Masters 1991; Meyer 1987; Meyer and Dewitt, 1990; Kahn, 1998). Even United States and other world tar sands and oil shales may produce oil during the 21st century. However, even with the sources just listed, new discoveries, increased recovery from old fields, conservation and improved efficiency of use, demand for oil will increase beyond the capacity of petroleum supplies.

World resources of natural gas are under-recognized and under-utilized. The ratio of known oil fields to gas fields is about 2 to 1, which does not represent the natural endowment of gas to oil.

United States natural gas estimates includes 167 TCF reserves, 896 TCF future discoveries and 141 TCF coal bed methane (CBM). Future discovery estimates for gas are very low. Natural gas will be aggressively searched for, discovered, produced and used in the 21st century. Enormous resources of natural gas are locked in methane hydrates in the deep oceans and arctic tundra. As much as 100,000 TCF is estimated to be trapped in gas hydrates (Finley and Krason, 1989; Krason, 1994; Haq, 1998). If only a few percent are ever commercially extractable it could extend the life of natural gas supplies for decades.

The infrastructure for worldwide distribution of natural gas and liquid natural gas (LNG) will expand and help fill the energy gap. Gas exploration and production are expected to expand rapidly as new distribution systems and markets are developed (True, 1999). Gas will reach markets as an economically competitive, preferred clean fuel. Increasing environmental concerns will help natural gas become the electrical industries most important fuel (Otto et al, 1999). Natural gas fired combined-cycle gas turbine and cogeneration gas-electric power plants are increasing the demand for gas throughout the world.

In the near future, fuel cells energized by natural gas to hydrogen technology will power an increasing percentage of automotive transport and supply selected commercial and residential electricity (Bensabat, 1999; Chang, 1999; Fouda, 1998). Hydrogen is the ultimate non-polluting, renewable and sustainable fuel of the future (Hefner, 1999). Gas to liquid (GTL) and possibly coal to liquid technologies will extend the life of the internal combustion engine for transportation use and help continue to supply petrochemical feedstocks (Fouda, 1998). ARCO-Syntroleum (Oil and Gas Journal, 1999) and Chevron- Sasol (Matske, 1999) have begun GTL pilot projects. Chevron Overseas President Matzke said "Gas to liquid technology is so promising that its development could create a paradigm shift throughout the petroleum industry."

World coal production of over three billion tons supplies 25% of the annual world energy demand and 37% of world electricity. United States coal production of over one billion tons per year supplies 23% of domestic energy demand and 57% of electricity. World annual demand for electricity is increasing 5% (International Energy Agency, 1999). Coal, the lowest cost fossil fuel, is abundant and widely distributed. It will continue to supply expanding electricity demand in the 21st century particularly in China and India. Coal, however, is the most polluting of the fossil fuels. It is blamed for environmental damage, health problems and elevating the earth's surface temperature. Near term reduction of emissions from world coal fired power plants is very unlikely. However, where natural gas is abundantly available, as in Europe, electric power plants are converting from coal to gas thus reducing emissions.

RENEWABLE NON-POLLUTING ENERGY SOURCES

International consensus, by the 1997 Kyoto Protocol, supports the development of renewable non-polluting energy sources to replace the combustion of fossil fuels. The goal is to reduce emissions of greenhouse gases below 1990 levels and thus avoid the possibility of climate change, global warming and sea level rise. Opportunities for reduction of carbon dioxide emissions and sequestration are being pursued. But significant reduction of carbon emissions in the near future by substitute fuels for petroleum-fueled vehicles and coal fired electric power plants is very unlikely to be achieved (Flannery, 1999). In fact some climate scientists now recognize that meeting the Kyoto accord will not significantly reduce the potential increase of the earth's surface temperature in the 21st century. They are recommending that society find ways to adapt to a warmer world.

Air and water pollution can be overcome by switching to clean energy sources. Conversion from fossil fuels to renewable, non-polluting energy sources will be the final solution to eliminate carbon dioxide, sulfur dioxide and nitrous oxides from the atmosphere. Commercialization and implementation of the technologies required for these renewable, non-polluting energy sources takes time which is one of our most limited resources. Renewable energy sources will fail if their enabling technologies do not improve to ensure affordability and convenience of use (Crow, 1998).

Both BP-Amoco-Arco and Royal Dutch Shell have purchased solar power companies and are entering the photovoltaic (PV) cell market. BP, by its recent purchase of Solarex, expects to have a one billion-dollar PV business by 2010 with 20% of the world market (Oil and Gas Journal, 1999). Shell International Renewables is investing $500 million in the next five years in solar, and sustainable forestry. Shell International Gas and Enron are investing in gas fired electric power plants. Both BP and Shell support sustainable development, which takes into account economic, environmental and social considerations (BP-Amoco 1998; van der Veer, 1997).

Nuclear power may plateau in the near future but its expansion will be needed before 2050. A negative view of nuclear power's future is presented in a World Watch Paper (Flavin and Lenseen, 1999). Modular, fail safe, economically competitive nuclear electric power plants, with zero emissions, can be built to replace coal-fired power plants. The nuclear waste disposal problem must be solved. The WIP site salt mines in southeast New Mexico are an excellent long-term residence for nuclear waste. If nuclear power, the largest non-carbon energy source continues to be discouraged in developed countries, coal, natural gas and renewable energy sources must increase to supply expanding world electrical energy demand.

SUSTAINABLE ENERGY SUPPLY

The incremental environmental impact of human activities will continue to concern both governments and industries. Demand growth for all resources will exponentially expand the volume of waste that the earth, oceans and atmosphere must absorb (Foster and Wise, 1999). These concerns encompass the quality of air, water, land, natural resources, and wildlife. The communication technology explosion has opened the flow of information, fostered the globalization of industry and increased the quality of life expectations in the developing world. It is also causing demand for more equitable distribution of resources. These events have put greater demands on both governments and businesses for improved performance and accountability.

The bottom line of 21st century business must be to help society achieve three interlocked goals; economic prosperity, environmental protection and societal equity (Elkington, 1998). To achieve these goals will require the collective international attention of both governments and industries.

CONCLUSIONS

The energy scenario presented here is not meant as a unique forecast. However, it presents a plausible, sustainable world energy supply for the 21st century. In the next few years, three main themes appear to be obvious. We should increase efficiency of energy use; clean up the energy we are using and continue to search for cleaner forms of energy (Robinson, 1998). Research and development efforts should begin now to accelerate the transition to renewable, non-polluting energy sources. A sustainable future world energy supply is a must. Oil and gas reserves must be preserved for future production of highest value products. Future generations will question why we burned so much of our valuable hydrocarbon resources.

Future unknowns are daunting. The changes we can anticipate are awesome. Pericles in 428 BC said, "The key is not to predict the future, but to be prepared for it." Future changes are complex, risky and threatening but offer challenges and opportunities. Sir Winston Churchill admonished that worrying should translate into advanced planning. We must plan ahead for the transition to renewable, non-polluting energy sources in the 21st century.

John D. Edwards, Energy and Minerals Applied Research Center, University of Colorado, Department of Geological Sciences, Campus Box 399, Boulder, CO. 80309, tel. (303) 492-6188; FAX (303) 492-2406 Email : edwards @ emarc.colorado.edu.

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ESTIMATED ULTIMATE
WORLD
LIQUID PETROLEUM
BILLION BARRELS
JAN-2000

CONVENTIONAL OIL		**CASE A**	**CASE B**
Crude Cum. Prod.		836 GBO	800 GBO
NGL Cum. Prod.		100 GBO	75 GBO
Crude Reserves		1016 GBO	800 GBO
NGL Reserves		100 GBO	125 GBO
FUTURE DISCOVERIES and FIELD GROWTH			
Crude Oil		583 GBO	200 GBO
NGL		100 GBO	50 GBO
UNCONVENTIONAL OIL			700 GBO
Venezuelan Heavy Oil		270 GBO	
Canadian Tar Sand Oil		300 GBO	
Coal Oil (not counted)		???	
Shale Oil (not counted)		???	
ULTIMATE LIQUI Oil PRODUCTION		**3305 GBO**	**2750 GBO**
WORLD NATURAL GAS			
Cum. Prod.	2200 TCF	366 BBOE	
Reserves	5150 TCF	858 BBOE	
Future Disc.	5791 TCF	965 BBOE	
Future Total gas	10,941 TCF	1823 BBOE	
NATURAL GAS TO LIQUID CONVERSION			
20% of future gas = 20% of 1823 BBOE		365 GBO	
ULTIMATE LIQUID PRODUCTIO		**3670 GBO**	**2750 GBO**
3305 GBO + 365 GBO = 3670 GBO			
FUTURE LIQUID PETROLEUM		**2734 GBO**	**1875 GBO**
3670 GBO - (836 +100)GBO = 2734GBO			

Table 1

Degolyer-MacNaughton 1998, OGJ 1998

ESTIMATED ULTIMATE
UNITED STATES
LIQUID PETROLEUM
BILLION BARRELS OIL EQUIVALENT
JAN 2000

CONVENTIONAL OIL			
Crude Cum. Prod.			180 GBO
Crude Reserves			21 GBO
NGL Cum. Prod.			36 GBO
NGL Reserves			8 GBO
FUTURE DISCOVERIES and FIELD GROWTH			
Crude Oil			140 GBO
NGL			30 GBO
ULTIMATE OIL PRODUCTION			**415 GBO**
UNITED STATES NATURAL GAS			
Cum. Prod.	840	TCF	140 BBOE
Reserves	167	TCF	28 BBOE
Future Disc.	1038	TCF	173 BBOE
Ultimate Recovery	2045	TCF	341 BBOE
Future Total Gas	1205	TCF	200 BBOE
NATURAL GAS TO LIQUID CONVERSION			
20% of Future Gas (0.2 x 2 200 BBOE) =			40 BBOE
ULTIMATE LIQUID PETROLEUM			**455 GBO**
415 GBO + 40 BBOE = 455 GBO			
FUTURE LIQUID PETROLEUM			**239 GBO**
455 GBO - (180 GBO+ 36 GBO) = 239 GBO			

Degolyer-MacNaughton 1998, OGJ 1998, MMS 1997, Pot.Gas Com. 1998

Table 2

PEAK YEAR of WORLD CRUDE OIL PRODUCTION
ESTIMATED ULTIMATE RECOVERY
BILLION BARRELS

Author	Company	Year	Est. Ult.	Peak Year
Hubbert	Shell	1969	2100	2000
Moody	Cons.	1978	3200	2004
Odell	Delft	1983	3000	2025
Bookout	Shell	1989	2000	2010
Townes	AAPG	1993	3000	2010
Cambell	Cons.	1994	1650	1997
Laherrere	Cons.	1994	1750	2000
MacKenzie	W.Res.Inst.	1996	2600	2007-2019
Applebey	BP	1996		2010
Ivanhoe	Cons.	1996		2010
VanderVeer	Shell	1997		2020
Edwards	Univ.CO.	1997	2836	2020
Bernabey	ENI	1998		2000-2005
Schollnberger	Amoco	1998		2015-2035*
Duncan & Youngquist		1998		2006
IEA	OECD	1998	2800	2010-2020**
EIA	DOE	1998	4700	2030**
Laherrere	Cons.	1999	2700	2010**
Edwards	Univ.CO.	2000	3670	2020-2030**

*Oil&Gas **Total Liquids(Crude& Heavy Oil,Tar Sd.Oil,GTL)

Table 3

WORLD CRUDE OIL RESERVES WORLD CUMULATIVE CRUDE OIL PRODUCTION 1990-2000

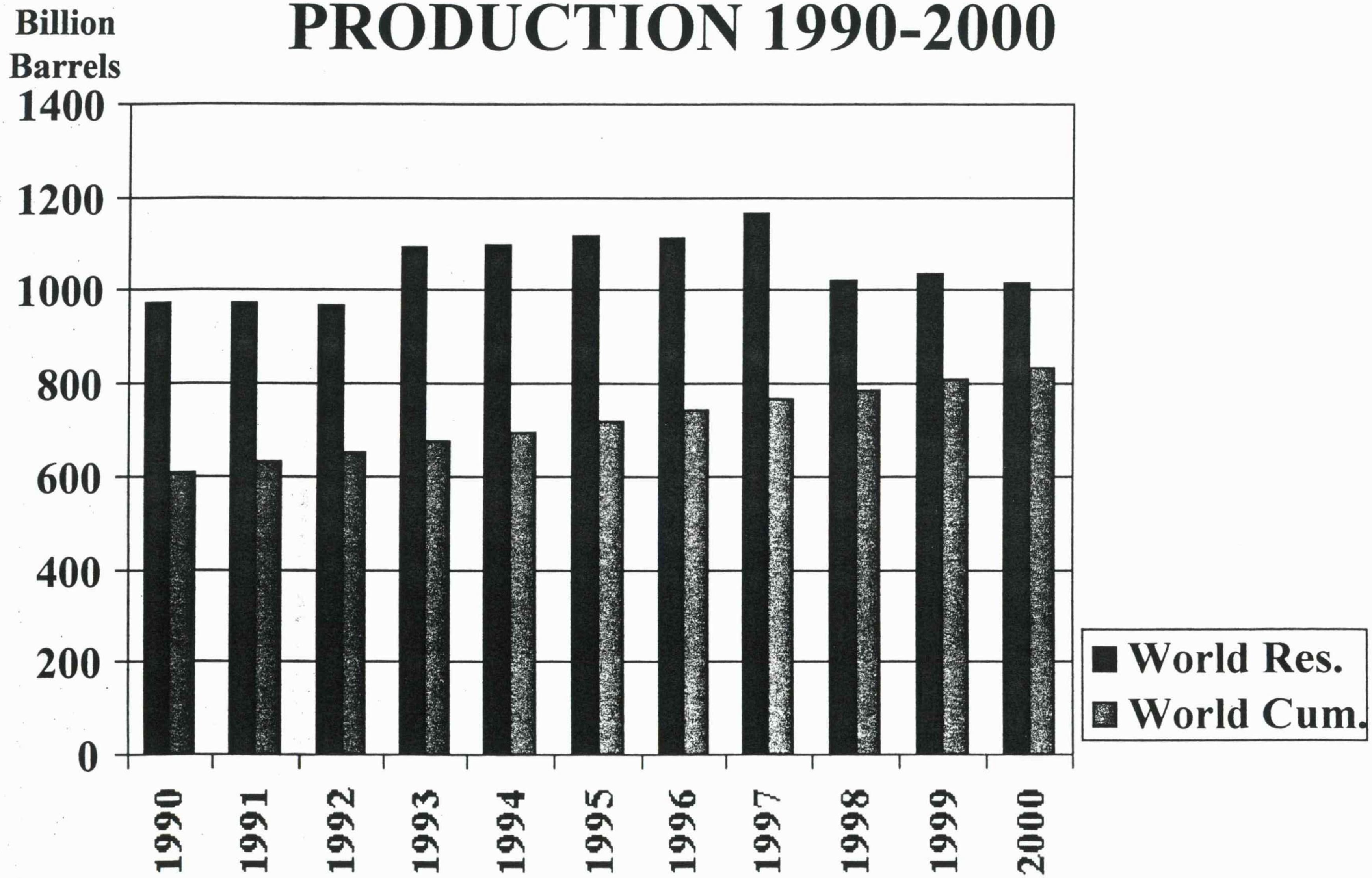

Figure 1

Degolyer & MacNaughton 1997, Oil and Gas Journal

15d

UNITED STATES PETROLEUM CONSUMPTION 1990-2000

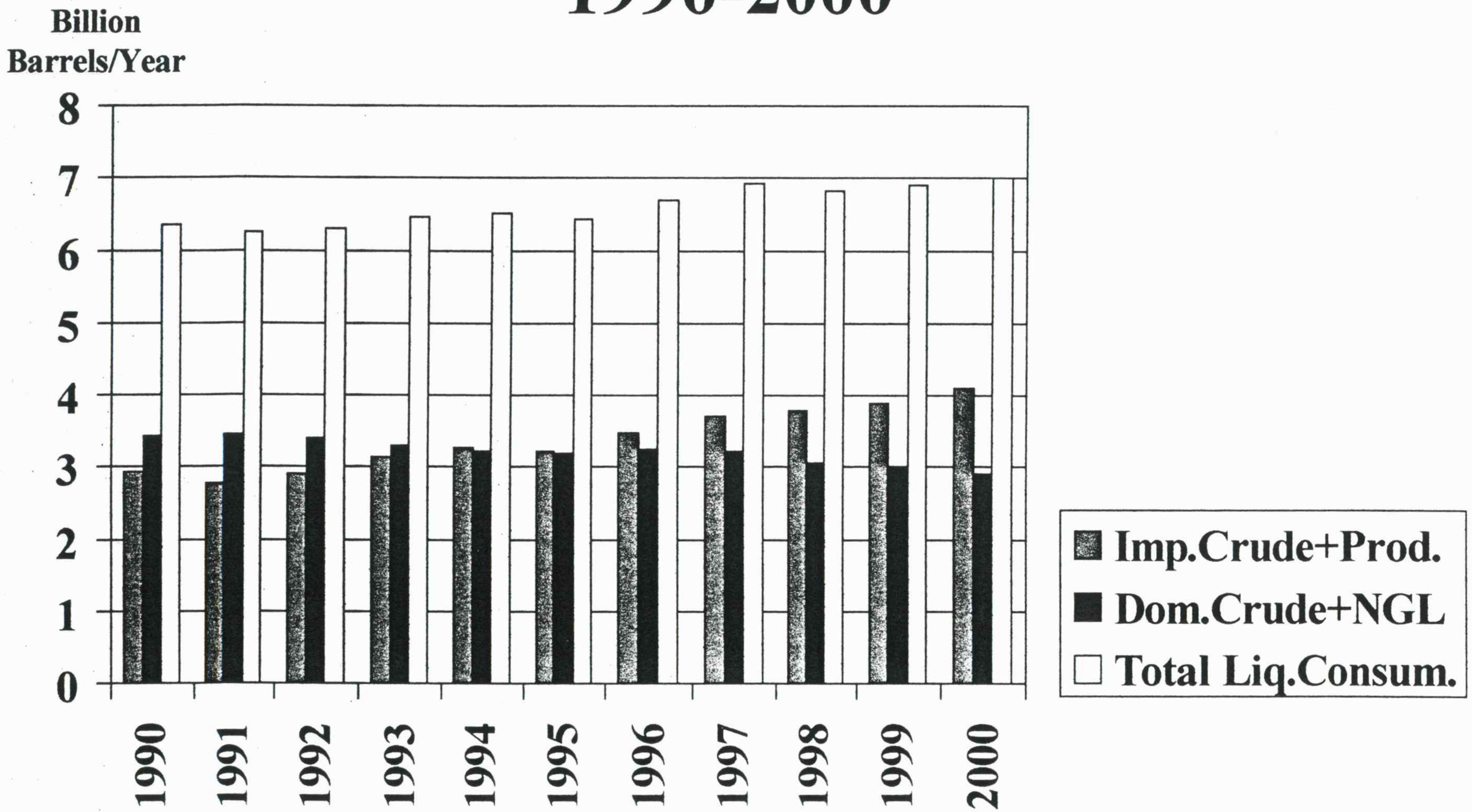

Figure 2

Degolyer & MacNaughton 1998, Oil and Gas Journal 1998, 2000

UNITED STATES RESERVES
CRUDE OIL + NGL = TOTAL LIQUIDS
1990-2000

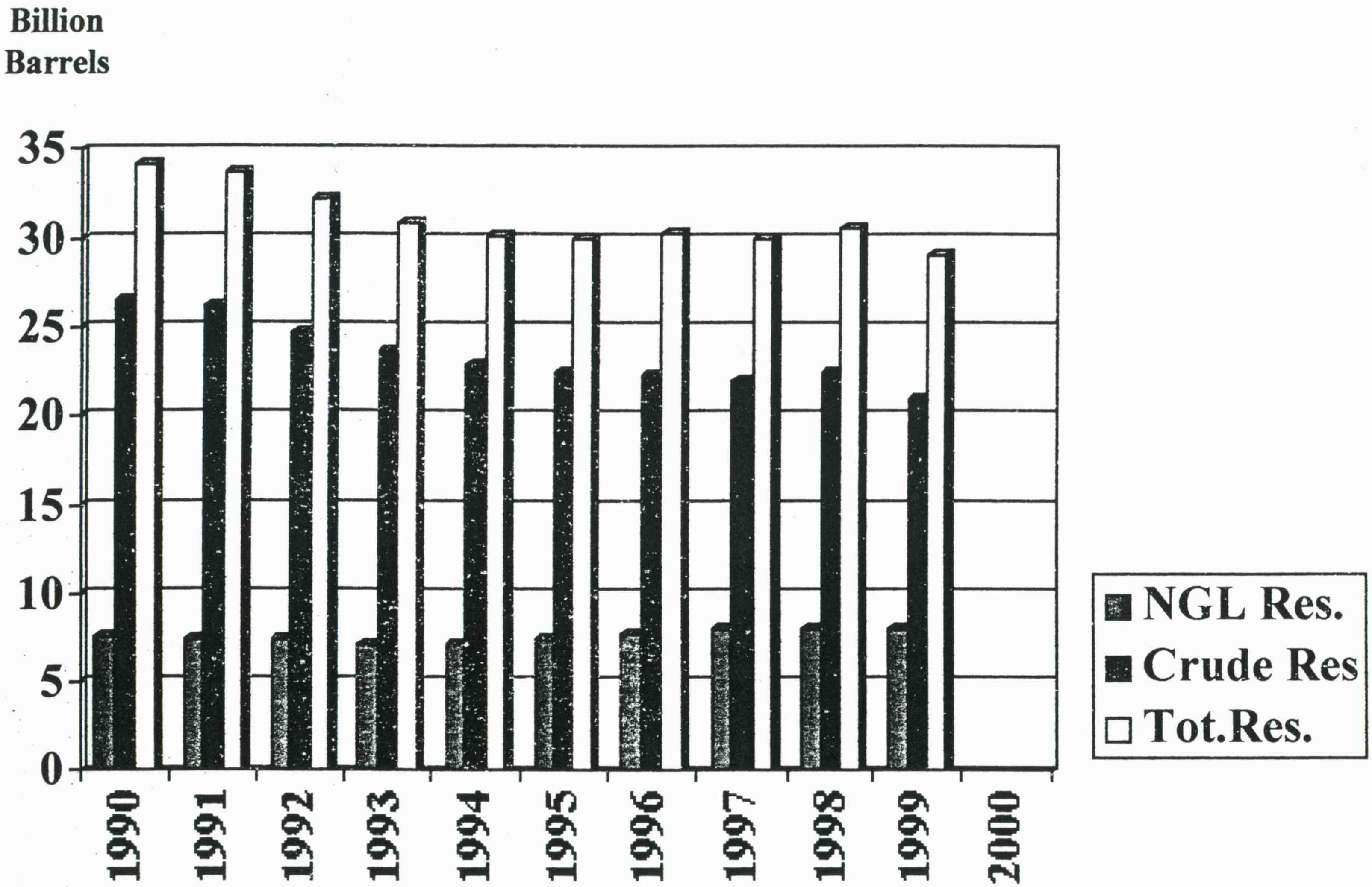

Figure 3

Degolyer & MacNaughton 1998, Oil and Gas Journal 1998, 1999c

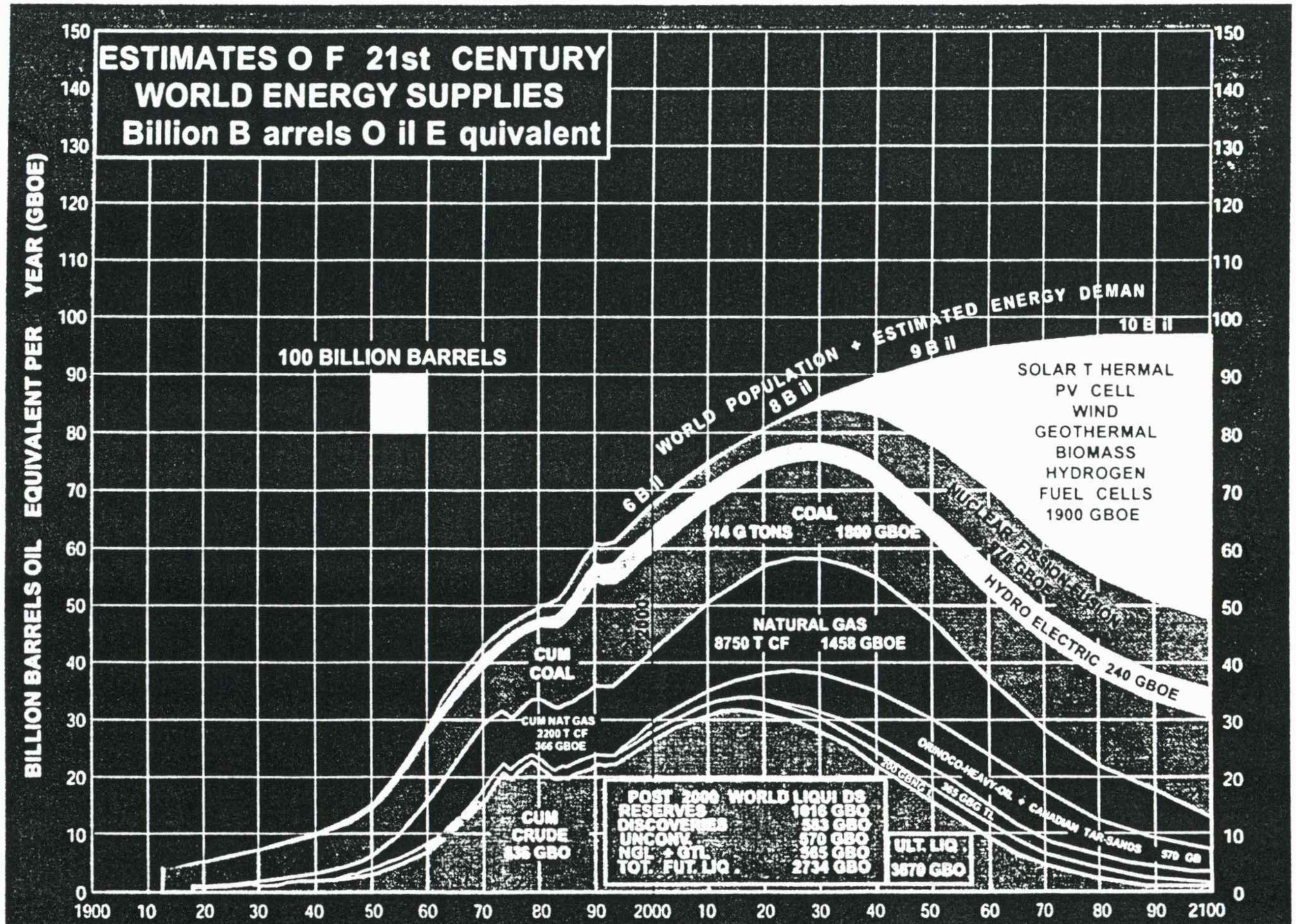
ESTIMATES O F 21st CENTURY
WORLD ENERGY SUPPLIES
Billion B arrels O il E quivalent
BILLION BARRELS OIL EQUIVALENT PER YEAR (GBOE)
100 BILLION BARRELS
WORLD POPULATION + ESTIMATED ENERGY DEMAN
6 B il
8 B il
9 B il
10 B il
SOLAR T HERMAL
PV CELL
WIND
GEOTHERMAL
BIOMASS
HYDROGEN
FUEL CELLS
1900 GBOE
NUCLEAR FISSION-FUSION
HYDRO ELECTRIC 240 GBOE
COAL
514 G TONS 1800 GBOE
NATURAL GAS
8750 T CF 1458 GBOE
CUM COAL
CUM NAT GAS
2200 T CF
366 GBOE
CUM CRUDE
836 GBO
POST 2000 WORLD LIQUI DS
RESERVES 1016 GBO
DISCOVERIES 583 GBO
UNCONV. 570 GBO
NGL + GTL 565 GBO
TOT. FUT. LIQ. 2734 GBO
ULT. LIQ
3570 GBO
ORINOCO-HEAVY OIL + CANADIAN TAR-SANDS
YEAR
1900 10 20 30 40 50 60 70 80 90 2000 10 20 30 40 50 60 70 80 90 2100
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150

Figure 4

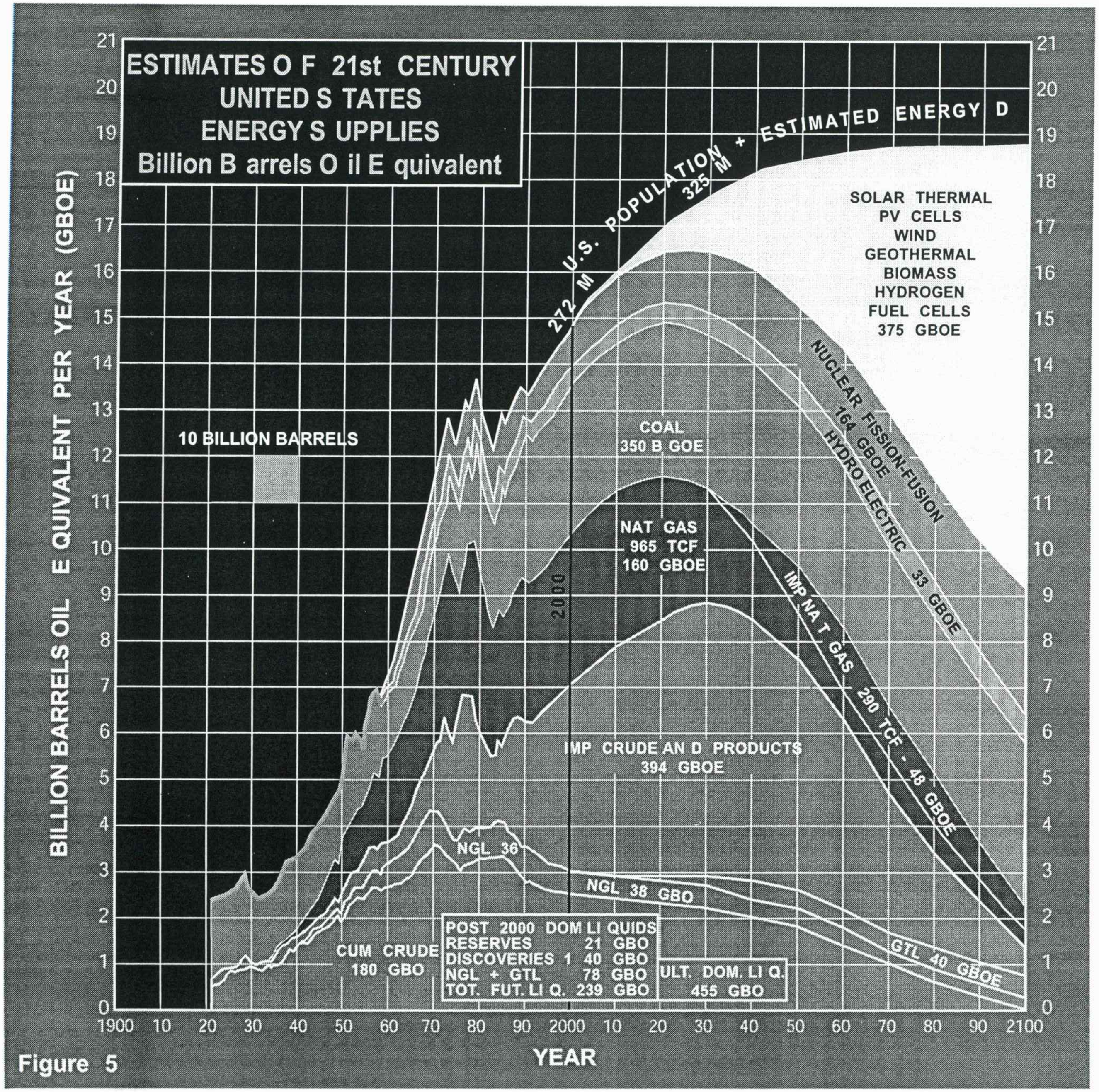
ESTIMATES O F 21st CENTURY
UNITED S TATES
ENERGY S UPPLIES
Billion B arrels O il E quivalent
BILLION BARRELS OIL E QUIVALENT PER YEAR (GBOE)
YEAR
10 BILLION BARRELS
U.S. POPULATION + ESTIMATED ENERGY D
272 M
325 M
SOLAR THERMAL
PV CELLS
WIND
GEOTHERMAL
BIOMASS
HYDROGEN
FUEL CELLS
375 GBOE
NUCLEAR FISSION-FUSION
164 GBOE
HYDRO ELECTRIC
33 GBOE
COAL
350 B GOE
NAT GAS
965 TCF
160 GBOE
IMP NA T GAS 290 TCF - 48 GBOE
2000
IMP CRUDE AN D PRODUCTS
394 GBOE
NGL 36
NGL 38 GBO
GTL 40 GBOE
CUM CRUDE
180 GBO
POST 2000 DOM LI QUIDS
RESERVES 21 GBO
DISCOVERIES 1 40 GBO
NGL + GTL 78 GBO
TOT. FUT. LI Q. 239 GBO
ULT. DOM. LI Q.
455 GBO
1900 10 20 30 40 50 60 70 80 90 2000 10 20 30 40 50 60 70 80 90 2100
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21

Figure 5

TIDES AND TRENDS IN THE WORLD'S ELECTRIC POWER INDUSTRY

Everett A. Sondreal, Michael L. Jones, and Gerald H. Groenewold
Energy & Environmental Research Center
PO Box 9018
Grand Forks, ND 58202-9018

INTRODUCTION

As we enter the 21st century, providing for affordable, environmentally acceptable, and reliable supplies of electricity will present unprecedented challenges and opportunities. Today, nearly 40% of the world's population does not have access to an adequate supply of energy (Menem, 1998). This tremendous growth opportunity has translated into projections of capacity addition of over 650 gigawatts over the 10-year period from 1997–2006 (Bergesen, 1998). Projections indicate that nearly 55% of this projected growth will occur in Asia. Growth in electrical generating capacity is being accompanied by a parallel change in structure in the electric power industry worldwide.

Prior to 1990, the electric power industry outside of the United States was owned and financed by governments. This situation has changed dramatically. The private sector now controls or is critically involved in nearly all world markets for electric power. At the same time, concerns over the availability of energy resources and the impacts of energy production on the global environment, principally global warming, are having a profound effect on developments in the world's electric power industry.

We live in a time of unprecedented change in the electric power industry. This paper discusses many of the factors that affect the future of this industry which is so critical to stable economic growth worldwide.

Industry Restructuring

The electric utility industry is undergoing unprecedented changes. Market pressures in the United States and throughout the world are forcing changes in industry ownership, regulatory environment, and the electric power service options that customers can expect. In the United States, the focus of these changes has been deregulation, that is, the movement from a regulated monopoly to a competitive marketplace. Initial movement toward deregulation in the United States occurred in response to the Public Utilities Regulatory Policies Act of 1978, which encouraged the supply of wholesale power to electric utilities from nontraditional sources, allowing nonutility power generators to enter the power generation market for the first time. The Energy Policy Act of 1992, through its electricity provisions, greatly accelerated the pace of competition in wholesale electrical trading (EIA [Energy Information Administration], 1999). These acts and society's desire to open the electrical market to competition have profoundly affected the structure of the electric utility industry in the United States. This change has already occurred in other former regulated monopolies (e.g., telecommunications, airlines, and natural gas industries) which have undergone similar changes in the recent past. In the United States, individual states have taken the lead in the deregulation of the electric power industry. According to the Edison Electric Institute (DOE, 2000b), 20 states and the District of Columbia either have final regulatory orders or laws that provide for competition in the electricity market. Additionally, five states have pending proposals that will be acted on in the near future.

It is clear that the classic vertically integrated utility that resulted in the electrification of the United States will change. The functions of generation, transmission, and distribution have all been affected by utility restructuring. With current legislation on the state level and the federal legislation noted above, significant progress has occurred to ensure competition in the generation component of the electric power business. This market change has resulted in the development of what is referred to as merchant plants. The term merchant plant refers to power production facilities developed with a minimum capital investment, eliminating the redundancy required for very high reliability normally designed into facilities developed under a regulated environment. A number of independent system operations have been approved by the Federal Energy Regulatory Commission. This structure, versus control of the grid by major generating groups, should facilitate equal access to wholesale markets by any generator. It is not clear at this time whether retail competition legislation will be enacted by all states. Under federal law, states have the right to disallow retail competition if it can be shown that it is in the consumers' best interest to maintain the monopoly. This debate will continue for some time, particularly in states where rural electric distribution cooperatives have been critical to successful electrification and remain a potent political and economic force.

Many countries throughout the world have traditionally used state-owned enterprises to meet the country's electricity needs. In today's global marketplace, many of these countries are finding that competition through a liberalized marketplace results in a reduced public sector financial burden as well as lower electrical prices, benefitting consumers. This reform is occurring worldwide. For instance, all European Union (EU) member states have introduced legislation that, at a minimum, has as its goal open electricity markets. Long-term plans are for a single European electricity market, introducing competition between states as well as within states of the EU. These developments have required major changes in many countries. For instance, 15 years ago, the electricity industry in the United Kingdom was a state-owned monopoly. Today, under a totally competitive generation picture, generators bid in the pool spot market every day and sell electricity only if their prices are competitive. At the same time, generators are no longer obligated to generate electricity; rather, they can choose to generate if they feel it is profitable.

Asia also has seen significant change in its electric power industry. The Asian economy is projected to show the most robust growth of all world regions through 2020. Expected to grow at an annual rate of nearly 5%, the electrical consumption of Asia accounted for ~17% of the world total in 1997 but will grow to ~28% by 2020. This spectacular growth will be dominated by the economies of the most populous nations of China and India. In both cases, this growth will require a liberalization of the power market to attract private capital. Asian nations have typically been less open to outright acquisitions of electrical assets but recognize that to raise the capital, privatization of assets will be necessary. In China, this desire for foreign investment resulted in deregulation of electrical prices in rural areas in 1998, and in 1999, the government announced plans to allow generators to bid competitively to access electrical grids. In India, in 1996, the central government announced policy changes aimed at the restructuring and corporatization of state electricity boards. In 1998, the government went further and eased its rules for foreign investment in the power sector. India hopes these changes will attract the massive private investment that will be required to fund the large expansion of its power generation capacity.

Latin America, as in Asia, has recognized the need to attract private capital to finance both the expansion and upgrade of the electric infrastructure required to support this region's economic growth. In this region, foreign investment has proceeded very aggressively and with limited controversy. In the period from 1990–1998, over $40 billion was invested in privatized electrical projects in Latin America and the Caribbean (EIA, 2000).

This dramatic restructuring throughout the world has had a profound effect on the industry. Private capital markets have responded very positively such that today there is no shortage of financing to meet current needs.

Growth in World Power Demand

World demand for electricity grew by 2.2% annually between 1990 and 1997, when the world population growth rate was 1.6%. The U.S. Census Bureau projects that world population will grow from 6 billion in 2000 to approximately 9 billion in 2050, with much of the growth occurring in developing nations which represent a vast untapped demand for electricity. Future growth in world demand for electricity is projected to accelerate to an average growth rate of 2.5% for the next two decades, causing consumption in 2020 to rise 76% above its 1997 level, while world population growth slows to an average rate of 1.1% to rise by about 30% during that same period (EIA, 2000).

There is wide disparity by region both in the current use of electricity and the expected rate of growth. Per capita use of electricity ranges from over 12,000 kilowatt hours per year in the United States to less than 100 kilowatt hours in less developed countries in Africa. The level of economic activity in industrialized countries measured by gross domestic product (GDP) correlates closely with per capita use of electricity at an average rate of about $3 GDP per kilowatt hour of electricity use, with the notable exceptions of Japan which achieves a higher GDP per kilowatt hour and countries in Eastern Europe and the Former Soviet Union (FSU) which are currently experiencing a lower GDP because of dislocations resulting from their transition from central planning to a market economy. Future growth rates for both GDP and electrical demand are highest in developing countries starting at a lower base, where annual rates of 4% to 7% are predicted for both of these parameters (EIA, 2000). China, which is the world's second largest consumer of electricity and currently uses 29% as much electricity as the United States, will add more generating capacity than any other nation in the world. Both China and India are expected to achieve a 3- to 4-fold increase in electrical generation by the year 2020 fueled principally on coal, and these countries could become ideal candidates for joint implementation agreements to mitigate carbon emissions. Future electrification in developing countries depends on extending and upgrading the transmission and distribution systems. Nearly one-third of the people in Central and South America and a major part of the population in Africa have no access to the electricity grid, and as much as 20% of India's electricity is lost in transmission or unaccounted for in metering. Future demand for electricity in the industrialized countries is projected to grow far more slowly, at a rate of 1.3% in Japan; 1.4% in Eastern Europe, the FSU, and the United States; and 1.7% in Western Europe (EIA, 2000).

The most important development in the United States and Western Europe is the increased level of competition among electricity suppliers under government deregulation policies which are bringing down prices for electricity. For example, German prices for industrial electricity fell by 37% between 1995 and 1999. Electricity companies throughout the world are entering an extremely dynamic period where they will be faced by the challenges of rapid growth, increased competition, changes in fuel and technology, and environmental problems including concerns over carbon emissions and global warming.

Changing Patterns of Fuel Use and Technology in Electricity Generation

World energy consumption for electric power generation between 1990 and 1997 was led by coal (38%), followed by hydro and other renewables (20%), nuclear (16%), natural gas (15%), and oil (11%) (EIA, 2000; BP Amoco, 1999). However, fuel use and generating technology are changing because of the influence of economic and environmental pressures. Availability of water will also affect the siting of steam-electric plants in some regions. The issues that will determine the contribution by each of these fuels to future electricity power generation represent a complex interplay of economic forces and environmental policies that cannot be well predicted at this time.

Coal

Coal is the world's leading fuel for power generation, accounting for 36% of the market, and its dominance is expected to continue at 34% in 2020 under policy-neutral projections that consider only market forces and existing environmental regulations without new policy drivers concerned with global warming. In the United States, the electric utility industry currently uses coal for 55% of its total generation, and the EIA's policy-neutral estimate for 2020 projects continued predominance of coal at a level of 52% (EIA, 1999). However, coal can be considered poised at a crossroad where it either moves toward a more competitive position in relation to natural gas based on the development of advanced coal-fired power systems or begins to experience a sharp decline assuming ratification of the Kyoto Climate Change Protocol. The economic disadvantage that coal is currently experiencing relative to gas in new power generating facilities, particularly in the United States and Western Europe, is a direct consequence of its higher capital cost and lower generating efficiency, both of which may eventually be substantially alleviated by new coal-fired power technologies that are attempting to enter the market. By increasing the efficiency of coal-fired units to a level approaching 50% at a capital cost close to $1000 per kilowatt, new technologies now in the development and demonstration stage could reverse the rush to gas by capitalizing on the twofold or greater fuel cost advantage that coal offers. Besides the challenges of efficiency and capital cost, new coal-fired generating units face increased restrictions on sulfur dioxide, nitrogen oxides, ash particulates, and air toxic emissions (e.g., mercury) which can likely be met with new or existing technologies. However, new technology cannot eliminate the inherently higher carbon emission from coal, although it would reduce it, since natural gas emits 40% less carbon than a high-grade bituminous coal even when burned in a unit having the same generating efficiency. The U.S. Department of Energy (DOE) has initiated an aggressive research program to find practical means of sequestering the carbon emitted from the combustion of all fossil fuels, but it is unlikely that this will have a decisive effect on coal use over the next decade.

A number of different coal-fired technologies are being developed in the United States, Europe, and Japan to offer higher efficiency at lower capital cost. These technologies integrate either a combustor or gasifier operating at an elevated pressure with a gas-cleaning system and a gas turbine and heat recovery system to provide many of the same advantages as those offered by a state-of-the-art combined-cycle gas-fired system. Different coal-fired designs are being tested for achieving high levels of efficiency and low emissions at reduced cost, principally through simplification in design and operation. For example, in the Piñon Pine Integrated Gasification Combined-Cycle (IGCC) demonstration project being performed under the U.S. DOE Clean Coal Technology Demonstration (CCTD) Program (DOE, 2000a) at the Sierra Pacific Power Company plant in Reno, Nevada, the air-blown KRW (Kellogg Rust Westinghouse) gasifier uses a fluidized bed of crushed limestone to capture sulfur and crack tars before passing the produced low-Btu gas through a hot-gas-cleaning system that removes most of the remaining sulfur and filters out the ash particles that would otherwise erode and destroy the blades in the gas turbine. Design simplifications in this demonstration include absence of the oxygen plant that would be required for an oxygen-blown gasifier, minimum gas cooling between the gasifier and the gas turbine, and elimination of complex chemical process steps that are needed to remove sulfur, tar, and particulates in some cold-gas-cleaning systems. Many different component designs and system configurations are being evaluated, which are beyond the scope of our review in this report. Two other IGCC systems are being demonstrated under the U.S. CCTD Program (DOE, 2000a): the Tampa Electric project using a Texaco entrained-flow gasifier and the Wabash River project using the Dynegy two-stage entrained-flow gasifier with an optimized cold-gas-cleaning system. Other plants representing different variations on the IGCC theme have been built in Spain, Germany, and the Netherlands. Next-generation systems under development in the United States by Foster Wheeler (Robertson and White, 1997) and M.W. Kellogg (Wheeldon and others, 1998) at the DOE Power Systems Development Facility in Wilsonville, Alabama, combine both combustion and gasification to achieve high carbon conversions and improved environmental control in a low-cost design. The Energy & Environmental Research Center (EERC) is working with the United Technologies Research Center (UTRC) under DOE sponsorship on still another combined-cycle system that heats pressurized air in a coal-fired high-temperature furnace to run a gas turbine, with a possible temperature boost from burning natural gas to achieve very high efficiencies (Ruby and others, 1999; Sondreal and others, 2000). In the more distant future, coal gasification will be integrated with gas-cleaning and fuel cell technologies to achieve what may be the ultimate efficiency potential for a coal-fired unit, approaching the 60% level that is already possible in a natural gas-fired combined-cycle design. After decades of development, opinions differ as to the state of readiness of advanced coal-fired power systems, and it cannot be predicted when the pace of this technological advance will have a major effect on coal use. It appears that reliable coal-fired designs that offer substantial cost and efficiency advantages over existing plants should be commercially available within the decade, but by then investment in gas-fired capacity will already have gained strong momentum in many regions. The projections of future coal use presented below from the EIA's analysis (2000) do not reflect quantum advances in technology for coal.

World use of coal, which was essentially flat between 1990 and 1997, is projected to increase from 5.3 billion short tons in 1997 to 7.3 billion tons in 2020, representing an average growth rate of 1.8% annually. Conservative estimates of recoverable world coal reserves include 560 billion metric tons of bituminous coal and anthracite and 520 billion tons of subbituminous coal and lignite (BP Amoco, 1999), comprising approximately 200 years' supply at current production levels. Future trends in coal use are expected to vary considerably by region. In Western Europe, coal consumption declined by 33% between 1985 and 1997, and it is expected to decline a further 23% below the 1997 level by 2020, principally due to the growing use of natural gas and, in France, nuclear power. Elimination of subsidies in the United Kingdom was a principal cause of a 50% loss in domestic coal production. Germany, Spain, and France are also currently taking steps to reduce their continuing subsidy payments. Coal consumption in the FSU and Eastern Europe has fallen by 36%, from 1373 million tons in 1988 to 877 million tons in 1997, and losses are projected to continue at a rate of 2.4% annually through 2020 owing to continuing economic reform and substitution of gas for coal in power production.

Increases in coal consumption are principally forecast in the United States and developing Asia. Coal use in the United States is expected to increase at an average rate of 1.1%, increasing from 1.1 billion tons to 1.3 billion tons between 1997 and 2020 (EIA, 2000) under the EIA's policy-neutral projection. However, the largest increase in coal use by far will occur in developing countries in Asia, with the increase of 1.3 billion tons projected for China and India together representing 97% of the total net increase in world coal use in 2020. Coal currently accounts for 75% of China's electricity fuels market, and this share is expected to remain constant through 2020, with the addition of approximately 180 gigawatts of new coal-fired generating capacity. In India, coal's share of electric power generation will decline from 78% in 1997 to 63% in 2020, with natural gas and renewable fuels making up for coal's lost share; however, coal use is still expected to rise by 3.1% annually because of the addition of approximately 50 gigawatts of new coal-fired capacity. The projected increases in coal use in China, India, and other developing countries would not be directly affected by ratification of the Kyoto Climate Change Protocol since these countries are not assigned binding targets for reducing carbon emissions, although they are required to implement mitigation programs. However, in industrialized countries, the use of coal could fall far below policy-neutral projections if the Kyoto Protocol were ratified and entered into force, requiring the stringent reductions in energy-related carbon emissions discussed in the section of this article dealing with the Kyoto agreement.

Natural Gas

Natural gas is becoming the fuel of choice for new electrical generating capacity around the world (EIA, 2000), with its share of power generation expected to nearly double from 15% to 26% between 1997 and 2020. Growth in the use of gas is projected to be particularly strong in North America and Western Europe, where it will displace coal and nuclear, and in Central and South America, where it will cut into the predominance of hydroelectric power. Gas firing is projected to account for between 86% and 92% of all new generating capacity in the United States over the next 20 years, increasing the share of gas-fired generation from 10% to 28%. Gas firing in the FSU, which already relies heavily on natural gas for electrical generation, is expected to rise from 49% to 61%. World natural gas reserves have more than doubled in the past 20 years due to the rapid pace of exploration and discovery, with the largest reserves located in the FSU (39%) and the Middle East (34%). Other regions also possess substantial gas reserves, including North Africa and Asia with 7% each, North America with 6%, and South America and Europe with 4% each. The world's total proven reserves (BP Amoco, 1999) of 145 trillion cubic meters (about 5100 trillion cubic feet) represent a reserve-to-production ratio of 63.4 years. Estimates of unproven reserves far exceed the proven reserves, by a factor of more than six in the United States. However, uncertainty with regard to estimates of natural gas resources has always been an issue in projecting supply availability. Additions to U.S. gas reserves, which rise and fall along with the price of gas and the level of drilling activity, are projected by EIA to keep pace with rising consumption until about 2010, after which time slower discovery will be balanced by higher production from offshore and unconventional sources and increasing imports from Canada. Gas is not expected to be transported from Alaska to the lower-48 U.S. states during the next 20 years.

Gas prices in the United States have experienced extreme volatility in the recent past. Prices have gone from under $2.00/MMBtu to over $5.00/MMBtu in approximately 1 year. Indications are that these higher prices will remain at least for the next 6 months, with no clear definition of how prices will change after that time. This price volatility demonstrates that pricing for natural gas is determined by market forces and not by the cost of production. It is not clear if world gas prices will return to an annual rate increase of 2% per year as projected by DOE (EIA, 1999) or what base price should be used to forecast the future price of natural gas. However, where supplies of natural gas are available, the gas industry can readily meet price competition from coal and nuclear for new electric generating capacity for the foreseeable future. The price of gas can be expected to stabilize at the highest level that meets competition based on the busbar cost of electricity, including the cost of environmental compliance.

Considerable expansion of pipeline capacity will be needed worldwide to satisfy the rising demand for natural gas. In the United States, some of the expected rise in demand can be met by increasing and leveling load on existing pipelines, so that a 37% increase in demand in 2020 can be handled by a 15% increase in pipeline capacity (EIA, 2000). U.S. additions in pipeline capacity are planned to move increased production from the Rocky Mountains, Gulf Coast, and western Canada regions to midwestern and eastern markets, and to connect new sources in eastern Canada with strong demand in New England. International pipelines will move increasing amounts of natural gas from Norway and Russia into Western Europe, from Algeria into Italy and Spain, and from Argentina and Bolivia into Chile and Brazil. In addition, increased availability of liquefied natural gas (LNG), which currently accounts for 5% of world gas consumption, will expand exports from Algeria, Indonesia, Malaysia, and Alaska to the largest LNG importers in Japan, South Korea, and France.

The use of natural gas for power generation is favored by rising efficiencies and falling capital cost per kilowatt hour generated. The efficiency of gas-fired combined-cycle plants has increased greatly and is approaching 60%, and the current cost of combined-cycle power units is only $449 per kilowatt in 1998 dollars, compared with $1102 per kilowatt for a coal-fired unit (EIA, 2000). Natural gas firing in combined-cycle plants is also favored by lower carbon emissions, which are 60% lower than for coal firing in a conventional steam plant.

Renewable Generating Sources

The development of economically competitive renewable generation is the bright hope for a sustainable quality of life into the distant future. We intuitively understand that fossil energy and other nonrenewable resources will eventually be depleted over a time scale of hundreds of years. Current concerns about global warming are causing many policymakers to question whether the use of coal and hydrocarbon fuels can be continued as a mainstay of electric power generation in the near term. However, electricity from wind, solar, and biomass resources are still severely constrained by high costs. Conventional hydropower, which currently accounts for 80% of renewable electricity in the United States, is forecast to decline slightly in absolute terms under the pressure of environmental and water management concerns, and DOE estimates that the hydroelectric share of the U.S. market will decline from 9% in 1998 to 6.5% in 2020 (EIA, 1999). The forecast addition of 620 megawatts of other renewable generating capacity does not offset the decline in hydropower, causing DOE's reference case to project an overall decline in the renewable share of U.S. electricity generation, from 11.3% in 1998 to 9.5% in 2020. DOE's estimates of non-hydroelectric renewable generation in 2020 range from 3.1% of total generation in the reference case to 4.6% in the high renewable case (EIA, 1999).

Most of the expected growth in renewable generation is credited to biomass, municipal solid waste (MSW), geothermal energy, and wind power. Biomass and MSW together are projected to increase by two-thirds by 2020, which accounts for the largest increase overall. More than half of the increase in biomass is for industrial cogeneration, particularly in the pulp and paper industries. U.S. wind power generating capacity increased by 860 megawatts in 1998 and 1999 to reach a level of about 2000 megawatts, spurred by the federal production tax credit. State mandates are expected to add 2400 megawatts of wind power capacity by 2010 and an additional 400 megawatts by 2020. Wind power can currently be generated at a cost under 5 cents per kilowatt hour, and it is expected to benefit most from any future policies that mandate renewable generation. A principal limitation of wind power is its intermittent supply. Geothermal generation would also benefit from policy incentives, whereas solar photovoltaic and thermal technologies will continue to remain too costly for central power generation.

The technology which has the largest potential for increasing renewable generation is the cofiring of biomass with coal in utility boilers. This option would allow biomass to be burned in large quantities at the relatively high efficiencies of large coal-fired generating units, which may be the most practical and cost-effective approach for reducing greenhouse gas emissions in the near term. While the emission of carbon dioxide that results from the combustion of biomass is relatively high, comparable to that for lignite coal, the biomass emission can be considered to be offset by reabsorption of CO_2 in the photosynthesis cycle that replenishes the biomass fuel. The sources of biomass that will be used initially will be low-cost municipal and wood wastes available close to utility plants. Dedicated supplies of biomass harvested from forest and agricultural sources are estimated to cost $2 to $3 per million Btu or more, which is double the cost of coal and comparable to the cost of natural gas. Widespread use of these higher cost bioresources will require adoption of government policy incentives. A $50 per ton carbon tax would make harvested biomass fuels highly competitive. In the absence of a policy driver, the DOE 2000 reference case estimate of biomass utilization for power generation is only 1% of coal-based electricity by the year 2020 (EIA, 1999). EPRI estimates a 2.3% displacement of coal at a net added cost of about $23 per metric ton of carbon, using biomass priced under $1 per million Btu (Hughes, 1998). However, the potential is much larger, since it is technically feasible to supply up to 15% of the thermal input to the boiler from biomass. Feeding biomass directly to the pulverizers in a coal-fired plant limits biomass input to about 2% of heat input, but the capital cost of retrofitting is under $50 per kilowatt of generating capacity. Use of higher percentages of biomass requires a separate feeding system at a cost of $175 to $230 per kilowatt. Credit for reduced emissions of SO_2 and NO_x can offset part of the cost, and cofiring can be profitable where locally available biomass wastes displace high-sulfur coal.

Different types of biomass combined with various ranks and qualities of coal represent a broad range of combustion performance. Principal biomass types include wood wastes, agricultural and logging residues, energy crops such as hybrid poplar and switchgrass, and municipal wastes containing paper and plastics. A high ratio of volatile matter to fixed carbon causes most biomass fuels to burn more quickly than coal in the boiler, and carbon burnout is not a problem for biomass fuel particles smaller than about 0.1 inch and moisture contents lower than 40%. NO_x emissions may be reduced by up to 20% by cofiring owing to lower fuel nitrogen, a lower firing temperature, and combustion staging due to early volatile burnout. The efficiency of a boiler fired on bituminous coal has been reported to be about 0.5% lower when firing 10% biomass owing to the higher moisture and oxygen contents of the fuel. Ash deposition and corrosion can vary widely because of the different potassium, phosphorus, and chlorine concentrations occurring in various biomass types. No increase in deposition has been reported for cofiring sawdust and clean wood waste, but instances of deposition and corrosion have been experienced when straw and other agricultural residues have been cofired. For some biomass types, either a high concentration of phosphorus or the combination of a high potassium content along with silica in the form of thin sheets (phytoliths) represents a unique ash deposition mechanism that will need to be resolved by researchers and boiler operators. Analytical methods previously used to correlate ash deposition with coal mineralogy are being refined and adapted by the EERC to understand deposition behavior when biomass is cofired.

Nuclear Power

In 1998, 16% of the world's total electricity was generated by nuclear plants. Nine countries met over 40% of their electrical demand with nuclear power, including France with 76%. However, EIA estimates that the nuclear share of world power generation will drop sharply to 10% in 2020 based on reference case projections (EIA, 2000). Factors contributing to the decline include cost overruns on past nuclear construction projects, high costs for disposing of spent fuel and decommissioning retired plants, and concerns over safety and environmental issues. Serious nuclear power accidents at the Three Mile Island plant in the United States in March 1979 and the Chernobyl plant in the Ukraine in April 1986 marked a strong increase in public concern over the safety of nuclear power plants. However, renewed interest in nuclear power could materialize in industrialized countries if the Kyoto Climate Change Protocol is ratified, if nuclear waste disposal problems are resolved, and if management practices can lower cost.

Plans call for a 32,000 megawatt net expansion of nuclear power in the developing countries of Asia by 2020, while the world's industrialized countries lose 64,000 megawatts overall (EIA, 2000). Additional nuclear capacity is being planned in China, South Korea, India, Taiwan and, possibly, Turkey, Brazil, and Argentina. Japan has ambitious plans for expanding nuclear power by 10,000 megawatts by 2010, but its nuclear capacity is expected to begin to gradually decline thereafter, with the remaining capacity depending on public support. Leaks at several nuclear power plants and a serious accident at a fuel reprocessing plant in Japan in September 1999 have increased public concern about plans for nuclear power expansion in the Far East.

Western Europe, which currently has 127,000 megawatts of nuclear power capacity and relies heavily on this source of electricity, has set aside plans for constructing new nuclear plants. National policies in Germany and Sweden are moving toward a phaseout of nuclear power, and petitions have been circulated in Switzerland for a national vote on nuclear power within 2 years. France, with half the nuclear capacity in Western Europe, has had to resolve problems of fatigue-induced cracking in its newest nuclear reactors, and future plans for nuclear expansion in France are uncertain pending scientific and public debate. France permanently closed its largest fast breeder reactor in 1998 but continues to operate a smaller breeder reactor for research. In Germany, an agreement between the government and nuclear utilities over the appropriate lifetime for reactors has been reached. The utility industry has agreed to shut down all reactors after an additional 35 plant years for the 19 plants within Germany. In Sweden, agreement was reached to shut down the first unit in 1999, almost 20 years after a national vote to end nuclear power. Nuclear power is a major issue in negotiations between the European commission and candidate members wishing to enter the EU. Bulgaria, Lithuania, and the Slovak Republic have agreed to decommission some of their older, Soviet-designed reactors between 2003 and 2009, and newer units are being upgraded to meet world safety standards.

The United States currently has 104 operable nuclear units with a generating capacity of 97,000 megawatts, which in 1998 provided 19% of total U.S. electricity generation. In the EIA's reference case projection, 41% of this nuclear capacity would be taken out of service by 2020 based on the assumption that many plants will be retired early owing to high maintenance costs after 30 years of operation (EIA, 1999). No new nuclear units are expected to be commissioned between now and 2020. Several sales of existing nuclear plants are currently being negotiated, which points toward a consolidation of the U.S. nuclear power industry that will lower the cost of nuclear power and make it more competitive in a deregulated electricity industry. While some nuclear plants are projected to be retired before the expiration of their 40-year operating licenses, as many as 16 are scheduled to submit applications for license renewals to the Nuclear Regulatory Commission in the expectation that investments in maintenance to correct the deficiencies of aging after 40 to 50 years will be less than the cost of building alternative capacity that would meet future goals for reducing carbon emissions. The EIA's highest nuclear projection indicates that relicensing of nuclear plants could eliminate the need for up to 16,000 megawatts of new fossil fuel-fired capacity and reduce U.S. carbon emissions by 14 million metric tons annually in 2020. National response to the Kyoto Climate Change Protocol may be the most important factor determining the future of nuclear power in the United States, and, ultimately, in other parts of the world.

Water Resources for Power Generation

Water is an essential resource for operating a steam-electric generating plant to meet requirements for boiler feed water, cooling tower makeup, wet scrubbing, and waste disposal functions such as ash sluicing. Higher water quality requirements must be met for boiler feed water, which entails dedicated water treatment facilities. Overall water requirements are substantial, with a 500-MW coal-fired plant typically requiring up to 5000 acre feet annually, assuming that a cooling tower is used to dissipate the heat rejected by the steam condenser. Most new plants are being built with cooling towers to avoid concerns over the thermal effects that result from once-through cooling with a return of warm water to its source. Air cooling is a technically feasible alternative that adds to plant cost and reduces generating efficiency. Most power plants are sited close to rivers or lakes that can supply the required quantity of water. In some regions, including many parts of the western United States, water supplies are scarce, and inability to obtain a water allocation can be an obstacle to siting a new power plant. In the future, reuse of produced water from petroleum production and refining or other industrial uses will become a more important source of cooling water for power production. The EERC has successfully demonstrated a low-cost freeze–thaw/evaporation (FTE®) process to clean up saline and oily wastewater from gas production by using natural freezing cycles in cold regions, which could supply water suitable for power plant use.

Environmental Regulation and Future Concerns

One of the most important factors in determining future makeup of the electric power industry will be environmental regulations. We are increasingly seeing environmental policy initiatives that transcend national boundaries, like the Kyoto Protocol.

The Kyoto Protocol

In industrialized countries, the primary source of uncertainty in energy forecasts is the Kyoto Climate Change Protocol, which would require large reductions in carbon emissions in most Annex I countries to be achieved between 2008 and 2012. Annex I to the Protocol includes the industrialized countries of Western Europe, the United States, Japan, and Australia, along with the transitional economies of the FSU and Eastern Europe. As of January 2000, 84 countries had signed the treaty, but none of the Annex I countries had ratified it. The treaty commits all of the Annex I countries to binding emission targets in reference to their 1990 levels that range from reductions of 8% for the EU, 7% for the United States, and 6% for Japan and Canada, to increases of 10% for Iceland and 8% for Australia. The Russian Federation and the Ukraine are held at their 1990 levels. Non-Annex I countries have no targets under the Protocol but are required to implement mitigation programs. Should the Kyoto Protocol be ratified and entered into force, it will have a profound effect on the use of energy in most of the industrialized world.

Compliance with the Kyoto Protocol in the Annex I industrialized countries becomes increasingly difficult with time because of large increases in carbon emissions that are forecast in the absence of policy restrictions, whereby the emissions for 2010 are projected by DOE to exceed 1990 levels by 33% in the United States, 21% to 40% in industrialized Asia and Australia, and 15% in Western Europe (EIA, 2000). The countries of the FSU and Eastern Europe have already experienced a substantial reduction in carbon emissions below 1990 levels because of their transition to a market economy, and projections indicate that they can easily meet their Protocol targets without policy intervention.

The largest increases in carbon emissions are expected to occur in the developing world, for which there are no targets under the Protocol. In 2010, the total carbon emissions for developing countries are projected to be 118% above the 1990 level, with China and India together estimated to account for over half of this increase. Proportionately, the emissions in developing countries, which represented only 28% of the world total in 1990, are projected to account for 44% of the world total in 2010, if all countries continue on a policy-neutral course, and 49% of the world total, if the Annex I industrialized countries meet their Protocol targets. Various Annex I countries are planning to meet their Kyoto Protocol targets in a variety of different ways, and in a competitive world, there will be economic winners and losers depending on the per capita and GDP energy intensity and fuel mix of different countries.

The United States will face difficult challenges in meeting its Kyoto goals in the electrical sector owing to a highly electrified economy and substantial reliance on coal as a generating fuel.

Without policy restrictions, total U.S. carbon emissions are expected to grow by 1.3% annually, exceeding 1990 levels by 15% in 2000 and 47% in 2020 (EIA, 1999). Electrical generation accounted for 37% of U.S. carbon emissions in 1998, compared with nonelectrical contributions of 33% for transportation, 20% for industrial, 6% for residential, and 4% for commercial. These percentage contributions change only slightly in the EIA's projections out to 2020. In 1998, coal accounted for 36% of total U.S. carbon emissions, but a much larger 87% of emissions from the electrical utility industry, which currently uses coal for 55% of its total generation. The policy-neutral EIA projection for 2020 indicates that coal would still be responsible for 81% of electricity-related emissions when coal is used for 52% of generation, whereas the growing use of natural gas would account for 18% of emissions from 28% of generation. The proportionally lower carbon emission from natural gas relative to its share of generation reflects the higher efficiency of the gas-fired combined-cycle generating plants that are projected to be built by the year 2020.

Executive actions and legislative proposals made by the Clinton Administration in response to global warming and the Kyoto Protocol could have immense effects on the electric power industry in the United States over time, starting with voluntary measures and leading to mandatory actions. The United States Climate Change Action Plan (CCAP), developed in 1993 to fulfill requirements under the 1992 United Nations Framework Convention on Climate Change, established voluntary measures to begin stabilizing greenhouse gas emissions at 1990 levels. The cornerstone of the CCAP for electric utilities is the Climate Challenge Program administered by DOE, which allows utilities to make formal commitments to reduce carbon emissions. Approximately one-third of the 166 million ton reduction in greenhouse gas emissions (measured as carbon dioxide equivalent) reported in 1997 under the CCAP was related to electricity generation, transmissions, and distribution (EIA, 1997). The largest emission reductions by utilities came from recommissioning or improving the performance of nuclear plants to replace coal-fired generation, with two Tennessee Valley Authority projects at the Browns Ferry and Watts Bar nuclear plants accounting for about 40% of total utility reductions. Other utility actions involved increased generation from natural gas, hydro, wind, and biomass; cogeneration; reduced losses in power lines and transformers; power dispatching rules that consider carbon emissions; and the reuse of coal ash to replace portland cement produced by calcining limestone, which results in sizable emissions of carbon dioxide. In addition, utilities sponsored most of the tree- planting projects performed for the purpose of sequestering carbon.

The success of the U.S. CCAP has been impressive, with reported reductions of about 2.5% of total U.S. emissions of greenhouse gases. However, most of the actions taken under CCAP are in-line with a "no regrets" policy which assumes that remedies can be found at little or no cost. The EIA's projection of a 1.3% annual increase in U.S. carbon emissions between 1998 and 2020 takes full account of these actions. Further measures are needed if greenhouse gas emissions are to be reduced to 1990 levels in accordance with the Kyoto Protocol, and several actions have been taken which affect the electric power industry. Final orders were issued by the Federal Energy Regulatory Commission (No. 888 and 889) in April 1996 to foster efficiency in electricity markets by providing open access to interstate transmission lines and setting rules on stranded costs for utility restructuring. Presidential Executive Order 13123, issued in June 1999, mandated a 25% energy reduction per square foot in federal facilities by 2010 and a commensurate greenhouse gas reduction of 30%. Executive Order 270400, in August 1999, established an interagency council to advance the use of biomass in power generation and bio-based products. In November 1999, Congress and the President agreed on a 30-month extension in the 1.5 cent per kilowatt hour production tax credit for new wind and biomass facilities. Federal support for research on energy efficiency and renewable energy has increased overall in recent years, although the DOE budget for renewable power technologies was cut 6% in fiscal year 2000. New appliance efficiency standards have been developed by DOE under the 1987 National Appliance Energy Conservation Act to take effect at the end of the moratorium enacted by Congress for the period from 1996 to July 2000. For the most part, these and other actions to date affect the electric utility industry only indirectly. However, the Renewable Portfolio Standards (RPS) in the Comprehensive Electricity Competition Act (CECA), submitted to Congress in April 1999, represent a direct mandate for the industry to invest in renewable generating facilities. Other provisions of the CECA would reduce carbon emissions by increasing efficiency, including an 8% investment tax credit for combined heat and power facilities.

The proposed RPS, which would be expected to be substantially revised before it is enacted by Congress, calls for specific levels of electricity generation to be met from renewable sources, starting with 2.4% for the years 2000 to 2004 and increasing to 7.5% by 2010. The RPS program would be administered through a renewable credit system operated like the current sulfur dioxide allowance trading system created under the Clean Air Act Amendments (CAAA) of 1990. Each kilowatt hour of electricity generated from a renewable source would receive one credit that could be held by the plant operator or sold to others to meet the required 7.5% renewable share. The mandate of the RPS falls short of an absolute requirement for generating electricity from renewable sources by providing for two limitations: 1) the price of renewable credits would be capped at 1.5 cents per kilowatt hour, above which credits could be purchased from DOE and 2) the 7.5% requirement would expire at the end of 2015 under a sunset provision. In order for the RPS to generate investment in renewable generation under these arrangements, the price increment of 1.5 cents per kilowatt hour must have an economic value over the period from the commissioning of the generating facility through 2015 sufficient to compensate for the higher cost of renewable generation in relation to the most economical option, which is likely to be a gas-fired combined-cycle plant. Otherwise, renewable generating facilities will not be built, the price of credits will rise above 1.5 cents, and utilities will pay the equivalent of a tax of 1.5 cents per kilowatt hour to DOE on 7.5% of the electricity they generate. Analysis performed by the EIA indicates that the RPS would have little effect on renewable generation within the limitations posed by the cap and sunset provision (EIA, 1999). However, removing these limitations would substantially expand generating capacity from wind, biomass, and geothermal, sufficient to reduce carbon emissions by an estimated 1.6% in 2020 at a related cost of 1.4% in the price of electricity if the incremental cost of the more expensive renewable capacity were spread across all electricity sales.

In the United States, none of the mitigation action proposed to date even begins to approach the level that will ultimately be required to meet the Kyoto Protocol targets. These targets are, in turn, only a down payment on the changes that may eventually be required in both the industrialized and developing countries if it proves necessary to rein in worldwide carbon emissions. The most recent policy analysis presented by the EIA (1999), which draws on many different sources including the DOE National Laboratories, the Massachusetts Institute of Technology, and EPRI, evaluates mitigation effects and economic impacts in terms of the incremental price increase for carbon fuels that would have to be added at the point of their consumption to reduce carbon emissions, expressed in dollars per ton of carbon. This added increment, which could take the form of a carbon tax, would be applied to all fossil fuels used for electrical generation and would be reflected in the delivered price of electricity. The amount required to be added to the price of carbon increases as the carbon reduction requirement increases, from zero for a policy-neutral case up to about $350 per metric ton of carbon for a case representing an annual reduction of 542 million metric tons from energy-related sources—which is the total annual reduction in U.S. carbon emissions required to reach a level 7% below 1990 in the period between 2008 and 2012. The significance of adding $350 per ton to the price of carbon can be gauged by a comparison with current prices for most utility coals, which are in the range of $10 to $30 per ton of coal, or about $25 to $50 per ton of carbon. In this most stringent reduction scenario, which assumes that all reductions are energy-related, the EIA estimates that coal use for electricity generation would be reduced by 78% in 2010 and would nearly disappear by 2020. Electrical generating requirements would then have to be met by a combination of conservation measures that lower electrical demand, improved efficiency and, primarily, switching to natural gas, renewable fuels, and nuclear power. The corresponding worst-case economic impacts are estimated by the EIA to be represented by an 86% price increase for electricity and about a 3% dip in GDP occurring within the period between 2008 to 2012, with nearly full recovery to policy-neutral GDP levels shortly thereafter.

Much smaller reductions in U.S. carbon emissions from energy-related sources would be needed if most of the required mitigation could be accomplished through international trading activities, net offsets from carbon-absorbing agricultural and forestry sinks, and reductions in other greenhouse gases. The most favorable case presented by the EIA estimates that an electricity price increase of only about 20% would be required if three-fourths of the emission reduction were from non-energy-related actions. However, flexibility to minimize energy-related reductions and impacts may be limited under the Kyoto Protocol by the principle that trading of emission credits "shall be (only) supplemental to domestic actions." Binding limits on flexibility for international trading of carbon emissions are being proposed by the EU and others to ensure equity in sharing the burden of emission reductions. Others, including many in the United States, argue that the most economically efficient means of reducing emissions is through unlimited use of trading. This very important issue, which will be taken up in the sixth Conference of the Parties to the Framework Convention, could well determine whether the Kyoto Protocol will be ratified and entered into force and if its goals can be met by the United States and other industrialized countries within practical limits of economic and political change.

Environmental Regulation for SO_x, NO_x, Particulates, and Toxic Metals

As has been stated previously, the regulation on CO_2 emissions contained in the Kyoto Protocol would profoundly affect future decisions on power generation. Although not as critical as CO_2, environmental regulations on SO_x, NO_x particulate matter, and toxic metals from energy production will also play a very significant role in determining future production strategies. In a deregulated market for electricity, these environmental impacts will be factored into the decision-making process via their impact on the cost of electricity. Additionally, the uncertainties associated with future environmental regulations and their effect on generating cost will affect investment decisions regarding new electrical generating capacity.

Environmental issues in electrical generation include air emissions, water pollution, and solid wastes. Nuclear energy has been profoundly affected by public concern over the inability of industry and government to come up with acceptable options for safe temporary storage and long-term disposal of radioactive solid wastes. This issue, together with concerns over the potential for catastrophic releases of radioactive materials from operating accidents at nuclear plants, essentially halted expansion of the nuclear industry nearly 20 years ago in the United States and many other countries throughout the world.

Coal-, oil-, and gas-based generation are all affected by air quality regulations. The CAAA of 1990 established a timetable for significant reductions in emissions of SO_x, NO_x, and particulates in the United States. In addition, 189 hazardous air pollutants (HAPs) were identified, for which the U.S. Environmental Protection Agency (EPA) was charged with setting standards based on "maximum achievable control technology" for major individual and area sources. The CAAA also directed the EPA to perform a study of HAP emissions from utility steam generating units to be completed by November 1993. The much-delayed study report issued in February 1998 (U.S. EPA, 1998) identified mercury from coal-fired utilities as the greatest potential concern, followed by uncertainties over dioxins and arsenic from coal-fired plants and nickel emissions from oil-fired units.

Mercury (Hg)

Mercury emission regulations for coal-fired utility boilers remain an open question in the United States. The Mercury Study Report to Congress submitted by the EPA in December 1997 (U.S. EPA, 1997) indicates there are significant risks to human health owing to mercury exposure and that the coal-fired utility industry is the largest single source of Hg in the United States. The EPA will make a regulatory determination in December 2000 on whether or not regulation of Hg from coal-fired boilers will be required. The review on the Toxicological Effects of Methylmercury issued by the National Academy of Science (August 2000), which supports the EPA's conservatively low reference dose of 0.1 micrograms per kilogram of body weight per day, will influence the EPA to set a stricter emission standard, which could be as stringent as 90% control. The issue presents significant challenges in that no widely applicable and economic technologies currently exist for controlling mercury emissions from all coal-fired boilers, which are equipped with various air pollution control devices and burn very dissimilar coals. Current estimates of the cost of Hg control vary widely from $5000 to $70,000 per pound of Hg removed, depending on coal type, existing air pollution control equipment, and assumptions on mercury control technology (Brown, 1999). All of the industrialized countries are considering similar strategies. Depending on the standards set by EPA in the United States and by other countries throughout the world, the impact on the cost of electricity from current and future coal power generation could be in the range of approximately 0.5 to 5 mills/kWh.

SO_x, No_x

Control of acid gases from utility boilers is required of the power generator to compete in electricity markets worldwide. In the United States, regulation of SO_x and NO_x is based on the federal 1990 CAAA, which established targets for emission reductions and tradeable allowances under an emission cap. Enforcement resides with the states, and in many cases, state implementation standards impose emission regulations that go beyond the minimum federal requirements.

SO_x emission regulations have resulted in a major shift in coal use, with the United States becoming far more dependent on low-sulfur subbituminous coals at the expense of higher-sulfur bituminous coal. In addition, approximately one-fourth of the U.S.'s generating capacity is currently scrubbed for sulfur, and scrubbers are projected to be installed on an additional 7% of U.S. generating capacity by about 2005 to comply with the Phase 2 sulfur emissions cap (EIA, 1999). This combined strategy, a shift to low-sulfur fuels and the addition of scrubbing technology, will allow U.S. utilities to meet current and anticipated regulations for sulfur. In other parts of the world, significant retrofit actions are being taken to control sulfur emissions in coal-fired plants. The countries of East Central Europe have initiated significant upgrades that involve scrubbers for existing coal-fired capacity and switching to gas-fired generation to reduce sulfur emissions from this region. Additional reductions will be required in many of these countries to meet the requirements of the EU. Increased use of sulfur control technology and a shift away from coal have occurred in the former East Germany and will occur throughout East Central Europe. In India and China, where coal use for power generation will increase dramatically, the control of sulfur oxides will be a significant component of the decision process regarding fuel and technology selection.

NO_x control technologies are available for all of the commonly used fuel forms. Technology options include combustion staging, reburn, and both noncatalytic and catalytic reduction techniques. Requirements for achieving lower levels of NO_x emission on coal-fired units have resulted in a move away from the use of low-NO_x burners and the installation of selective catalytic reduction (SCR) technology worldwide. In the United States, EPA has issued rules that require large reductions in NO_x emissions in 22 eastern states to meet ambient air quality standards for ground-level ozone. These rules, which were challenged in court but substantially upheld in a March 2000 decision, will require most coal-fired utility boilers in the affected states to install SCR control technology at a cost that typically adds 5% to 10% to the plant capital investment.

Requirements for lowering NO_x emissions will tend to favor the installation of additional gas-fired capacity, since more stringent control requirements can be met at a lower cost with this premium fuel.

Particulate

The control of fine particulate remains an issue for fuels that produce significant amounts of ash, including coal, biomass, and heavy oil. Advanced technologies are either available or are at an advanced stage of development to achieve particulate removal efficiencies of 99.99% using control devices such as the advanced hybrid particulate collector (AHPC) developed by the EERC or the compact hybrid particulate collector (COHPAC) developed by EPRI. In the United States, the stringent limit on fine ambient particulate matter smaller than 2.5 microns set by the EPA in 1997 will also require additional control of SO_x and NO_x emissions which generate secondary particulates in the atmosphere.

CONCLUSIONS

The electricity generating industry in the United States and throughout the world has undergone significant change. This industry will continue to move in the direction determined by market forces as countries around the world see the advantage to their citizens of allowing competition rather than centralized command and control to meet the future requirements of their growing populations for affordable electricity. The other forces that will shape the future of the electrical industry are technological advances that improve efficiency and lower cost and environmental policies concerning carbon emissions that could profoundly change fuel choice. Both of these major forces are beginning to influence decisions in the electrical industry, but it will likely take a decade or more for their full effect to be realized. It is impossible to clearly predict the structure of the future electrical industry, but we believe the following observations can be made:

- Restructuring of the power industry to encourage competition in electrical generation will continue in the United States and around the world. The largest future source of electricity will be large merchant plants organized as independent power producers to sell wholesale electricity competitively to the electric grid. In the United States, 46% of all new electrical generation commissioned since 1990 has been built by non-utility generators. A smaller but increasingly significant source of wholesale power will come from cogeneration by energy-intensive industries such as petroleum refining where low-grade fuel by-products and waste heat can be used to generate electricity.

- Significant additions and improvements in the electrical distribution grid over larger geographical regions will be needed to ensure reliable availability and reasonable price stability in a competitive wholesale market for electricity.

- Restructuring of the power industry in the United States in a way that eliminates or reduces the stabilizing influence of state public service commissions on the supply and price of electricity will be slowed by a political backlash unless wide fluctuations in electrical prices with seasonal and regional swings in demand can be resolved contractually. The special relationship that has historically existed between generating and distributing cooperatives serving rural areas represents one model that may be adopted in different forms to stabilize the wholesale market for electricity.

- Distributed generation outside the large electrical grids will grow in underdeveloped countries and regions where isolated populations live in remote regions. It will also help to fill a niche market demand for renewable power in developed countries. This category will not represent a sizeable percentage of world power generation, but it will provide a proving ground for new technologies such as gas-fired microturbines or fuel cells, new wind turbine generators, and solar voltaic or thermal systems.

- Restructuring of electrical distribution down to the retail level will occur slowly through reorganization of various related organizations including state public service commissions, investor-owned utility companies, and distribution cooperatives. Competition in providing service will emphasize reliability and price stability as much as price. Rate structures will increasingly include demand charges and discounted rates for interruptible service for less critical functions such as water heating.

- Coal will remain the dominant fuel for electrical generation through 2020. This will change only if and when carbon taxes are adopted worldwide.

- The use of gas for power generation will grow substantially. Gas prices will go up, and regional price instabilities will increase as demand for this premium fuel in the power industry accelerates. Major investment in exploration and pipelines will be required. LNG trade will see significant increases.

- The use of nuclear power will decline in the short term but will increase substantially in the longer term. The supply of fuel for conventional nuclear power is very large, and the problem of nuclear waste disposal will be resolved. A stable political and social environment will become increasingly important to the future growth of nuclear power to address the risk of nuclear accidents and the strict control of weapons-grade fissionable materials.

- The use of renewable energy from biomass and wind will increase only slightly in the next two decades without a significant policy driver. Opportunities will be limited to niche markets in the near term, with broader acceptance growing over time with technological advances and increases in the cost of competing fuels. A significant carbon tax or similar policy initiative could radically alter this scenario and make biomass cofiring with coal an immediate widespread opportunity.

- The greatest uncertainties in determining the future mix of fuels that will be used to produce electrical power concern implementation of the carbon emission reductions called for in the Kyoto Protocol and possible further reductions that are forecast by some policymakers to be needed to control global warming. The ability to use international trading in carbon emissions to provide a flexible response may determine whether the Kyoto Treaty is ratified by the United States and can be successfully implemented worldwide.

- Coal as the world's current leading fuel for power generation is at a crossroad where it either moves toward resolving its environmental challenges and regains its competitive advantage over natural gas or suffers a decline that could be precipitous with ratification of the Kyoto Protocol, absent carbon emissions trading. A wealth of new technology is available for improving the efficiency and environmental acceptability of coal-fired generation based on decades of research and development. For now, the technical and financial risks posed by new technologies and by uncertain environmental policies are forestalling investment in new coal-fired generating plants in the United States and Europe. An economical technology for sequestering the carbon dioxide produced by coal combustion would resolve much of the current uncertainty. Sequestering is the subject of vigorous investigation, but its commercialization as a major force in the market will likely not occur in the next decade. Major investments in technology development and demonstration are still required to allow lower-grade carbon fuels like coal to continue to provide customers with the cost benefits of these abundant resources.

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ALTERNATIVE ENERGY SOURCES

Walter Youngquist
Consulting Geologist
P.O. Box 5501
Eugene, Oregon 97405

Oil fuels the modern world. No other substance can equal the enormous impact which the use of oil has had on so many people, so rapidly, in so many ways, and in so many places around the world.

Oil in its various refined derivative forms, such as gasoline, kerosene, and diesel fuel, has a unique combination of many desirable and useful characteristics. These include a current availability in abundance, a currently high net energy recovery, a high energy density, ease of transportation and storage, relative safety, and great versatility in end use. Oil is also useful as more than an energy source. It is the basis for the manufacture of petrochemical products including plastics, medicines, paints, and myriad other useful materials. Finally, the asphalt "bottoms" from refineries have converted millions of miles of muddy trails around the world into paved highways on which transport vehicles fueled by oil run.

Alternative energy sources must be compared with oil in all these various attributes when their substitution for oil is considered. None appears to completely equal oil.

But oil, like other fossil fuels, is a finite resource. True, there will always be oil in the Earth, but eventually the cost to recover what remains will be beyond the value of the oil. Also, a time will be reached when the amount of energy needed to recover the oil equals or exceeds the energy in the recovered oil, at which point oil production becomes no more than a break-even, or a net energy loss situation.

Oil being the most important of our fuels today, the term "alternative energy" is commonly taken to mean all other energy sources and is used here in that context. Realizing that oil is finite in practical terms, there is increasing attention given to what alternative energy sources are available to replace oil. The imperative to pursue alternative energy sources is clearly established by two simple facts. The world now uses more than 26 billion barrels of oil a year, but new discoveries (not existing field additions) in recent years have been averaging less than seven billion barrels yearly. The peak of world oil discoveries was in the mid-1960's. Inevitably, the time of the peak of world oil production must follow, with most current estimates ranging from the year 2003 (Campbell, 1997) to 2020 (Edwards, 1997). Significantly, all estimates of production peak dates are within the lifetimes of most people living today.

The amount of energy an individual can directly or indirectly command largely determines that individual's material standard of living. This, of course, also applies to nations as a whole. To provide adequate energy for future generations introduces the concept of sustainability. What significant energy sources can be drawn on indefinitely?

"Sustainable" is a popular and pleasant word, but when it is used it needs to be clearly defined and placed within certain parameters. The term "sustainable growth" is popular with Chambers of Commerce as well as with corporations, but if this means increase in use of any resource, including land for more people, more water for more people, and more and more food, or more "things", then the term "sustainable growth" is an oxymoron (Bartlett, 1994). Growth in terms of numbers of anything cannot be sustained indefinitely. Sustainable growth in terms of better medical care, improved sanitation, and other related qualities of life, and of intellectual endeavors, among other things, is possible, and should be a continual goal.

Any consideration of "sustainable" must also be framed in the concept of a fixed size of population. People use resources. And all energy resources, even solar energy, are limited (Hardin, 1993). The problem of population size is politically sensitive and therefore largely avoided in discussions. But the energy problem cannot be sustainably solved if the demand target is a continually growing population. It is important to keep this overriding fact in mind. Eventually it will have to be faced. In defining a sustainable society, it is also necessary to determine what reasonable standard of living is to be achieved. This does not lend itself to an easy definition as various cultures have differing views.

In considering what significant (in terms of quantity and quality) sustainable alternative energy sources may exist, the factors of population and living standards must be addressed. These matters are beyond this discussion, which simply presents the basic facts of alternative energy sources. How these sources, with their advantages and limitations may be applied to society at large is here left for economists, sociologists, and politicians.

Energy Interchangeablity

There is much casual popular thought that energy sources are easily interchangeable. "When we run out of oil we will go to alternative fuels." "We can run our cars on solar energy." Such statements are legion. But the transition to alternative fuels will not be simple nor as convenient as is the use of oil today, and it will involve much time and financial investment. Energy carriers in terms of varied end uses and ease of handling and storage, are not easily interchangeable.

We here briefly examine alternative energy sources as to their advantages, limitations, and their prospects for replacing oil in the ways and great volumes in which we use oil today. Alternative energies closest to conventional oil (from wells) are first considered, and then our energy horizons are expanded.

Energy sources can be divided into renewable and nonrenewable.

ALTERNATIVE ENERGY SOURCES

Nonrenewable	Renewable
Oil sands, heavy oil	Wood/other biomass
Natural gas	Hydro-electric power[2]
Coal	Solar energy
Shale oil	Wind energy
Gas hydrates	Wave energy
Nuclear fission	Tidal power
Geothermal[1]	Fusion
	Ocean thermal energy conversion
[1]Renewable for space heating	[2]Not renewable with reservoirs

NONRENEWABLE ENERGY SOURCES

Oil Sands/Heavy Oil

This oil exists in huge quantities (trillions of barrels) particularly in Alberta, Canada and Venezuela. It is true oil but in deposits which take special methods to recover the oil. Oil sands must either be mined, or recovered by the SAGD (SAG-D) process (steam assisted gravity drainage) in which steam is injected in the upper of two parallel pipes and the oil is collected in the lower pipe. The oil must have lighter hydrocarbons added to it to allow it to flow and be processed into conventional petroleum products. Heavy oil deposits can be injected with hot water or steam. Because of the energy expended in these processes, the net energy recovery is considerably less than oil from conventional drilled wells.

At present about 500,000 barrels a day are recovered from the Athabasca oil sands of Alberta. To increase this 10-fold to 5 million barrels a day would be a very large task, with severe environmental limitations. This must be put in the perspective of the 76 million barrels of oil the world now consumes daily. Other similar oil deposits have the same problems of scale and net energy recovery. In total, oil sands and heavy oil can replace conventional oil only to a small degree. Canada's domestic needs for oil, with its growing population and increasing industrialization, will likely soon absorb all the additional oil which can be produced from oil sands and heavy oil with no surplus to export.

Natural Gas

Natural gas is methane (CH_4) which commonly has minor quantities of noncombustible gases such as carbon dioxide and nitrogen associated with it. Natural gas is termed "associated gas" when it occurs with oil, or "nonassociated gas" when it is not found with oil. Natural gas is derived from organic material and can be formed at essentially normal atmospheric temperature (such is the origin of "swamp gas" and the gas associated with garbage dumps, now in places used for fuel to generate electric power).

Oil also is derived from organic materials, but to derive oil from organic material, the material must pass through an "oil window". This is a temperature-time relationship ranging from 70°C to about 150°C (158-302°F). Below about 16,000 feet (4880 meters), the Earth is so hot that oil cannot exist and only gas is found below that depth.

In terms of energy, one cubic foot of gas at one atmosphere has 1000 Btus. Fifty-six hundred cubic feet (157 cubic meters) of gas has the same energy equivalent as one barrel of oil. Natural gas is the cleanest burning of the fossil fuels, and for that reason is the fuel of choice over coal for electricity production as boiler fuel and in gas turbines. Natural gas can be used as a substitute for gasoline or diesel fuel in internal combustion engines, and is so used in a few places.

Natural gas is commonly moved by pipeline. It can be shipped in cryogenic tankers but this is expensive and does not lend itself economically to large scale transport, whereas oil is shipped economically worldwide. Natural gas can be converted to a liquid (GTL--gas to liquid), and such conversion plants are being built in areas not served by pipelines (e.g., the North Dome Field of Qatar). The end product is a high grade substitute for gasoline. However, the volumes of GTL which can be produced are modest and somewhat more expensive than gasoline.

Natural gas is more widely distributed than oil. But estimates are that in total its energy in reserves is equal to or slightly less than that in world oil reserves. Natural gas (and in GTL) is an alternative energy to petroleum, but natural gas is also a finite fossil fuel.

Coal

Coal is a very large energy source, but it must be mined, it is not nearly so easy to handle and transport as is oil, and it has much less energy density. For use in producing electricity in power plants (burned under boilers), coal can replace oil. But converting it to a liquid fuel which might be used in motor vehicles is expensive, and doing this on a scale which could significantly replace oil in vehicle use would require impossibly large mining projects. Coal can replace oil in some uses. Although considerable progress has been made, coal production and burning still have environmental problems which are of major concern. Adding to the greenhouse effect is one. The energy in coal reserves worldwide is greater than oil, but it, too, is a finite fossil fuel.

Shale Oil

Production of oil from oil shale has been attempted at various times for nearly 100 years. So far, no venture has proved successful on a significantly large scale (Youngquist, 1998b). One problem is that there is no oil in oil shale. It is a material called kerogen. The shale has to be mined, transported, heated to about 450°C (850°F), and have hydrogen added to the product to make it flow. The shale pops like popcorn when heated so the resulting volume of shale after the kerogen is taken out is larger than when it was first mined. The waste disposal problem is large. Net energy recovery is low at best. It also takes several barrels of water to produce one barrel of oil. The largest shale oil deposits in the world are in the Colorado Plateau, a markedly water poor region. So far shale oil is, as the saying goes: "The fuel of the future and always will be." Fleay (1995) states: "Shale oil is like a mirage that retreats as it is approached." Shale oil will not replace conventional oil.

Gas Hydrates

These are very large deposits of methane which are in a solid substance composed of water molecules forming a rigid lattice of cages. These are discussed separately in this treatise.

Nuclear Fission

There are two isotopes of uranium, uranium-235 and uranium-238. Only uranium-235 is fissionable, and it is only .7 percent of all uranium. The 99.3 percent which is uranium-238 is not fissionable, but uranium-235 can be used to produce a new element from uranium-238, plutonium-239, which is fissionable. Although uranium in both forms is a finite resource, converting uranium-238 to plutonium-239 (a process called "breeding") could possibly extend our use of uranium for power by perhaps 100 times (Meyers, 1983). However, plutonium is an exceedingly toxic substance, and also the basis for a deadly bomb. Because of this there is much opposition to the breeder reactor, and to uranium for power in general due to safety and environmental considerations. However, coal and uranium are the only two alternative sources of energy which can be developed in large amounts, and provide a dependable base load in the reasonably near future. Nuclear power development has been stopped in the United States. Elsewhere, some countries are abandoning nuclear power (e.g., Sweden, Germany), whereas others are pursuing it (e.g., Japan, Russia). Ultimately, however, nuclear power in any form is nonrenewable because uranium reserves are limited.

The end product of nuclear fission is electricity. How to use electricity to efficiently replace oil (gasoline, diesel, kerosene) in the more than 700 million vehicles worldwide has not yet been satisfactorily solved. There are severe limitations of the storage batteries involved. For example, a gallon of gasoline weighing about 8 pounds has the same energy as one ton of conventional lead-acid storage batteries. Fifteen gallons of gasoline in a car's tank are the energy equal of 15 tons of storage batteries. Even if much improved storage batteries were devised, they cannot compete with gasoline or diesel fuel in energy density. Also, storage batteries become almost useless in very cold weather, storage capacity is limited, and batteries need to be replaced after a few years use at large cost. There is no battery pack which can effectively move heavy farm machinery over miles of farm fields, and no electric battery system seems even remotely able to propel a Boeing 747 14 hours nonstop at 600 miles an hour from New York to Cape Town (now the longest scheduled plane flight). Also, the considerable additional weight to any vehicle using batteries is a severe handicap in itself. In transport machines, electricity is not a good replacement for oil (Jensen and Sorensen, 1984). This is a limitation in the use of alternative sources have where electricity is the end product.

Where oil is used for electric power production, nuclear fission can replace oil as a fuel. However, in the U.S. now only about 2 percent of electric power is generated from oil. Elsewhere, such as island economies, oil is now the chief source for electric power generation and nuclear fission has the prospect of significantly replacing that oil.

Geothermal Energy

This is heat from the Earth. In a few places in the world there is steam or very hot water close enough to the surface so that the resource can be reached economically with a drill. The steam, or hot water flashed to steam, can turn a turbine, turning a generator producing electricity. At best, because of the scarcity of such sites, geothermal energy can be only a minor contributor to world energy supplies, and the product is electricity, which is subject to limited end uses. It should be noted that all electric power geothermal generating site reservoirs are now declining, because the geothermal requirements to produce electric power draw down the reservoirs faster than their recharge ability. Some projects are now reinjecting water from the condensed steam back into the reservoir to see if this problem can be mitigated, but results so far are inconclusive. However, when lower temperature reservoirs are used for space heating, with a more modest demand on the reservoir using down-well heat exchangers or ground to air heat pumps using the natural heat flow of the Earth, geothermal energy appears to be a renewable energy source.

RENEWABLE ENERGY SOURCES

Wood and Other Biomass

Wood has long been used as a fuel, now to the extent that large areas worldwide are being deforested resulting in massive erosion in such places as the foothills of the Himalayas, and the mountains of Haiti. Wood can be converted to a liquid fuel but the net energy recovery is low, and there is not enough wood available to be able to convert it to a liquid fuel in any significant quantities.

Other biomass fuel sources have been tried. Crops such as corn are converted to alcohol. In the case of corn to ethanol, it is an energy negative. It takes more energy to produce ethanol than is obtained from it (Pimentel, 1998). Also, using grain such as corn for fuel, precludes it from being used as food for humans or livestock. It is also hard on the land. In U.S. corn production, soil erodes some 20-times faster than soil is formed. Ethanol has less energy per volume than does gasoline, so when used as a 10 percent mix with gasoline (called gasohol), more gasohol has to be purchased to make up the difference. Also, ethanol is not so environmentally friendly as advocates would like to believe. Pimentel (1998) states:

> Ethanol produces less carbon monoxide than gasoline, but it produces just as much nitrous oxides as gasoline. In addition, ethanol adds aldehydes and alcohol to the atmosphere, all of which are carcinogenic. When all air pollutants associated with

> the entire ethanol system are measured, ethanol production is found to contribute to major air pollution problems.

With a lower energy density than gasoline, and adding the energy cost of the fertilizer (made chiefly from natural gas), and the energy costs (gasoline and/or diesel) to plow, plant, cultivate, and transport the corn for ethanol production, ethanol in total does not save fossil fuel energy nor does it's use reduce atmospheric pollution.

A comprehensive study of converting biomass to liquid fuels by Giampietro and others (1997) concludes:

> Large scale biofuel production is not an alternative to the current use of oil, and is not even an advisable option to cover a significant fraction of it.

Hydro-electric Power

Originally thought of as a clean, non-polluting, environmentally friendly source of energy, experience is proving otherwise. Valuable lowlands, which are usually the best farmland, are flooded. Wildlife is displaced. Where anadromous fish runs are involved as in the Columbia River system with its 30 dams, the effect on fish has been disastrous. Only to a small extent is hydro-electric power truly renewable. This is when the "run of the river" without dams is used, as, for example with a Pelton wheel. If reservoirs are involved, in order to provide a dependable base load as is the case of most hydro-electric facilities, hydro-electric power in the longer term is not a truly renewable energy source. All reservoirs eventually fill with sediment. Some reservoirs have already filled, and many others are filling faster than expected. A dam site can be used only once.

We are enjoying the best part of the life of huge dams. In a few hundred years Glen Canyon Dam and Hoover Dam will be concrete waterfalls. And, again, the end product is electricity, not a replacement for the important use of oil derivatives (gasoline, etc.) in transportation equipment.

Solar Energy

This is a favorite possible source of future energy for many people, comforted by the thought that it is unlimited. But, quite the contrary is true. The Sun will exist for a long time, but at any given place on the Earth's surface the amount of sunlight received is limited--only so much is received. And at night, or with overcast skies, or in high latitudes where winter days are short and for months there may be no daylight at all, or available in small and low intensity quantities. Direct conversion of sunlight to electricity by solar cells is a promising technology, and already locally useful, but the amount of electricity which can be generated by that method is not great compared with demand. Because it is a low grade energy, with a low conversion efficiency (about 15%) capturing solar energy in quantity requires huge installations--many square miles. About 8 percent of the cells must be replaced each year. But the big problem is how to store significant amounts of electricity when the Sun is not available to produce it (Trainer, 1995), for example, at night.

The problem remains unsolved. Because of this, solar energy cannot be used as a dependable base load. And, the immediate end product is electricity, a very limited replacement for oil. Also, adding in all the energy costs of the production and maintenance of PV (photovoltaic) installations, the net energy recovery is low (Trainer, 1995).

Wind Energy

This energy source is similar to solar in that it is not dependable. It is noisy, and the visual effects are not usually regarded as pleasing. The best inland wind farm sites tend to be where air funnels through passes in the hills which are also commonly flyways for birds. The bird kills have caused the Audubon Society to file suit in some areas to prevent wind energy installations. Locally and even regionally via a grid (e.g. Denmark) wind can be a significant electric power source. But wind is likely to be only a modest help in the total world energy supply, and the end product is electricity, no significant replacement for oil. As with solar energy, the storage problem of large amounts of wind generated electricity is largely unsolved. Wind cannot provide a base load as winds are unreliable.

Wave Energy

All sorts of installations have been tried to obtain energy from this source, but with very modest results. Piston arrangements moved up and down by waves which in turn move turbines connected to electric generators have been tried in The Netherlands, but the project was abandoned. Waves are not dependable, and the end product is electricity, and producing it in significant quantities from waves seems a remote prospect.

Tidal Power

It takes a high tide and special configuration of the coastline, a narrow estuary which can be dammed, to be a tidal power site of value. Only about nine viable sites have been identified in the world. Two are now in use (Russia and France) and generate some electricity. Damming estuaries would have considerable environmental impact. The Bay of Fundy in eastern Canada has long been considered for a tidal power site, but developing it would have a negative effect on the fisheries and other sea-related economic enterprises. It would also disturb the habits of millions of birds which use the Bay of Fundy area as part of their migration routes. Tidal power is not a significant power source. The end product is electricity.

Fusion

Fusion involves the fusion of either of two hydrogen isotopes, deuterium or tritium. Deuterium exists in great quantities in ordinary water, and from that perspective fusion is theoretically an almost infinitely renewable energy resource. This is the holy grail of ultimate energy. Fusion is the energy which powers the Sun, and that is the problem. The temperature of the Sun ranges from about $10{,}000^{0}$C on its surface to an estimated 15 to 18 million degrees in the interior where fusion takes place. Containing such a temperature on Earth in a sustainable way and harnessing the heat to somehow produce power has so far escaped the very best scientific talent. However, even if commercial fusion were accomplished, the end product again is electricity, not a direct convenient replacement for oil.

Ocean Thermal Energy Conversion (OTEC)

Within about 25 degrees each side of the equator the surface of the ocean is warm, and the depths are cold to the extent that there is a modest temperature differential. This can be a source of energy, using a low boiling point fluid such as ammonia which at normal atmospheric temperature of 70^0F (21^0C) is a gas, colder water can be pumped from the deep ocean to condense the ammonia, and then let it warm up and expand to gas. The resulting gas pressure can power a turbine to turn a generator. But the plant would have to be huge and anchored in the deep open ocean or on a ship, all subject to storms and corrosion, and the amount of water which has to be moved is enormous as the efficiency is very low. How to store and transport the resulting electricity would also be a large problem. OTEC does not appear to have much potential as a significant energy source, and the end product is electricity.

NOT PRIMARY ENERGY SOURCES

Hydrogen and Fuel Cells

References are sometimes made as to using these for energy sources. Neither is a primary energy source. Hydrogen must be obtained by using some other energy source. Usually it is obtained by the electrolysis of water, or by breaking down natural gas (methane CH_4). Hydrogen is highly explosive, and to be contained and carried in significantly usable amounts it has to be compressed or cooled to a liquid at minus 253^0C. Hydrogen is not easy to handle, and it is not a convenient replacement for pouring 10 gallons of gasoline into an automobile fuel tank.

Fuel cells are being developed for use in transportation (automobiles, trucks, buses, etc.) but fuel cells have to be fueled with hydrogen. Fuel cells are not a source of energy in themselves, but are a possible ultimate substitute for the internal combustion engine. However, putting the infrastructure in place to effectively and economically produce and store hydrogen on the widespread basis as oil and its derivatives are today, is an enormous, costly, and long term task. The ultimate result can hardly be as versatile and convenient as is the use of oil products today around the world.

LIVING OFF OUR CAPITAL AND THE LIMITS OF TECHNOLOGY

We now live in very fortunate times. In the combination of the versatility of end uses, energy density, ease of handling and storage, and being now able to produce it relatively inexpensively and in great volume, there is no energy source comparable to oil. But living in a chiefly petroleum fueled economy and in a fossil fuel economy in general, we are living off our capital, which is unsustainable.

In a very perceptive volume for the time it was written, British physicist C. G. Darwin (1952) recounts the several "revolutions" which have taken place in the progress of human history, such as the most recent one, the Industrial Revolution. He states there is one more revolution coming:

> The fifth revolution will come when we have spent the stores of coal and oil that have been accumulating in the earth during hundreds of millions of years...it is obvious that there will be a very great difference in ways of life...a man has to alter his way of life considerably, when, after living for years on his capital, he suddenly finds he has to earn any money he wants to spend...The change may justly be called a revolution, but it differs from all the preceding ones in that there is no likelihood of its leading to increase in population, but even perhaps to the reverse.

There is a popular belief that somehow technology can indefinitely rescue the human race from whatever predicament it may get itself into--solve all problems. Pimentel and Giampietro (1994) have warned:

> Technology cannot substitute for essential natural resources such as food, forests, land, water, energy, and biodiversity...we must be realistic as to what technology can and cannot do to help humans feed themselves and to provide other essential resources.

Bartlett (1994) has observed:

> There will always be popular and persuasive technological optimists who believe that population increases are good, and who believe that the human mind has unlimited capacity to find technological solutions to all problems of crowding, environmental destruction, and resource shortages. These technological optimists are usually not biological or physical scientists. Politicians and business people tend to be eager disciples of the technological optimists.

This is not to say that technology cannot continue to produce many good things in the future. But we must not confuse technology which uses resources with creating the resources. The world is finite; there are limits. Nature has given us a great inheritance formed in the Earth by myriad geological processes over millions of years consisting of a huge variety of resources, including, importantly now, fossil fuels. This is a nonrenewable bank account against which we have been writing larger and larger checks as the needs of an increasingly industrialized growing world population have been supplied.

But eventually this account will be exhausted, and we will have to bestir ourselves to get out and live on current income, the first need of which apparently will be to replace oil. How many people can a renewable energy resource income support? And what will be the resources we will use to do this?

Cohen (1995) has discussed this, as is the title of his book, "How Many People Can the Earth support?" But, perhaps the question should be phrased "how many people should the Earth support?"

The optimum size of this population can hardly be estimated now with any great degree of accuracy, but some suggestions have been made. Pimentel and Pimentel (1996) believe that a world population of two billion might be sustained in some reasonable degree of affluence. Other estimates have been made and it is significant that most of them determine a figure which is substantially smaller than is the size of today's population.

Trainer (1995), in a comprehensive study of renewable energy sources, has made a well-supported clear statement:

> Figures commonly quoted on costs of generating energy from renewable sources can give the impression that it will be possible to switch to renewables as the foundation for the continuation of industrial societies with high material living standards. Although renewable energy must be the sole source in a sustainable society, major difficulties become evident when conversion, storage and supply for high latitudes are considered. It is concluded that renewable energy sources will not be able to sustain present rich world levels of energy use and that a sustainable world order must be based on acceptance of much lower per capita levels of energy use, much lower living standards and a zero growth economy.

CONCLUSIONS

Transition to an entirely renewable sustainable energy resource economy with resulting changes in lifestyles is inevitable. Will it be done with intelligence and foresight or will it be done by harsh natural forces? This is one of the main challenges which lie before us.

It seems likely that a sustainable energy mix will be broader that it is today where oil and natural gas make up more than 50% of our supplies. And energy in total will likely be more costly than our energy bill today. The transition to this wider diversity of energy sources will proceed slowly and probably be somewhat provincial depending on what regional resources are available.

Energy is the key which unlocks all other resources, and it will continue to be the key to human physical prosperity. It is significant that both the per capita use of oil, and the per capita use of energy in total both peaked in 1979 and have been falling ever since (Duncan, 2000). We may already be seeing the beginning of the fifth revolution to which Darwin referred.

The British scientist and statesman, Sir Crispin Tickell (1994) has clearly summed up our situation:

> We have done remarkably little to reduce our dependence on a fuel [oil] which is a limited resource and for which there is no comprehensive substitute in prospect.

The challenge of conversion to alternative energy sources with the concurrent problems of population size and stabilization, and adjustment of economies and lifestyles is clearly at hand. A realistic appraisal of the future encourages people to properly prepare for the coming events. Delay in dealing with the issues will surely result in unpleasant surprises. Let us get on with the task of moving orderly into the post-petroleum paradigm.

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WHAT SHOULD WE DO NEXT ON THE MOON AND THEN MARS AND WHY?

H. H. Schmitt
Dept. of Nuclear Engineering
University of Wisconsin-Madison
1500 Engineering Drive
Madison, WI 53706
schmitt@engr.wisc.edu

It is doubtful that the United States or any government will initiate or finance a return of humans to the Moon or a human expedition to Mars. The private sector, however, may find a business rationale for a return to the Moon, based on the economic return from the extraction of lunar helium-3 and its use as a fusion fuel on Earth as a future economic and environmental alternative to fossil fuels. By-products of helium-3 extraction from the lunar regolith will include hydrogen, oxygen, and water - valuable consumables needed elsewhere in space. Thus, the next return to the Moon will approach work on the lunar surface very pragmatically with humans in the roles of exploration geologist, mining geologist/engineer, heavy equipment operator/engineer, heavy equipment/robotic maintenance engineer, mine manager, and the like.

A business enterprise based on lunar resources will be driven by cost considerations to minimize the number of humans required for the extraction of each unit of resource. Humans will be required, on the other hand, to prevent costly breakdowns of semi-robotic mining, processing, and delivery systems, to provide manual back-up to robotic or tele-robotic operation, and to support human activities in general. The creation of capabilities to support mining operations also will provide the opportunity to support renewed scientific exploration at much reduce cost as the cost of capital for launch and basic operations will be carried by the business enterprise. Science will be a profit center for the business, but at a cost to scientists much below that of purely scientific human effort.

During the early years of operations the number of personnel will be about six per mining/processing unit plus four support personnel per three mining/processing units. Cost considerations also will drive business to encourage or require personnel to settle, provide all medical care and recreation, and conduct most or all operations control on the Moon. Technology and facilities required for success of a lunar commercial enterprise will enable the conduct and reduce the cost of continued scientific investigations on and from the Moon, exploration and settlement of Mars, asteroid interception and diversion, and many other space activities.

On Mars as well as the Moon, humans will provide instantaneous observation, interpretation, and assimilation of the environment in which they work and in the creative reaction to that environment. Human eyes, experience, judgement, ingenuity, and manipulative capabilities are unique in and of themselves and highly additive in synergistic and spontaneous interaction with instruments and robotic systems. Due to inherent communication delays and the cost of returning samples, mission support, including sample analysis, for these activities of necessity will be initially in Mars orbit and then on the surface. As on the Moon, cost considerations favor the development of self-sufficiency and the early settlement of Mars.

SOME REFLECTIONS ON THE SUSTAINABILITY OF WATER RESOURCES

William M. Alley
U.S. Geological Survey
411 National Center
Reston, VA 20192

INTRODUCTION

Increasing attention is being placed on how to manage ground-water and surface-water resources in a sustainable manner (Alley and others, 1999; Gelt and others, 1999; Sophocleous, 1998). Yet, resource sustainability with respect to water, as well as many other natural resources, has proved to be an elusive concept to define in a precise manner and with universal applicability. Application of the concept of sustainability to water resources requires that the effects of many different human activities on water resources and on the overall environment be clearly understood and quantified to the extent possible.

Water-resources sustainability is defined here in a broad context as development and use of water resources in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences. The definition of "unacceptable consequences" is largely subjective and may involve a large number of criteria. Ideally, society determines the tradeoff between water use and changes to the environment and sets a threshold for what level of change becomes undesirable. Of course, this ideal is difficult to achieve in practice.

Five major aspects of water-resources sustainability will be discussed and illustrated through examples:

1. Water resources cannot be developed without altering the natural environment. These alterations are dynamic. Thus in many respects, one must manage water resources for change. The concept of a single "safe yield" that is constant with time is not realistic in many, if not most, circumstances.
2. Water-resource sustainability must be defined within the context of the complete hydrologic system. For example, what may be established as an acceptable rate of ground-water withdrawal with respect to changes in ground-water levels may reduce the availability of surface water to an unacceptable level now or in the future.
3. Perhaps the most important attribute to the concept of water-resources sustainability is that it fosters a long-term view toward management of water resources.
4. One's perspective on water-resources sustainability is very much a function of the scale at which the hydrologic system is analyzed.

5. Meeting the challenges of water-resources sustainability will increasingly involve innovative approaches using various combinations of conjunctive use of ground water and surface water, artificial recharge, and water reuse.

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WATER SUSTAINABILITY AND ECOLOGY

James Triplett
Chairman, Department of Biology
Pittsburg State University
Pittsburg, KS 66762-7552

INTRODUCTION

Sustainability

The term sustainability has become a paradigm of modern ecological thought and a buzz-word of political banter. It is touted as the basis for economic modeling, yet it has a different meaning for many users, which has produced some confusion. Environmentalists and ecologists (not the same thing) tend to view it as the "use of resources that will allow the indefinite survival of ecosystems" (Bush, 2000). Economists, on the other hand, use it "as an allocation of resources that leaves future generations no worse off than present generations. It is a founding assumption of economics that all resources have substitutes and that human ingenuity will identify them" (Bush, 2000). To me, it suggests the ability to use or do something in perpetuity without fear of depletion, essentially carrying the connotation of renewability or non-depletion.

Environmentalist and Ecologist

Frequently, the general public and those at odds with the ecological community will treat the two terms as though they are synonymous. While it is true that many ecologists are environmentalists, the converse is typically not true. An environmentalist is a person who has a strong commitment to protecting the environment and relies on concerns that have a mixture of factual and emotional bases. They are members of society, but are not necessarily scientists. An ecologist is a scientist who studies the organisms of an ecosystem, the interaction between those organisms and their interaction with their environment. They work from a basis of factual information and use science as their tool. Membership in either group does not mean that they are automatically radical or extremist in their view. Obviously, those who do operate in that fashion draw the most attention and, in some cases, disdain.

Communication Challenges

Ecology is a discipline that has an extensive technical vocabulary, making interaction with other disciplines difficult. However, terminology is not the only reason ecologists tend to communicate poorly. It has been my observation throughout my career working with a variety of groups in an attempt to resolve conflicts over resource management, that we are different. Ecologists and, for that matter, most biologists work from a different frame of reference than other scientists and the general public. To loosely parallel Gerhard and Hanson's (2000) description of "geologists", biologists view life on earth as an incredibly interconnected and interdependent system. While struck with the tremendous diversity presented by all forms of life, biologists are keenly aware of the ultimate similarity that exists in the basic structure and function of even the most dissimilar forms. The shared plan for cellular respiration, protein synthesis and especially the instruction set to construct and operate the organism puts life in its context. This tends to cause biologists to discount humankind as being apart from or different than other organisms. In other words, biologists tend to view humans as just another organism in the scheme of life. This frequently causes problems in communication with other humans.

ECOLOGY

Natural Ecosystems

The concepts of classical ecology are based on observations and investigations into the structure and function of "natural" ecosystems. By that I mean ecosystems that are relatively free from human impact. These basic relationships are accepted as the rules by which organisms interact with each other and their environment. One of the most basic of these tenets is the capacity of organisms to reproduce at an exponential rate; what we call the J-curve. This is particularly evident in situations where organisms discover or invade new areas. Another is the relationship between the numbers of individuals of a given species that can be supported by the resources of the place where they live. This is termed the carrying capacity and captures the notion that resource limitation places a lid on the number of individuals the environment will sustain for an extended period of time. The description normally used puts a population into a new environment where it starts increasing as though there were no limits (J-curve), but as resources diminish, the rate of increase slows until the population comes into equilibrium with the available resources; what we call the S-curve.

While these concepts specifically address populations of a species, in general, the total biomass of all organisms within a given ecosystem is resource limited regardless of how the interactions of competition, predation and decomposition divide that biomass among the different species. It is also true that climatic conditions and mineral resources will play a role in the overall richness of the system, however, ultimately the big resource limitation in the sky is the sun. Natural systems are solar powered. They are photosynthetically based, which is why the world is green. There are a few minor exceptions dependent on chemosynthesis, such as the ecosystems associated with hydrothermal vents. The point is, most natural ecosystems are dependent on and limited by the solar footprint in their area.

Human Systems

If we look at our estimates of human population numbers through time, it appears as if it too was limited. For centuries, as humans participated as an integral part of the natural system and were hunter-gatherers, their numbers changed little. Several advances were important early on that brought minor increases, such as acculturation and agriculture. All paled in comparison to the impact of the industrial revolution. The discovery and use of fossil fuels in combination with the developing technology for increased efficiency in their use essentially lifted the lid on the human population. Instead of being resource limited, we have continually bumped up the bar, raising the carrying capacity for the human population. Since the early 1800's, the human population has been growing at an exponential rate, a J-curve. We are no longer constrained by the rules of the natural system, but by the same token, we are now outside that system.

Natural systems don't have fossil fuels, so they are limited by current solar input, humans aren't. Natural systems don't have to mine to bring in mineral resources to support the enhanced energy and technology, humans do. And lastly, natural systems don't generate more than can be recycled in the system, so they don't have landfills and waste dumps, but humans do. Our systems differ from natural systems in that we have a high overhead that requires importation of energy and materials as well as exportation for disposal of wastes that are not reused in the system. Both of these activities raise questions of sustainability.

WATER RESOURCES

Water Availability

Best evidence suggests that we have it all. The third rock from the sun is thought to be the only place, at least in this solar system, where water exists in liquid form. We have a lot. More than 1,404 million cu km (370 billion gallons) covering 70% of the earth's surface (Cunningham and Saigo, 1999). Even though less than 1% of that is available as fresh water for human use, it still represents about 1,500 cu m (400,000 gallons) per person per year. That sounds like a lot and should be enough by most standards, but it is not evenly distributed. Iceland has the highest per capita water supply at 670,000 cu m (177 million gallons), which is 68 times that of the U.S.. Kuwait and Bahrain have zero water supply and have to use desalinized sea water or imports (Cunningham and Saigo, 1999). It is this uneven distribution that concentrates people in some areas and creates conflicts between people in others. Water is one of the most important and limiting natural resources for human populations.

Conflict over water has been a persistent part of human history. Logically, areas with the least amount of water such as the arid portions of the western U.S. and the Middle East have had the most problems. Part of the reason for the Six-Day War waged by Israel was an effort by Syria to divert part of the flow of the Jordan River (Cunningham and Saigo, 1999). More recently and closer to home, the State of Kansas just won a lawsuit against Colorado over flows in the Arkansas River. Kansas currently has a suit pending against Nebraska over flows in the Republican River, and on 9/26/00 Kansas filed a lawsuit against the U.S. Army Corps of Engineers to prevent them from releasing water from federal reservoirs in the state to support downstream navigation on the Missouri River. Interstate compacts and other agreements that were entered into with good intentions tend to get ignored when water supplies are needed within a state.

Water Quality

The amount of water is not the only issue that impacts what is available for use. The condition of the water or its quality is a very critical factor as it can drastically affect and limit its usefulness. In some cases, water quality is affected by natural sources such as high salinity in streams from salt-bearing intrusions or radioactive minerals from groundwater flow through deposits in the aquifer. Other sources come largely from human activity such as municipal and industrial wastewater discharges and agricultural runoff. Regardless of the source, that water is unavailable for many uses without the application of appropriate technology and a significant amount of energy. In short, dirty water is not very useful and is expensive to clean up.

Water quality issues can be almost as contentious as quantity. Here again, it is an issue of do unto others. When it is there, water flows downstream, which means that downstream users receive the end product of what the upstream users have done to the water. Kansas sued for and received restoration of the flows in the Arkansas River, but it suffers from excessively high dissolved solids as most of the water was used for irrigation first before it was returned to the river. The Sierra Club and Kansas Natural Resources Council recently sued the EPA to make them enforce the requirements of the Clean Water Act. This forced Kansas to initiate the development of Total Maximum Daily Loads for its impaired streams. An additional suit has forced EPA to reject some of Kansas' regulations and promulgate new regulations to protect water quality. The original Clean Water Act of 1972 established a sequence of water quality improvements that included two benchmarks. Initially, all navigable waters were to be "fishable and swimmable" by 1983 with zero discharge by 1985. We are still trying to meet the first benchmark, and the second, zero discharge, is still under debate as to whether it is realistic or affordable (Goldfarb, 1995). Back when the human population was smaller and less concentrated in large cities, it was pretty easy for a person to go off into the sticks and farm or ranch how they pleased without worrying much about getting on anyone else's nerves. It was also pretty easy for the city to collect its wastewater and with minimal treatment successfully apply the engineering axiom "the solution to pollution is dilution". We are many now and have a much higher overhead than before. Increasingly, we impact others and particularly our water resources. That means we also have an increasing responsibility to clean up after ourselves.

Ecological Issues

All of the tugging and pulling between human populations over the availability and quality of water does not always result in positive conditions for natural systems. In most instances, they lose. In western Kansas, the Ogallala aquifer is the primary source of water for a huge and prosperous agricultural enterprise. Irrigation has provided the means to grow crops such as corn to fatten large herds of beef for slaughter and shipment. Each and every step of this process requires massive amounts of water. In addition, an entire support community has been attracted which requires additional water resources. The use rate in most areas however, has grown to exceed the recharge rate. Aquifer levels have dropped significantly in most areas, which has made it more expensive to operate. Because of the lowering of the water table, streams have become losing rather than gaining, and many have dried up. This is obviously hard on aquatic ecosystems, but it also impacts the larger, riparian and prairie ecosystems.

Changes in water quality may produce changes in natural systems from total extirpation to alterations in community structure. When we use streams for disposal of everything from human and livestock waste to waste heat, we change the nutrient base and the environment in which that system developed. At nontoxic levels, the system may be able to absorb the waste, but it will invariably change the nature of the system. Even with the best treatment of wastewater, additional nutrients, not part of the systems recycling, will be added. This usually results in eutrophication and the replacement of the original, preferred group of organisms with ones that are usually less desirable, i.e. cyanobacteria. Invariably, when human systems come in contact with natural systems there will be changes, since we don't participate as part of the natural system, but are outside of it. Those changes are usually to the detriment of natural systems.

Why should we care? The world has moved on. The notion of a pristine, natural system that is not impacted by human activity is becoming a fond memory. Virtually all systems are affected by humans to some extent. Well, the issue of biodiversity aside, it seems to be in our best interest to care. While we may be operating outside the natural system, those systems are operating within our human systems. The degree to which we depend on them is unclear, particularly the least affected ones. However, we are heavily dependent on highly modified systems to support our activities. For all our great technology, we have yet to come up with anything better than biological decomposers to manage our organic waste. We're still dependent on the "bugs" no matter how new or sophisticated our treatment plants may be. Then there is the issue of solace. Why do we flock to the parks and preserves in such great numbers that our mere presence has strained their existence?

SUSTAINABILITY

Human Population

One of the most important driving forces behind the changes we see is the increasing human population and the concomitant demand for resources, especially water, to support it. It is very difficult to compare the graph of the human population since the 1800's to the graph of natural populations in equilibrium and not wonder why the human curve is still so steep. Many prognosticators believe that water may possibly become the single primary limiting factor in that process. One liberal estimate put the lid at a little over 10 billion if 9,000 cu km of water was available annually to support everyone, and at 16 billion if 14,000 cu km were available (Cohen, 1995). That assumes that the water could be distributed equally, everyone was equally productive and people would share. Water will surely serve as a constraint on development and growth. As the Ogallala is depleted in the great plains, small towns are drying up, and in the Middle East, insufficient water to make a project work is enough to recommend to the World Bank that a project not be funded (Cairncross, 1993).

Human Nature

"Of all of nature's resources, none is more likely to be consumed at less than it costs to deliver it than water" (Cairncross, 1993). In developed countries in particular, we take water for granted. In some instances, people believe they own the water. That which flows across their property or sits beneath their land is theirs to do with as they wish. The notion that it belongs to everyone is foreign to them. It's movement in the ground, across the land and in the air makes it a commonly held resource. We do tend to think of it as free. But for the most part, we only pay to have it pumped, treated and distributed. We don't always pay for its protection, management and depletion. As such we tend not take care of it or use it wisely. About 70% of the world's use of water is for irrigation, but only about a third of it actually grows crops (Cairncross, 1993). Lack of conservation, leaky systems and poor application results when there is no or little cost associated with the use of the resource. As in the case of the Ogallala, the pricing of the water does not account for the cost of its depletion, so there are no meaningful constraints on its use (Cohen, 1995). It does not get in their pocket.

Prognosis

We have lots of water. We have it all, and it is one of our most renewable resources. With our existing and future technology along with our additional energy supplies, we can desalinize seawater, tow in icebergs, clean up pollutants and pipe the water from shore to shore. Ultimately, it becomes an issue of energy limitations. All we have to do is be willing to pay the costs, assuming we know what they are. We are headed down this road, and I am not proposing that we abandon our path. I do however, feel that some of the signs suggest we proceed with caution and keep our headlights on. Technological advancements may, as they usually do, progress at a faster rate than our understanding of their impacts. This leaves a major set of findings to the arena of hindsight. Based on history, we can assume with confidence, that we can make the technological leaps to push back the apparent limits on energy and resources - but at what cost? Social and political costs may not be most severe as a result of direct impacts of supply and consumption, but as indirect effects, long delayed as they manifest slowly in biological systems. Functional processes in biological systems compensate until overwhelmed, hiding the growing imbalance until the system is dysfunctional. We think we understand some of what we know about the rules for natural systems. We have two reason to worry; either we don't know what the rules are for human systems, or of more concern, is that they are the same as for natural systems.

POSTSCRIPTS

A brief note on biodiversity. It is very difficult to explain the importance of biodiversity to someone with a different frame of reference on life. It is sort of like trying to convince a strict creationist about evolution. Suffice it to say that it is inherent in my understanding of the way the world works. I have some concerns when species disappear, not only because of the loss of the genetic diversity and the player in the system, but I wonder if this is the canary in the mine tunnel or just chicken little. I am also uncomfortable in role of omnipotence when it comes to deciding who goes and who stays. When things disappeared during the great extinctions, they tended to be the most dominant creatures with the highest overhead.

Good science seems to be the cure for all ills. I heard a lot about that when I chaired the Kansas Special Commission on Surface Water Quality for the Governor and the Legislature. On that topic I offered the following: "Many people believe all that is needed to get the "right" answer is "good science". They tend to view science as black or white and very concrete. However, "good science" is more subjective than most believe. In fact, the answers are no better than the questions. The more society knows and understands about an issue, the better the questions that can be asked. The only good questions for the scientific method are those that can be proven false - science can prove things false, but cannot necessarily prove things to be true. At one time, the collective wisdom said the world was flat. The questions one might ask then would be markedly different from those based on what is now known. Knowledge based on science builds on itself, and changes, as it should, based on the best available knowledge. So, from technology, we use the Best Management Practice, and from science, we use the Best Available Knowledge" (Triplett, et.al. 1998)

In addition, I would add a little anecdote from Cohen (1995): "A little boy wanted to know the sum of one plus one. First he asked a physicist, who said, 'If one is matter, and the other is antimatter, then the answer is zero. But if one is a critical mass of uranium and the other is a critical mass of uranium, the that's an explosive question.' Unenlightened, the little boy asked a biologist. She said, 'Are we talking bacteria, mice or whales? And for how long?' In desperation, the boy hired an accountant. The accountant peered closely at the little boy and said, 'Hmmm. One plus one? Tell me, little boy, how much do you want one plus one to be?"

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WATER SUSTAINABILITY: GEOLOGICAL PERSPECTIVES ON THE EVERGLADES WATER SUPPLY PROBLEM

Thomas M. Scott and Walter Schmidt
Florida Geological Survey
903 W. Tennessee Street
Tallahassee, Fl 32304-7700

INTRODUCTION

"There are no other Everglades in the World. They are, they have always been, one of the unique regions of the earth, remote, never wholly known. Nothing anywhere else is like them: their vast glittering openness, wider than the enormous visible round of the horizon, the racing free saltness and sweetness of their massive winds, under the dazzling blue heights of space"[1]

The Everglades are indeed unique. It is a landscape typified by the perception of flatness and, yet, contains amazing beauty. The diversity of its flora and fauna, the dense entanglement of the tree islands and mangrove forests, the blue-green hues of Florida Bay have attracted explorers and scientists alike. The vast organic-rich wetland sediments caught the attention of agricultural interests which ultimately had dramatic effects upon the `Glades. More recently, the suburban expansion of Florida's southeastern coastal cites has invaded the realm of the alligator. Our society's desire to control nature and annex the Everglades for agricultural activities and flood control created a severe water problem, altering the character of the region. Now, in order to save the Everglades and provide for a burgeoning population, water resources must be considered in a new light.

The Everglades, Florida Bay, Big Cypress Swamp, Lake Okeechobee and the Kissimmee River system have attracted national attention as the result of man's alteration of the environment (Figure 1). The issue has become highly political and many local, State and Federal agencies are addressing the issues of water resources and the restoration of the region. It is not only a State issue but, because the Everglades is a national treasure, it is also a Federal issue.

BRIEF HISTORY

Native Americans occupied the region in and around the Everglades for millennia. Their influence on the natural environment was minimal as they strived to survive the floods and droughts. With

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[1] Marjory Stoneman Douglas, The River of Grass, 1947.

the advent of cities and towns along the coast and the development of modern technologies, man invaded the Everglades. The modifications to the landscape were designed to control the hydroperiod and flow of water in the region, thereby reducing the threat of floods and improving the land for agriculture and development. As was the mindset of the time, the early Florida Geological Survey was charged with helping to drain the wetlands for agricultural purposes. During the 20th century, dikes, canals and water control structures became a mainstay of the southern Florida landscape as attempts were made to control nature. The sheet flow of water through the `Glades was interrupted by the shunting of water to the ocean. The changes to the hydroperiod and the lowered water levels caused numerous changes to occur. Organic soils and peat deposits dried and oxidized resulting in a lowering of the land surface. The flora and fauna of the region were impacted and concerns for the "Everglades Ecosystem" came to the forefront.

Rapidly increasing populations of the southeastern Florida coastal cities placed a strain on the surface-water and ground-water resources. With less recharge to the surficial aquifer system and over pumpage coupled with natural climatic fluctuations, salt-water intrusion occurred along the coast, contaminating water supplies. With the advent of the Central and Southern Florida Flood Control District (later the South Florida Water Management District), efforts to control water use and distribution began in earnest.

GEOLOGY OF THE EVERGLADES

The Everglades is just the latest phase of the geological evolution of southern Florida. Millions of years of marine sedimentation interspersed with beds deposited in freshwater environments created the late Cenozoic geologic framework of this region. However, the Everglades developed during the last 5,000 years as sea level rose in response to the melting of the North American glacial ice sheet. Within the last 100 years, human modifications have had a dramatic effect on the `Glades.

The historic Everglades extend from Lake Okeechobee southward to Florida Bay. Thousands of feet of Cenozoic carbonate rocks, comprising the Floridan aquifer system, underlie the Everglades region. The aquifer system is highly transmissive and has interspersed low permeability layers. The Floridan aquifer system is overlain by a mixture of sand, silt, clay and carbonate sediments, forming the intermediate aquifer system and confining unit and the surficial aquifer system. The intermediate confining unit provides an effect seal for the Floridan aquifer system.

The late Pleistocene sediments, approximately 125,000 years old, underlie the Everglades wetlands and vary from north to south (Figure 2). The region near Lake Okeechobee to the latitude of Fort Lauderdale is underlain by a mixture of fossiliferous sand and limestone, the Fort Thompson Formation. South of the latitude of Fort Lauderdale, the Miami Limestone underlies the Holocene sediments of the Everglades. Pleistocene sediment deposition along the east coast had an effect on the formation of the Everglades. The Anastasia Formation, a coquina of sand and shell, was deposited to the north of Fort Lauderdale. It grades to the west into the Fort Thompson

Formation and to the south into the Miami Limestone. The Anastasia Formation and the coastal portion of the Miami Limestone form the Atlantic Coastal Ridge that naturally restricted the eastward flow of surface water to the Atlantic Ocean (Figure 3). This is an important factor in the formation of the Everglades since it forced the water sheet flow to move southward rather than eastward.

Approximately 5,000 years ago, the Everglades began forming. As sea level rose following a glacially-induced low stand 17,000 years ago, marshlands of the Everglades formed in response to the sheet flow of water in southern Florida. Not only did this water flow southward but it provided recharge to the Biscayne Aquifer, the primary aquifer supplying groundwater to the cities on the southeastern coast. Some of the freshwater flowing through the Everglades was naturally channeled into Florida Bay, developing a unique and interesting ecosystem in the bay. Florida Bay is the present day site of carbonate (limestone) deposition.

THE WATER SUPPLY PROBLEM

A slow-moving, sheet of freshwater historically flowed southward from the Kissimmee River, in central Florida, to the coastal bays of southern Florida (Figure 4). The sheet of water covering much of southern Florida supported a varied and unique ecosystem. At the same time, the water with its varying hydroperiod, rendered a vast area virtually unusable by man. The Everglades was often viewed as worthless wasteland inhabited by "gators" and mosquitoes. Early inhabitants believed that the area needed to be "reclaimed" and developed. In the 1800s, agricultural and development interests began constructing canals to drain the swamp with little knowledge of the impact on the environment. The 1850 federal Swamp and Overflowed Lands Act gave the Everglades to Florida provided it could be drained. Although private efforts to drain the region failed, public efforts succeeded and, by the 1930s, 400 miles of canals had been dredged. Dredging of canals continued well into the 1900s as Florida's population grew rapidly (Figures 5 and 6). In 1948, Congress created the Central and South Florida Project designed to provide water and flood protection for urban development. The project was also charged with providing water for the Everglades National Park, for the preservation of fish and wildlife habitat, and the prevention of salt water intrusion. As a result of agricultural and development interests, more than 50 percent of southern Florida's wetlands have been destroyed.

The alteration of the landscape has dramatically affected the hydroperiod and ecosystem of the remaining natural areas. The effects include impacts on ground-water resources, surface-water distribution, degradation of wildlife habitat, and damage to the Everglades and Florida Bay. It becomes quite obvious that the major problem is a water supply issue - who gets the water, where the water goes, the quality of the water and the timing of its availability. In order to sustain the growth in southern Florida, avoid destroying Florida Bay and preserve the Everglades, a balance must be achieved. There must be a sustainable water supply to meet these needs.

The water supply problem is not only a surface water issue. Groundwater is a major problem in the southern Florida region. The highly productive Biscayne Aquifer, the only freshwater aquifer in the area, underlies part of the Everglades. The demand for water can not be met by the Biscayne Aquifer alone. This creates competition for water between the human population and the environment.

SUSTAINABLE WATER SUPPLY

Developing a sustainable water supply for the Everglades and southern Florida requires the restoration of the ecosystem and the introduction of technologies to conserve and store water (Figure 7). Both efforts are being conducted simultaneously and will take years to complete. The efforts include many local, State, and Federal agencies and private groups.

The restoration of the ecosystem began in earnest in 1972 with the passage of the Land Conservation Act by the Florida Legislature which authorized the State to purchase environmentally endangered lands. The "Save Our Everglades" program was created by Governor Bob Graham in 1983. The program, a partnership between the South Florida Water Management District and the State government, was to work toward restoring the ecosystem to what it was like in 1900. It affects the region that includes the Kissimmee River Basin, Lake Okeechobee, the Everglades, Big Cypress Swamp, Florida Bay, Biscayne Bay and the Ten Thousand Islands.

The Surface Water Improvement and Management Act (SWIM) of 1987 required the water management districts to develop plans to clean up and preserve water bodies of the State including estuaries and bays. The South Florida Ecosystem Restoration Task Force, a cooperative effort between six federal departments, began its efforts in 1993 to restore and protect the ecosystem. In 1996, the task force was expanded to include other federal, state and local governments and the Miccosukee and Seminole tribal representatives. The governor's Commission on a Sustainable South Florida, initiated by Governor Lawton Chiles, was active from 1994 to 1999. It was tasked with "making recommendations for achieving a healthy Everglades ecosystem."

In 1992 and 1996, the U.S. Army Corps of Engineers was authorized to conduct an in-depth review of the Central and South Florida Flood Control Project and to develop a detailed plan to restore and preserve the natural ecosystem in southern Florida. The subsequent review, the Central and Southern Florida Project Comprehensive Review Study (The Restudy), created plans to capture 1.7 billion gallons of water per day that is currently lost to the Atlantic and Gulf. Part of this water will be stored in a series of reservoirs and through the use of proposed aquifer storage and recovery wells (ASR) for later use. The Restudy also plans for the return of the proper quantity and quality of water to the ecosystem at the proper times. The project will cost $7.8 billion over 38 years to construct and $182 million to operate each year. The plan calls for 80 percent of the "captured" water to be returned to the ecosystem and 94 percent of the pre-drainage flows returned to the Everglades National Park. The plan is to restore the hydrology by 50 percent by 2010. The Water Resources Development Act of 2000, to enable the restoration plan, is currently under consideration by Congress.

The implementation of aquifer storage and recovery technology, in order to help maintain a sustainable water supply for southern Florida, is being considered as a portion of the restoration effort. As many as 300 wells may be drilled to depths ranging up to 3,000 feet in the Floridan aquifer system. The ASR process will be used for short term storage of seasonal waters (wet season), longer term storage for use in drought years, to restore groundwater levels and to enhance well field production. Before the ASR process is implemented, we must have a better understanding of the lithologic parameters and aquifer characteristics of the rocks. Many questions remain that must be answered prior to the implementation of a major ASR program. The implementation of the ASR project is estimated to take 20 years or more. The initial pilot project will cost $27 million.

CONCLUSIONS

The natural environment and our society both require clean, freshwater to thrive. Population growth requires land for development and agriculture. Anthropogenic changes in southern Florida destroyed the delicate natural balance that defined the Everglades ecosystem, an ecosystem controlled by its water supply and hydroperiod. This system, which begins in central Florida with the Kissimmee River Basin and terminates to the south in Florida Bay, has been channelized, drained, developed and abused. The results have been environmental degradation, habitat loss, changes in the flora and fauna, and ground-water and surface-water problems. The restoration of the Everglades ecosystem requires a re-allocation of water resources in the region and innovative approaches to supplying water to the environment and to the burgeoning population of southern Florida. Sustaining the restored ecosystem requires a commitment to provide the water necessary to maintain its viability.

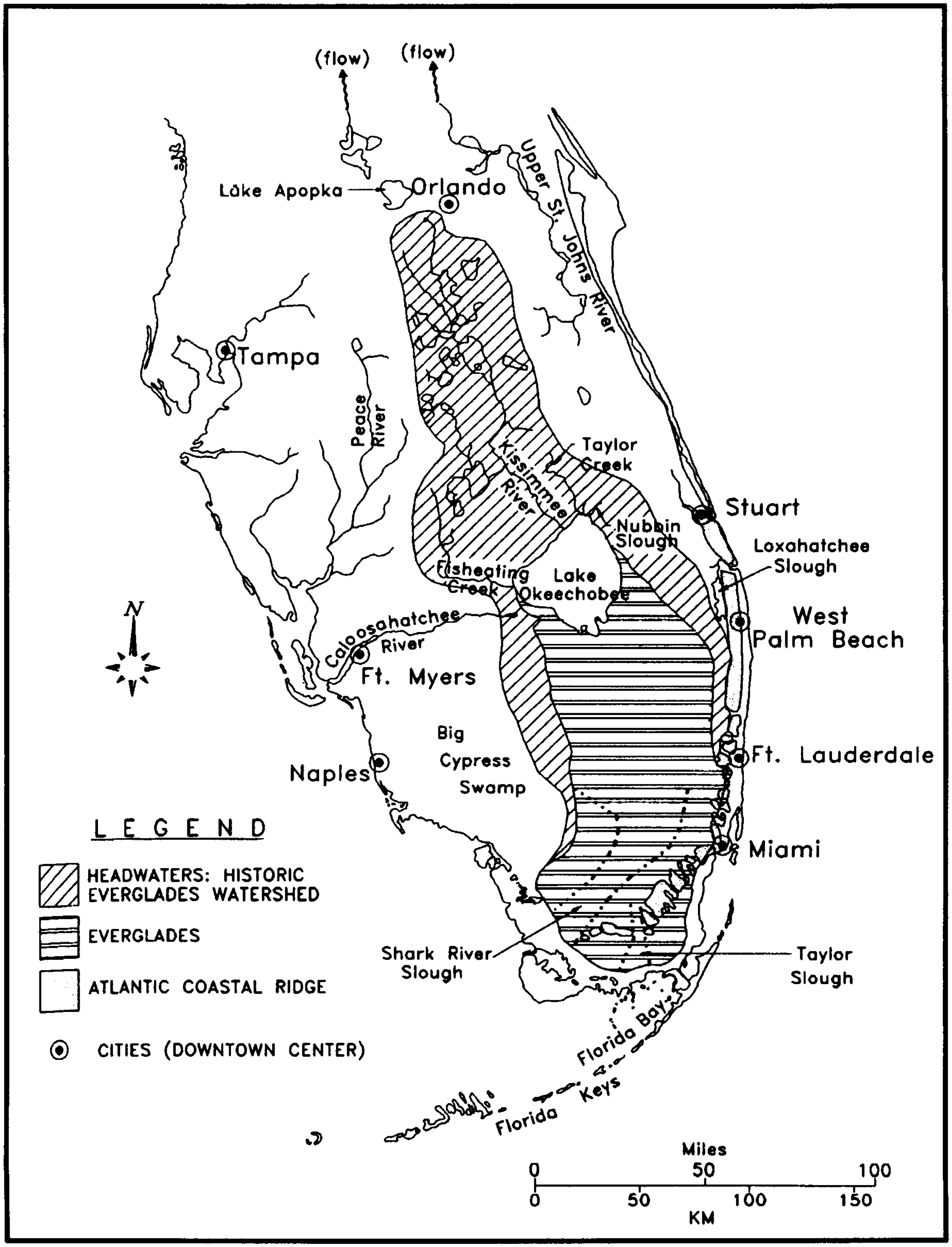


Figure 1 - The historic Everglades watershed.

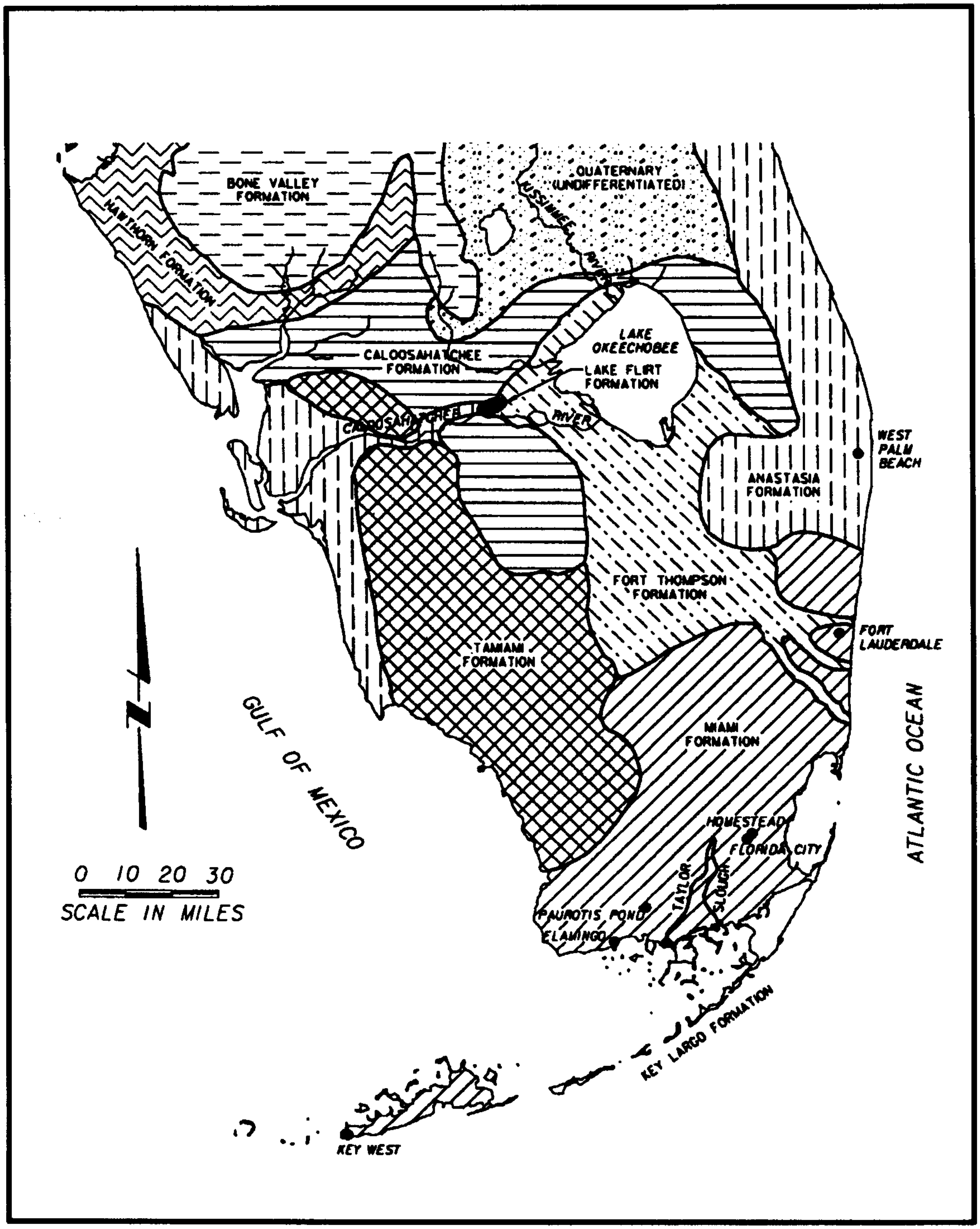


Figure 2 - Geologic map of southern Florida.

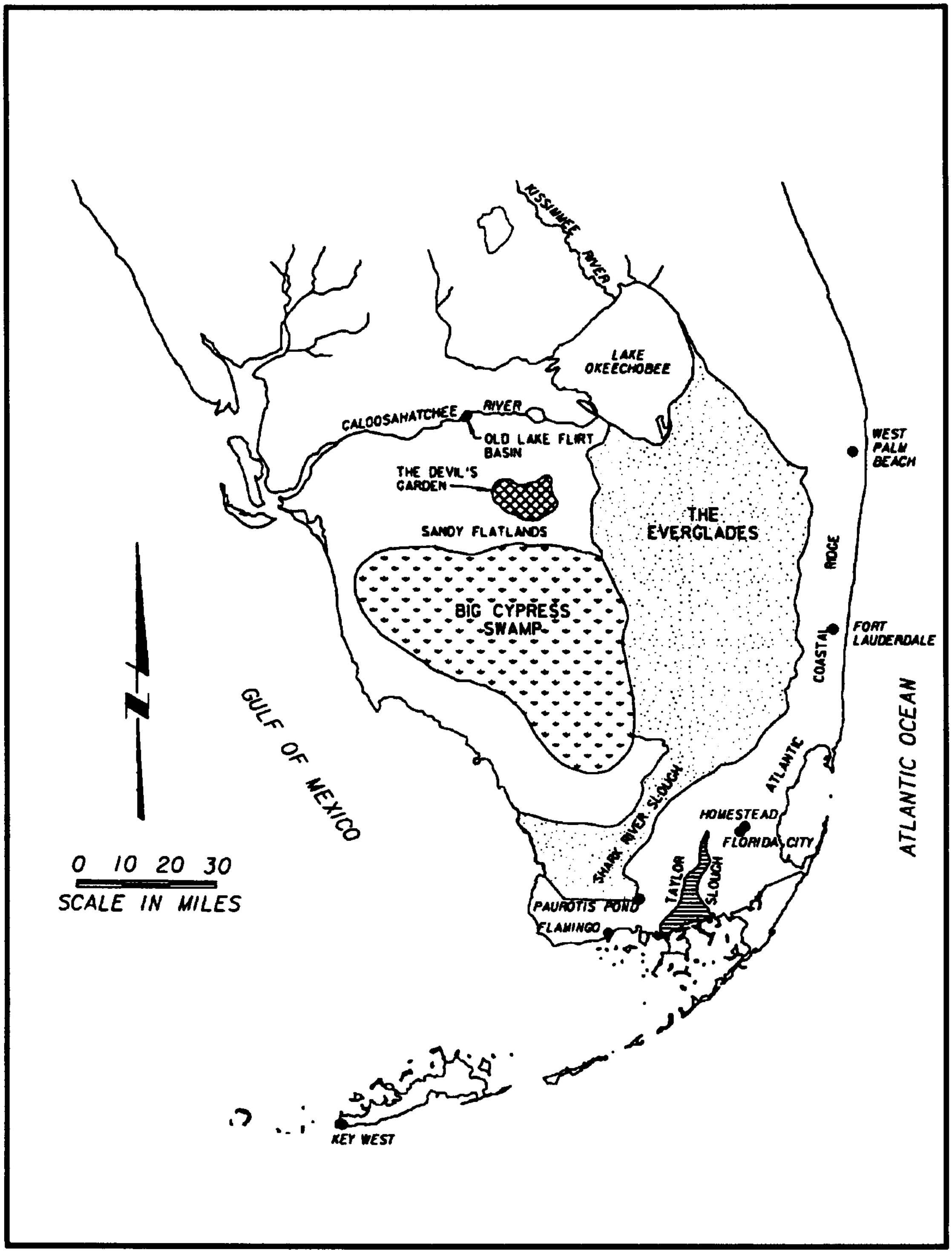
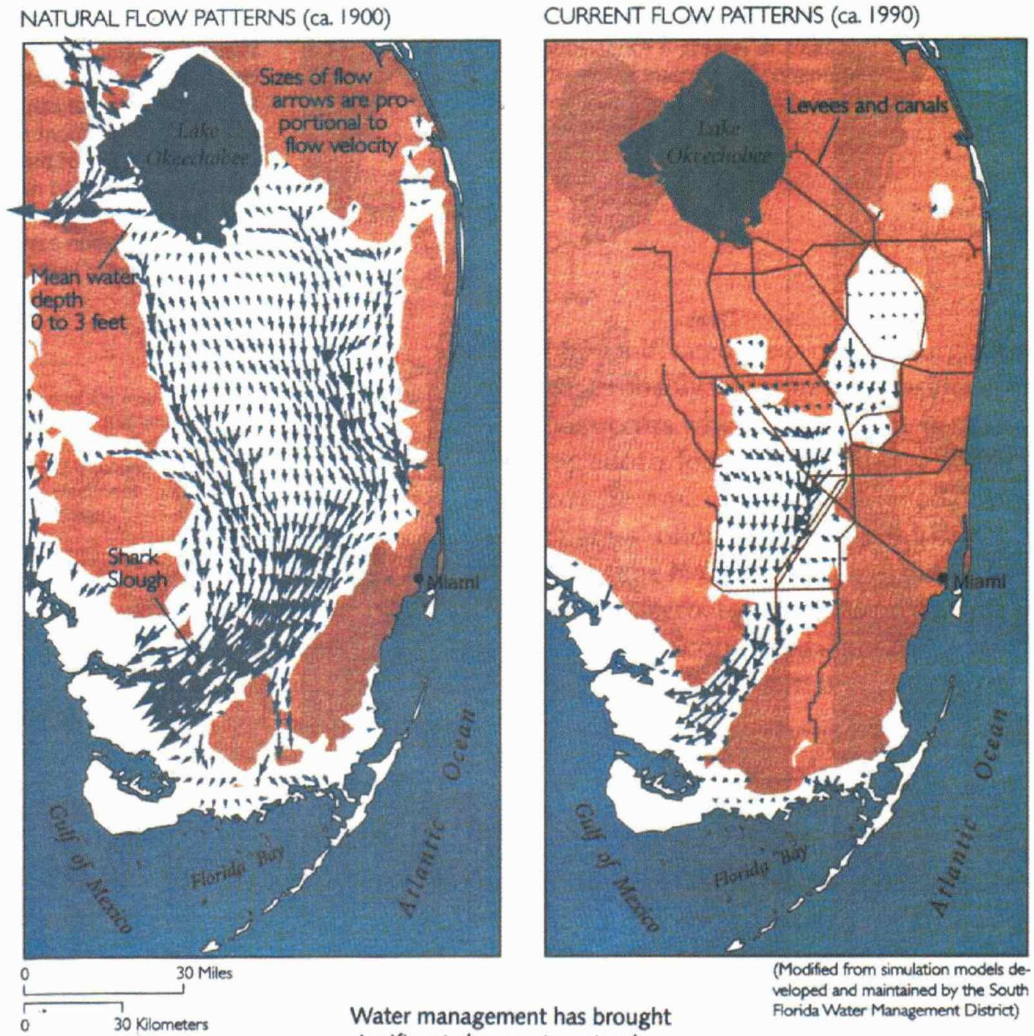


Figure 3 - Geomorphic map of southern Florida.



Water management has brought significant changes to natural overland flow patterns.

Under natural conditions surface water moved from Lake Okeechobee southward, then turned southwest through a constricted area called Shark Slough.

After canals and dikes were constructed for the agricultural and water-conservation areas, sheet flow practically disappeared from the northern Everglades and diminished to the south.

Figure 4 - Historical and present-day flow patterns.

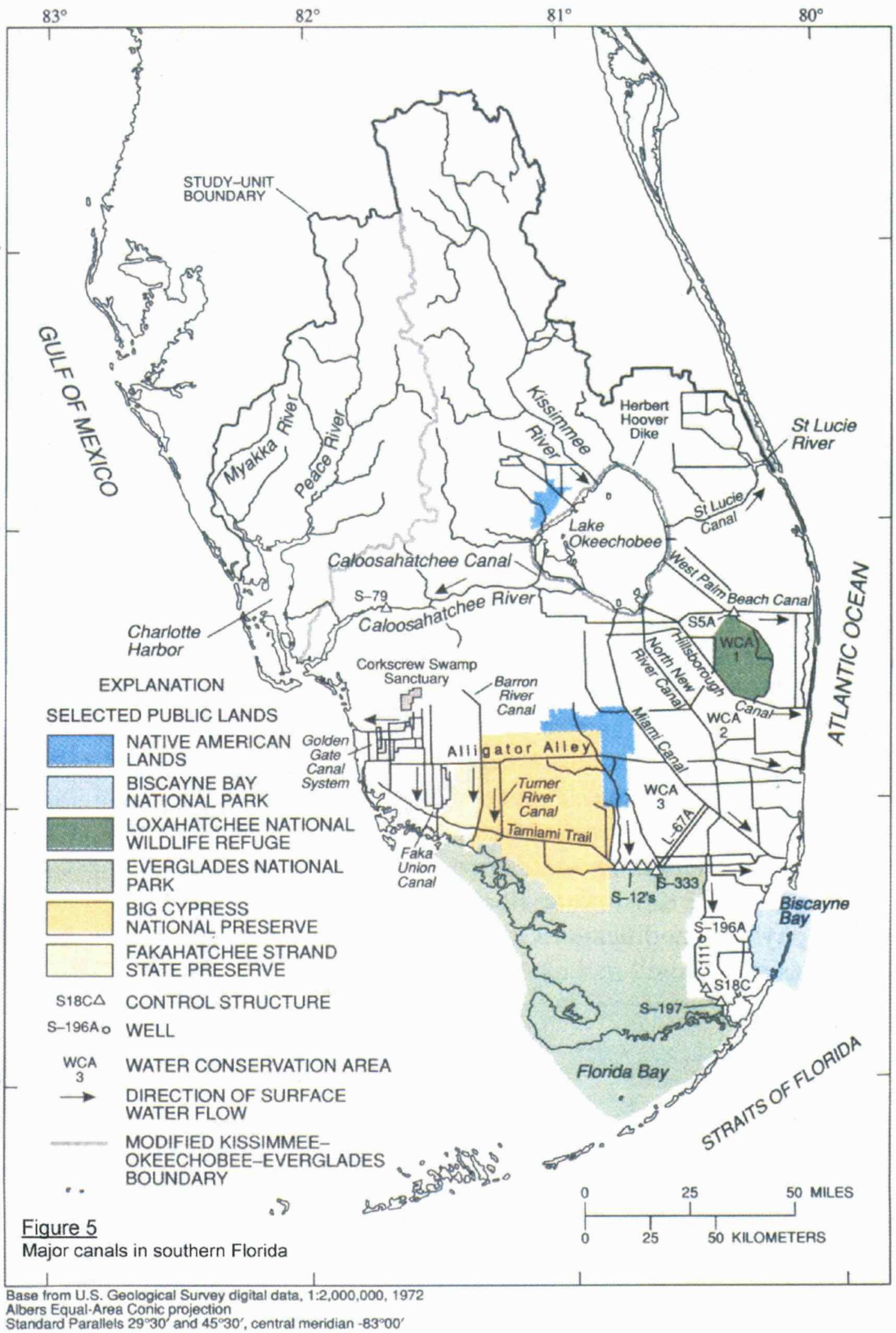


Figure 5 - Major canals in southern Florida.

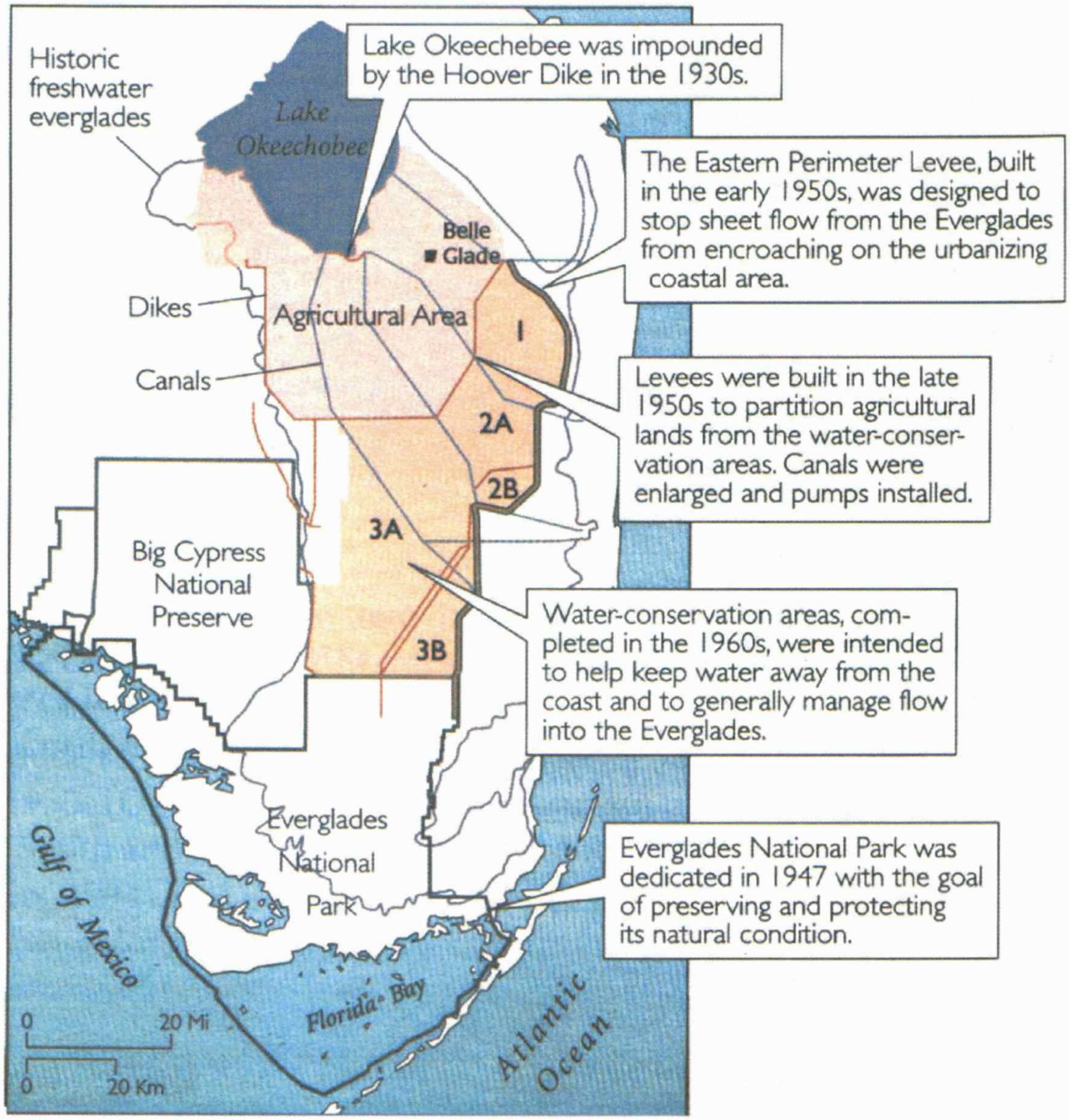


Figure 6 - Water control in southern Florida.

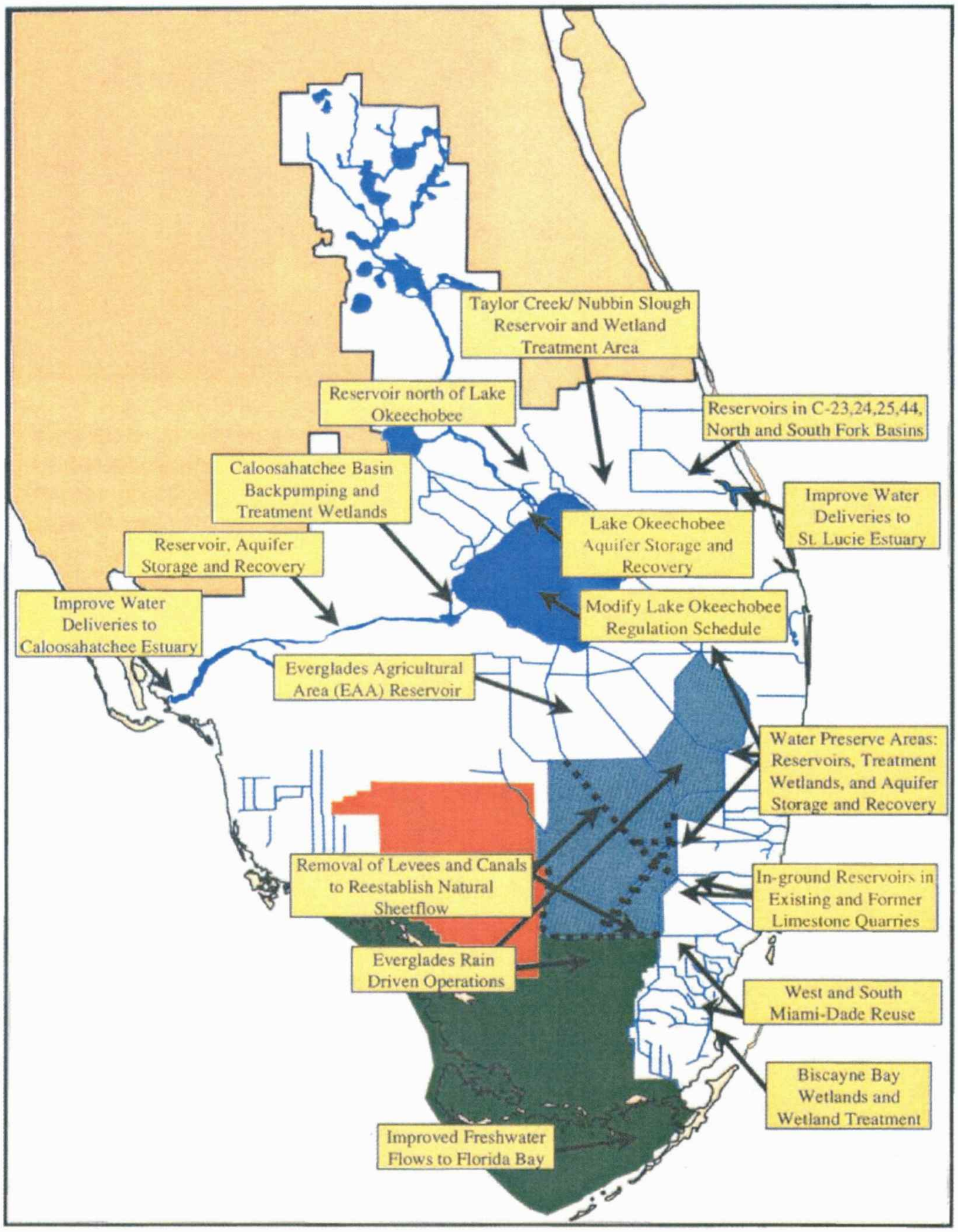


Figure 7 - The restoration plan.

THE KANSAS WATER MANAGEMENT MODEL

Lee C. Gerhard
Kansas Geological Survey
1930 Constant Avenue
Lawrence, KS 66047

INTRODUCTION

Kansas needs water for agriculture, industry and municipal use. Agricultural irrigation is a mainstay of the state's economy. Although the population of the state grows steadily, it remains at about 2% of the nation. The Kansas agricultural industry feeds the nation; one farmer feeds 129 people, a large impact on the national food supply. Growth in agriculture has required tapping large fossil water reservoirs, especially the Ogalalla Formation, a porous and permeable Tertiary Age sedimentary blanket that supplies water to eight states. ("The High Plains Aquifer" in western Kansas includes the Ogalalla Formation and undifferentiated younger Quaternary sediments.) Declines in the water levels in this important reservoir, industrial growth, and supplying water to burgeoning population centers drove legislation during the last half of the 20th Century to devise a water management process. That process is foremost in the country in its comprehensive nature, citizen involvement, and funding. We present it as model for other water-use-intensive states and nations to consider for adoption.

The water resources of Kansas are its groundwater reservoirs (including the Ogalalla aquifer), surface water reservoirs, farm ponds of several types, and free-flowing streams. Rainfall ranges from more than 40 inches in southeastern Kansas to less than 20 inches in western Kansas (Goodin et al, 1995) (Figure 1). Water use in 1998 (latest available data, Kansas Water Office) was 4,121,718 acre feet (an acre foot is approximately 325,850 gallons) (Figure 2).

Although water planning was initiated in 1917 (Kansas Water Office, 1997), the present water planning and regulatory process was instituted in 1981, with the creation of the Kansas Water Office and the Kansas Water Authority. In the intervening time, water consumption had changed dramatically, from surface water use to the development of the groundwater-based irrigated agricultural economy of today.

The Kansas Water Plan was established in 1985, with legislation to implement the plan forthcoming since that time. It is a lively process, with legislative sessions usually having one or more issues to consider. The final major piece of legislation that makes the Kansas water planning and management system a model for the nation is the implementation of dedicated funding for the Kansas Water Plan. The author played a small role in that legislative battle. The annual funding is about $16,000,000, and includes research funding. The Water Authority recommends to the Governor how to allocate the money, and its recommendations have generally been accepted.

A primary attribute of the model is that there is no one "water czar," rather, collaborating state agencies and public groups meet through the Kansas Water Authority to determine future actions and to review agency activities. No one political appointee can substantially change the process. A second primary attribute is citizen involvement in the water management system.

The purpose of this paper is to document the water planning and management process of Kansas as a model for others to use.

THE ISSUES

Water quality of both groundwater and surface water resources has been and continues to be a major priority for water managers. Both natural and anthropogenic contamination is present, exacerbated by increased population density in some areas, and increased livestock density in others. Current quality concerns are herbicides and nitrate from agricultural activities. Advent of large-scale confined animal feeding operations have magnified nitrate concerns. Waste disposal and storm runoff from population centers are also significant concerns. Part of the quality issue is reduced stream flow rates that may be related to both extended irrigation and modern farming conservation practices. Most surface waters of the state contain large amounts of suspended sediment.

Water quantity is actually a more significant issue than quality. Some communities are unable to supply the needs of their residents, even in non-drought years. The City of Hays, for instance, is continually looking for additional water resources to supplement those of poor quality and limited quantity, and has had water use restrictions in place for many years. The Wichita urban area is likely to face water shortages owing to both increased needs and declines in water quality from existing sources. Their problems include salinity increases caused by former improper saltwater disposal from old oil fields, and they have no additional resources to tap without reaching out to reservoirs in other areas of the state.

Much of the quantity concern is the reduction of water levels in the High Plains Aquifer, the single major source of irrigation ground water in the region. Although stream (alluvial) aquifers, the Dakota Sandstone aquifer, and isolated other aquifers are present, the High Plains Aquifer has supplied tremendous quantities of water for irrigated crops since the 1950's. Declines in the water level within the western part of this system are serious, as recharge has not kept up with withdrawals and some parts of the aquifer system are essentially depleted. Pre-development water columns were over 300 feet in some areas, especially the southwestern portion of Kansas. Some of this area has had more than 60% depletion, over 150 feet of water removed (Kansas Geological Survey Website, 2000). Natural recharge is slow, and the water depleted was likely Pleistocene fossil water (O'Connor, pers. Comm.).

Costs of irrigation are climbing as pumping requires more energy for deeper water levels. The cost of natural gas for pumping fuel is a significant restriction on the use of irrigation water.

For irrigation wells in fluvial aquifers, the amount of stream flow becomes significant. Kansas has successfully litigated with Colorado over water volumes in the Arkansas river, depleted in Colorado by ground water pumping as well as reservoir diversions. The accompanying problem is that the return flows from irrigation are poor quality compared to the original water, and those waters infiltrate the stream banks and aquifers, lowering the quality of irrigation and municipal waters.

Stream flow is also lowered by reduction of water levels in the High Plains aquifer, reducing spring flows into surface waters. Stream aquifer irrigation use decreases stream flow. Kansas history records many more active flowing springs in the western portion of the state, springs that fed perennial rivers that now contain little water during the late summer. It is the writer's conclusion that reduced ground water levels in the High Plains aquifer and water extraction from stream aquifers have reduced stream flows.

Further compounding reduced surface stream flows, agriculture has been both trained and required to minimize surface runoff. Not one drop of runoff water is desired. Farmers are legally required to terrace sloping fields and are encouraged to develop watershed dams. Stock water from artificial ponds is a way of life. All of these water conservation efforts decrease the amount of water moving into stream channels.

THE MODEL

Kansas state water management and planning requires consideration of two water sources, free flowing streams and ground water. The major constituencies are agricultural irrigation, industry, municipalities, and "other", small users (as compared to the three large consuming groups). There are several levels of management, and several legally mandated agency responsibilities (Figure 3).

The foci of water regulation are the Kansas Water Office (surface water, administration of state-owned reservoir waters, and coordination of water policy), the Kansas Department of Health and Environment (water quality), and the State Engineer, Department of Agriculture (water rights administration). Other state agencies with less significant water administration responsibilities are the State Conservation Commission and the Kansas Corporation Commission (oil and gas regulation). The Kansas Department of Wildlife and Parks has an obvious vested interest in water flows and availability. The Kansas Department of Commerce and Housing has interest via industrial and tourism development. The Kansas Geological Survey, University of Kansas, conducts water research and Kansas State University conducts research in agricultural water use.

The Kansas Water Authority is unique in that this body, which recommends policy and budget to the Governor, is composed of citizen members who are all voting members, and ex officio members, who lead state agencies, but do not vote. This important distinction enables vested interests (state agencies) to debate their issues, but gives them no vote in the solution to the issues (Figure 4). The Kansas Water Authority is charged to consult with and be advisory to the

Governor and the Legislature; review plans for water resource development, management, and use; study laws related to water resources management issues and make recommendations on legislation; make recommendations to other state agencies for coordination of activities; review budget estimates pertaining to the state's water resources; and approve any amendments to state water plan or planning act or any other legislation concerning water resources before submission to legislature (K.S.A. 74-2622). The purpose of the Kansas Water Plan is to accomplish coordinated management, conservation, and development of the water resources of the state (K.S.A. 82a-903).

When Kansas jettisoned older water management programs in favor of the Kansas Water Office and the Kansas Water Authority in 1981, they imbued water policy with two fundamental principles. First, the public will significantly control water policy. Second, water management shall be distributed in Kansas, so that no one party can unreasonably drive water use and practice. Several devices have been employed to accomplish the principles.

Citizen-controlled water management first derived from the State Engineer's water regulatory system, where Groundwater Management Districts effectively and legally monitor and regulate local ground water use efficiency, but not groundwater rights. In the present water management system, Basin Advisory Committees are appointed by the Kansas Water Authority in each of the state's twelve river basins. No state official may sit on a basin advisory committee. These committees annually report prioritized recommendations for water-related activities in their basin to the Water Authority. The recommendations are assembled by the Water Authority (staff of the Water Office provide support to the Authority) and the necessary changes and implementation devices are drafted. Once the draft water plan implementations and changes are approved by the full Authority, informal public hearings are held on each river basin.

Public comments, both in testimony and writing, are considered in the final draft of the water plan implementation document, which is then again given full public review before adoption by the Water Authority. The Water Office prepares any necessary legislation. Most items approved for implementation do not require legislation, but do require various agencies to initiate projects or update earlier work. In this time of constricting state budgets, before 1989, many projects were delayed or slowly accomplished (Figure 5).

In 1989, then Governor Mike Hayden sponsored development of a dedicated funding source for Water Authority projects. The bill passed the Senate by the one vote necessary, by a senator who was rapidly transported from a Kansas City hospital to the floor of the Senate in Topeka, cast the deciding vote, and was returned to the hospital. Previously, the legislature had designated state lottery funds for economic development. To fund the Water Plan, they placed some of these funds into the water plan funding bill, then added a special tax on fertilizer and pesticide use, industrial, stock water, and municipal water use, fines and fees for pollution and sand mining on state lands, and some general fund money. This brought all citizens directly into funding the implementation of the water plan. About $16 million a year now goes to fund water plan projects (Table 1). None of the money can be used to support permanent staff positions in any agency.

Some of the accomplishments of this funding include development of handicapped fishing and parks access, support for the Governor's Water Quality Initiative pilot projects, initiation of water rights banking, purchase of federally owned reservoir capacity, support of a pilot project in artificial groundwater recharge, and conducting a long term study of the hydrology of the Dakota Aquifer (funded for 14 years, but completed in 8). Access to stable funding enables long term planning to succeed. Normal appropriation processes do not provide that benefit.

One very large benefit to the entire state was the initiation of the state's geographic information system, originally based on natural resources, from Water Plan funds.

Central or distributed control of water management has been debated in Kansas for many years. With the 1981 establishment of the Kansas Water Office, the state embarked on a policy of distributed water management that has withstood several legislative attempts to institute a Department of Environment that would pre-empt all other water management activities. In 1981, the Kansas Water Office was given the responsibility of coordinating all water management activities, but no authority to dictate what those activities would be. Legal separation of groundwater rights administration from other activities, federal mandates on water quality, and research are the exceptions to the coordination responsibility. In practice, water agencies commonly work together except for fundamental disagreements in policy development. That is where the Kansas Water Office and Water Authority are most helpful. Frequent task force meetings addressing common concerns, meetings of agency heads, and strong interpersonal relationships between agency staffs make the system work. In one sense, there is a water "czar," because the governor appoints all agency heads and the chair of the Kansas Water Authority. The research groups are not directly in this chain, but are appointed through the Board of Regents, whom the Governor does appoint.

Funding of the state water plan is another rationale for interagency cooperation, because the amount of funding for various agency projects is significant, and non-cooperating agencies would not fare well in the appropriation process. The writer has had many years of experience working within this system as an ex officio member of the Authority and has been involved with many of its more difficult negotiations.

SUMMARY

Water management in Kansas is accomplished through a citizen-intensive process that has served the water-dependent state well. Citizen involvement has enhanced solution of otherwise fractious issues by bringing together diverse elements of the interest groups and coordinating these interests with the state agencies responsible for specific policy and regulatory practices. The ultimate goal of all these efforts is the wise and fair use of Kansas water resources.

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TABLE 1
WATER PLAN FUNDING FOR FY 2001

Agency/Program	Actual FY 1999	Gov. Rec. FY 2000	Approved FY 2000	Governor FY 2001	Approved FY 2001
State Conservation Commission					
Buffer Initiative	31,279	128,721	128,721	80,000	80,000
Conservation District Aid	1,023,250	1,032,750	1,032,750	1,035,500	1,035,500
Multipurpose Small Lakes	231,000	231,000	231,000	230,000	230,000
Nonpoint Source Pollution Asst.	2,904,154	3,124,846	3,124,846	3,000,000	3,000,000
Riparian and Wetland Programs	100,000	125,000	125,000	200,000	200,000
Water Resources Cost Share	4,350,307	4,549,693	4,549,693	4,450,000	4,450,000
Watershed Dam Construction	818,287	845,426	845,426	805,000	805,000
Total--Conservation Commission	$ 9,458,277	$ 10,037,436	$ 10,037,436	$ 9,800,500	$ 9,800,500
Kansas Water Office					
Assessment and Evaluation	--	--	--	200,000	200,000
Basin Assessment	106,638	25,000	25,000	--	--
Cheney Agricultural Nonpoint Source	--	25,000	25,000	--	--
Federal Cost-Share Programs	--	100,000	100,000	250,000	250,000
GIS Data Access and Support Center	166,793	162,800	162,800	177,300	177,300
GIS Data Base Development	305,987	250,000	250,000	250,000	250,000
Groundwater Condition Evaluation	--	75,000	75,000	70,000	70,000
Kansas Water Resource Institute	138,500	--	--	--	--
Milford and Perry Storage Acquisition Costs	--	--	--	--	--
MOU - Storage Operations and Maintenance	450,845	489,663	489,663	429,787	429,787
PMIB Loan Payment for Storage	246,197	267,394	267,394	270,413	270,413
Public Information	38,429	30,000	30,000	30,000	30,000
Public Water Supply - GIS	--	--	--	--	--
Stream Team	--	--	--	--	--
Stream Gauging Program	382,580	400,000	400,000	370,000	370,000
Technical Assistance to Water Users	560,463	440,000	440,000	440,000	440,000
Water Resource Education	55,228	70,000	70,000	60,000	60,000
Water Quality in Upper Arkansas	--	75,000	75,000	--	--
Weather Modification	390,000	360,000	360,000	349,000	349,000
Total--Kansas Water Office	$ 2,841,660	$ 2,769,857	$ 2,769,857	$ 2,896,500	$ 2,896,500
Wildlife & Parks					
River Recreation	--	--	--	--	--
Stream Monitoring	44,856	50,000	50,000	50,000	50,000
Total--Wildlife & Parks	$ 44,856	$ 50,000	$ 50,000	$ 50,000	$ 50,000
KSU--Western Ks. Irrigation Research Project	$ 28,057	$ --	$ --	$ --	$ --
Department of Agriculture					
Floodplain Management	109,048	110,619	110,619	131,849	131,849
Best Management Practices		--	--	50,000	50,000
Interstate Water Issues	146,206	193,157	193,157	202,795	202,795
Subbasin Water Resources Management	529,000	685,000	685,000	649,145	649,145
Total--Dept. of Agrriculture	$ 784,254	$ 988,776	$ 988,776	$ 1,033,789	$ 1,033,789
Health & Environment					
Assessment of Sediment Quality	--	125,000	125,000	50,000	50,000
Contamination Remediation	1,472,826	1,390,000	1,390,000	1,397,840	1,397,840
Local Environmental Protection Program	1,991,481	1,800,000	1,800,000	1,800,000	1,800,000
Nonpoint Source Program	461,387	925,000	925,000	469,430	469,430
TMDL Initiatives	--	--	--	220,000	220,000
Use Attainability Analysis	--	--	--	200,000	200,000
Total--Health & Environment	$ 3,925,694	$ 4,240,000	$ 4,240,000	$ 4,137,270	$ 4,137,270
KCC--Well Plugging	$ 400,000	$ 400,000	$ 400,000	$ 400,000	$ 400,000
Total Water Plan Expenditures	$17,482,798	$18,486,069	$18,486,069	$18,318,069	$18,318,059

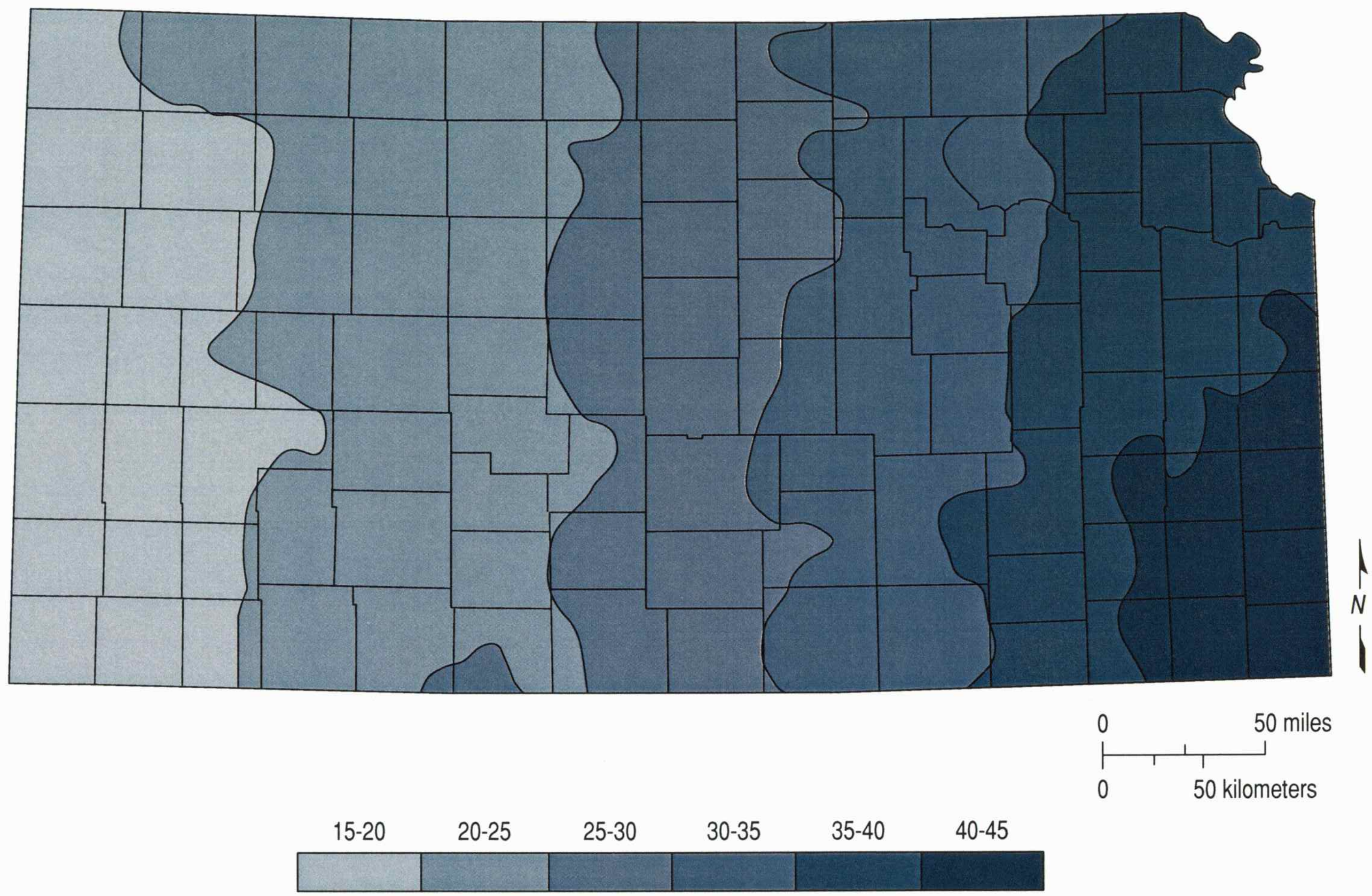

Figure 1. Precipitation patterns in Kansas.

Irrigation:	3,443,065	acre feet
Municipal:	422,818	
Industry:	118,907	
Recreation:	62,361	
Stock Water:	31,626	
Other:	42,941	
Total Kansas Use:	**4,121,718**	**acre feet**

Figure 2. Kansas water useage, FY 1995.

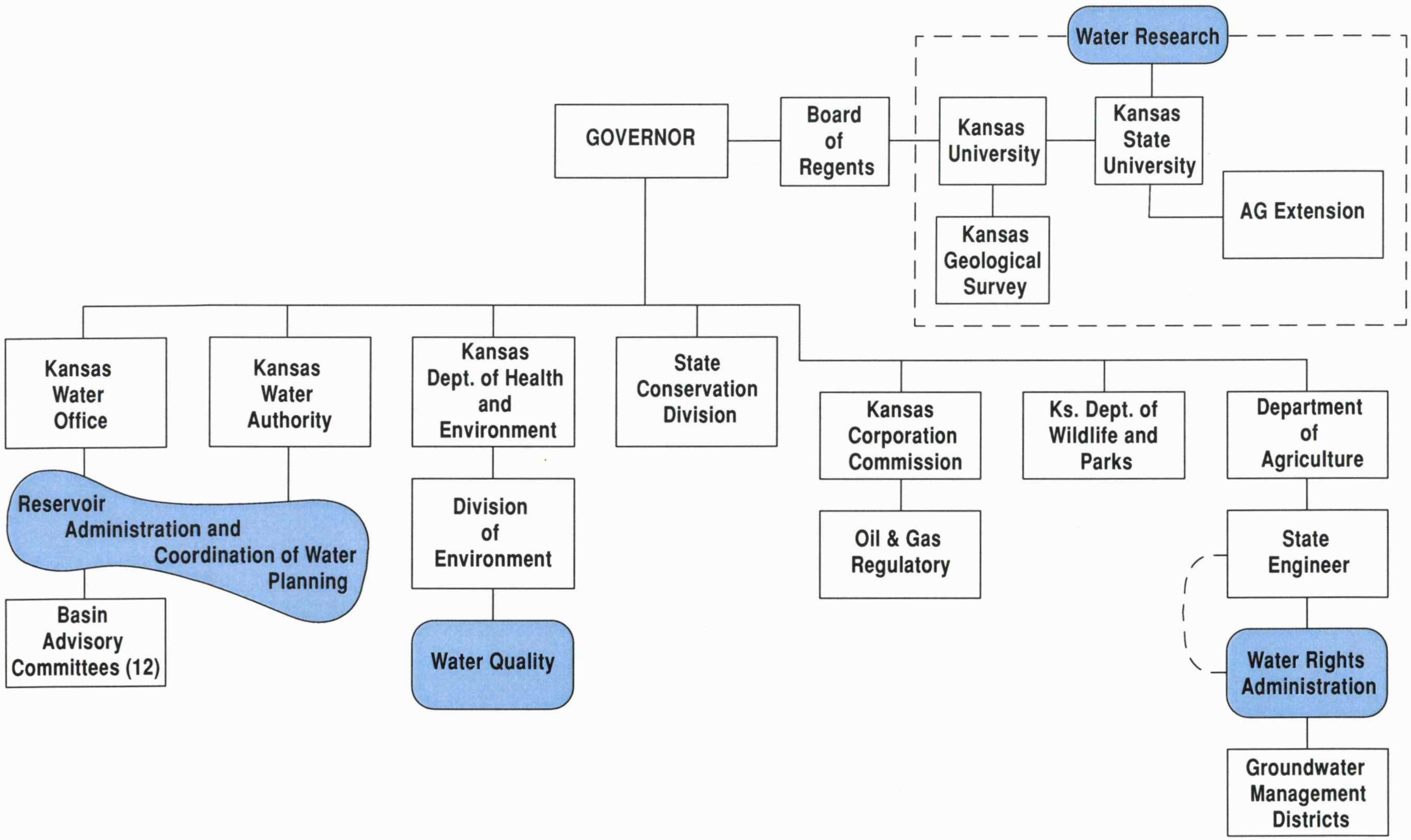

Figure 3. Organization chart of Kansas water management.

A. Voting Members (Citizens)

One member appointed by the Governor (Chair)
One member appointed by the President of the Senate
One member appointed by the Speaker of the House
One member representing the environmental community
One member representing the State Association of Watersheds
One member representing the Kansas Association of Conservation Districts
One member representing of League of Municipalities
Two members representing the public
One member representing Kansas Rural Water Association
One member representing Kansas Association of Commerce and Industry

B. Non-voting Ex Officio Members

Secretary, Department of Agriculture
Chief Engineer, Division of Water Resources
State Geologist, Kansas Geological Survey
Director, Division of Environment, Kansas Dept. of Health and Environment
Director, Kansas Water Office
Secretary of Kansas Department of Commerce and Housing
Director, State Conservation Commission
Director, Oil and Gas Regulatory Division, Kansas Corporation Commission

Figure 4. Membership of the Kansas Water Authority.

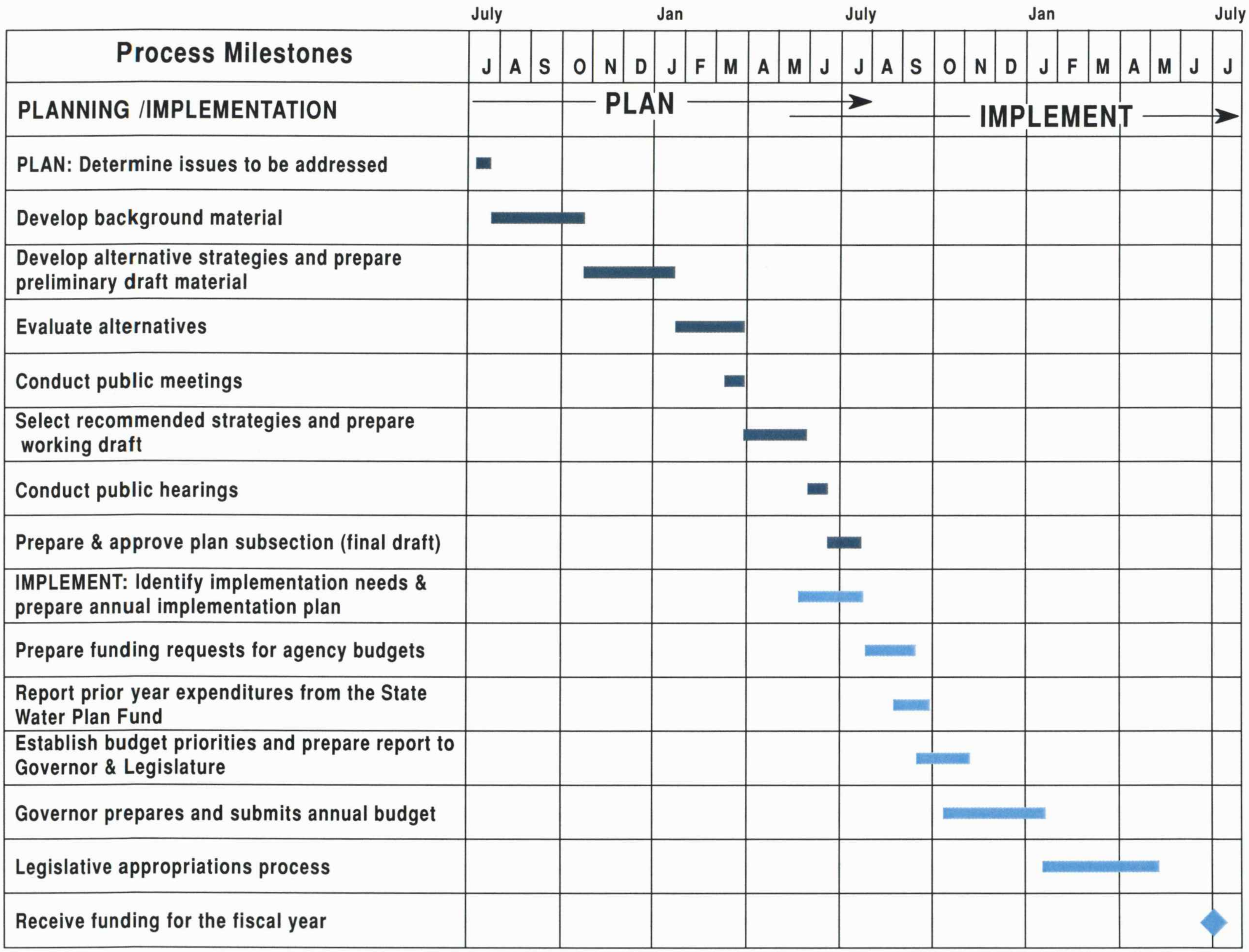

Figure 5. State water planning and implementation process.

APPENDIX A
STATE AGENCY MISSIONS

Kansas Department of Agriculture

To administer assigned laws and programs related to commodity commissions, dairy inspections; agricultural commodities assurance program; meat and poultry inspection; pesticide use; plant protection and weed control; weights and measures; grain warehouse inspection; and water resources.

Kansas Department of Commerce and Housing

To foster economic development through the promotion of business, commerce and industry.

Kansas Corporation Commission

To regulate rates, service and safety of public utilities, common carriers, motor carriers, and regulate oil and gas production.

Kansas Geological Survey

To conduct geological studies and research and to collect, correlate, preserve, and disseminate information.

Kansas Department of Health and Environment

To optimize the health of Kansans and to preserve, protect, and remediate the natural resources.

KSU-Research and Extension

Dedicated to a safe sustainable competitive food and fiber system through integrated research, analysis and education.

Kansas Department of Wildlife & Parks

Conserve and enhance Kansas' natural heritage, its wildlife and its habitats; provide the public with opportunities for the use of the natural resources.

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From safe yield to sustainable development of water resources—the Kansas experience

M. Sophocleous*

Kansas Geological Survey, The University of Kansas, 1930 Costant Ave., Lawrence, KS 66049, USA

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Abstract

This paper presents a synthesis of water sustainability issues from the hydrologic perspective. It shows that safe yield is a flawed concept and that sustainability is an idea that is broadly used but perhaps not well understood. In general, the sustainable yield of an aquifer must be considerably less than recharge if adequate amounts of water are to be available to sustain both the quantity and quality of streams, springs, wetlands, and ground-water-dependent ecosystems. To ensure sustainability, it is imperative that water limits be established based on hydrologic principles of mass balance. To establish water-use policies and planning horizons, the transition curves of aquifer systems from ground-water storage depletion to induced recharge of surface water need to be developed. Present-day numerical models are capable of generating such transition curves. Several idealized examples of aquifer systems show how this could be done. Because of the complexity of natural systems and the uncertainties in characterizing them, the current philosophy underlying sustainable management of water resources is based on the interconnected systems approach and on adaptive management. Examples of water-resources management from Kansas illustrate some of these concepts in a real-world setting. Some of the hallmarks of Kansas water management are the formation of local ground-water management districts, the adoption of minimum streamflow standards, the use of modified safe-yield policies in some districts, the implementation of integrated resource planning by the City of Wichita, and the subbasin water-resources management program in potential problem areas. These are all appropriate steps toward sustainable development. The Kansas examples show that local decision-making is the best way to fully account for local variability in water management. However, it is imperative that public education and involvement be encouraged, so that system complexities and constraints are better understood and overly simplistic solutions avoided.

Keywords: Water sustainability; Safe yield; Transition curve; Stream-aquifer systems; Integrated resource planning; Kansas water management

1. Introduction

In general, the time has passed when abundant supplies of water were readily available for development at low economic, social, and environmental costs. Now we are in what Hufschmidt (1993) called the period of the "maturing water economy," with increasing competition for access to fixed supplies, a growing risk of water pollution, and sharply higher economic, social, and environmental costs of development. Few areas of public policy are as contentious as the management of our water resources.

Around the world, most of the easily developable water has been developed, and future water management will depend on obtaining more out of existing

* Tel.: +1-913-864-3965; fax: +1-913-864-5317.
E-mail address: marios@kgs.ukans.edu (M. Sophocleous).

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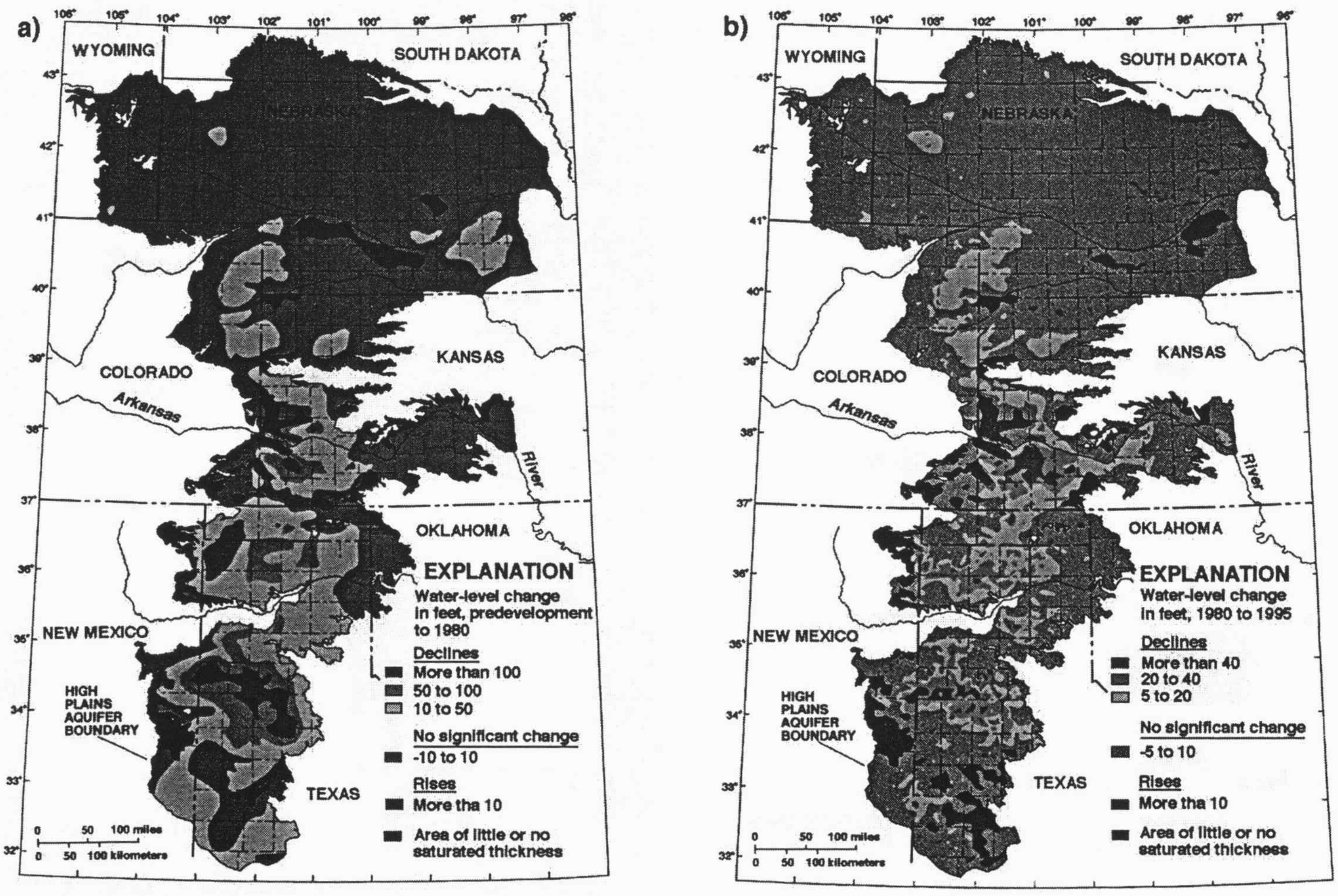

Fig. 1. Water-level changes (in ft) in the High Plans aquifer (A) predevelopment to 1980; (B) 1980–1995. To convert to meters multiply by 0.3048. Adapted from US Geological Survey (http://www-ne.cr.usgs.gov/highplains/hpactivities.html).

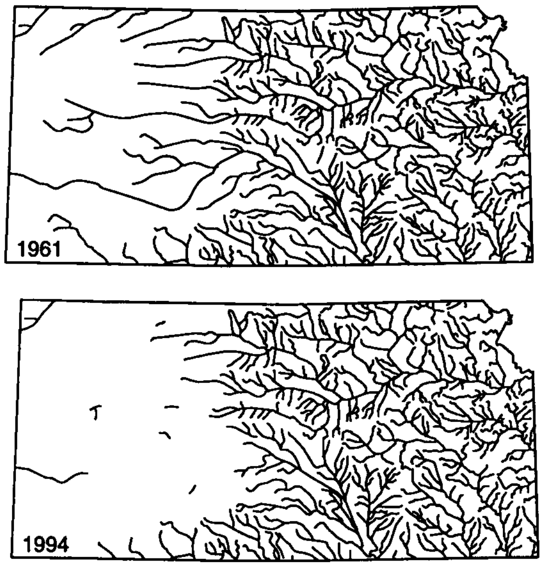

Fig. 2. Major perennial streams in Kansas, 1961 versus 1994 (adapted from Angelo, 1994).

supplies. The great challenge facing the world today is how to cope with the impact of economic growth on the environment. Sustainable development emerged during the late 1980s as a unifying approach to concerns about the environment, economic development, and quality of life. The World Commission on Environment and Development (1987), better known as the Brundtland Commission, defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This intergenerational perspective implies that we must use the water resources in ways that are compatible with maintaining them for future generations, thus constraining *our* management of water.

Although progress has been made in defining the goals of sustainable development, the mechanisms to bring about these changes are still a matter of debate. The challenge is to turn the principles of sustainable development into achievable policies. The move from principle to practice is far from easy. Like other abstract concepts, sustainable development is a powerful and dynamic concept that will continue to be refined.

Science can explore the implications of different interpretations of sustainability, but it can not choose the "correct" interpretation for society. Nonetheless, if sustainable development of water resources is to have any meaning, it must be based on sound hydrologic analyses and appropriate technologies.

The objectives of this overview presentation are: (1) to explore the hydrologic underpinnings and shortcomings of the sustainability concept of safe yield as a basis for developing ground-water planning policy; (2) to provide a brief examination of our evolving broader environmental sustainability concepts; and (3) to highlight the path Kansas has taken towards achieving water sustainability, as a case example. This paper represents a critical synthesis of water sustainability issues from the hydrologic perspective. The focus on Kansas is intended to emphasize selected applications of the concepts presented.

2. Safe yield and underlying hydrologic fundamentals of the concept

2.1. Hydrologic principles

Safe yield is commonly defined as the attainment and maintenance of a long-term balance between the amount of ground water withdrawn annually and the annual amount of recharge (Sophocleous, 1997; Sophocleous and Sawin, 1997). Therefore, safe yield allows water users to pump no more ground water than is replenished naturally through precipitation and surface-water seepage, generally known as natural recharge. But safe yield ignores the fact that over the long term under natural or equilibrium conditions, natural recharge is balanced by discharge from the aquifer by evapotranspiration or into streams, springs, or seeps. Consequently, if pumping equals recharge, eventually streams, marshes, and springs may dry up. Continued pumping in excess of recharge also may eventually deplete the aquifer. This has happened in several locations across the Great Plains (Sophocleous, 1998c). Probably the best-known example is the Ogallala or High Plains aquifer, where declines of more than 30 m over a 30-yr period were common in parts of Texas, New Mexico and Kansas (Fig. 1). Maps comparing the perennial streams in Kansas in the 1960 to those of the 1990 (Fig. 2) show a marked decrease in kilometers of streamflow in the western third of the state.

To understand this depletion, a thorough knowledge of the hydrologic principles (concisely stated by Theis, 1940) is required. Under natural conditions, prior to development by wells, aquifers approach a state of dynamic equilibrium: over hundreds of years, wet years in which recharge exceeds discharge offset dry years when discharge exceeds recharge. Discharge from wells upsets this equilibrium by producing a loss from aquifer storage; a new state of dynamic equilibrium is approached when there is no further loss or minimal loss from storage. This is accomplished either by an increase in recharge, a decrease in natural discharge, or a combination of the two.

Consider a stream-aquifer system such as an alluvial aquifer discharging into a stream. (Please note that I use the term "stream" in the broadest sense of the word; the issues, approach, and results also apply to rivers, lakes, ponds, and wetlands). A new well drilled at some distance from the stream and pumping the alluvial aquifer forms a cone of depression. The cone grows as water is taken from storage in the aquifer. Eventually, however, the periphery of the cone arrives at the stream. At this point, water will either start to flow from the stream into the aquifer, or discharge from the aquifer to the stream will appreciably diminish or cease. The cone will continue to expand with continued pumping of the well until a new equilibrium is reached in which induced recharge from the stream balances the pumping.

The length of time, t, before an equilibrium is reached depends upon (1) the aquifer diffusivity (expressed as the ratio of aquifer transmissivity to storativity, T/S), which is a measure of how fast a transient change in head will be transmitted throughout the aquifer system; and (2) upon the distance from the well to the stream, x. For radial flow of ground water, a tenfold increase in distance from the surface-water body causes a hundredfold delay in the response time, whereas a change in diffusivity is linearly proportional to the response time (Balleau, 1988). Generally, if the wells are distant from the stream, it takes tens or hundreds of years before their influence on streamflow is felt.

Once the well's cone has reached an equilibrium size and shape, all of the pumping is balanced by flow diverted from the stream. In that case, there is no difference between a water right to withdraw ground water from the well, as described, and a water right to divert from the stream at the same rate. A crucial point, however, is that before equilibrium is reached (that is, before all water is coming directly from the stream), the two rights are not the same (DuMars et al., 1986). Until the perimeter of the cone reaches the stream, the volume of the cone represents a volume of water that has been taken from storage in the aquifer, over and above the subsequent diversions from the stream. It is this volume that may be called *ground-water depletion*. Thus, ground-water sources include ground-water (or aquifer) storage and induced recharge of surface water.

2.2. Limitations of safe yield

The concept of safe yield is often associated with the annual exploitation of a single product—the number of trees cut, the number of fish caught, the volume of water pumped from the ground or river—without destroying the resource base (Sophocleous, 1997). However, other resources inevitably depend on, interact with, or flow from the exploited product. We can maximize our so-called safe yield of water by drying up our streams, but when we do, we find that the streams were much more than just containers of usable water. This is what happened with a number of streams in Kansas, such as the Arkansas River from western Kansas up to the city of Great Bend in south-central Kansas (the author visited the dry streambed of that river at multiple locations during the summer of 1985, and at other times), the Pawnee River, and other streams in west-central Kansas.

The conventional safe-yield approach is limited and restrictive. It fails to address the beneficial impacts of natural ground-water discharge on related ground-water-dependent ecosystems, and on the surface-water system in general. To many people, safe yield is equated with an annual yield on which a water user can rely. It is easily confused with a water right (i.e. a right under which a person may lawfully divert and use water). However, any change in conditions, such as changes in vegetation, land use, urbanization, location of pumping wells, incorporation of new water supplies, or climate change would require calculation of a new yield.

For example, closely spaced wells will cause much more rapid decline of local water levels than the same number of wells more widely dispersed. In some

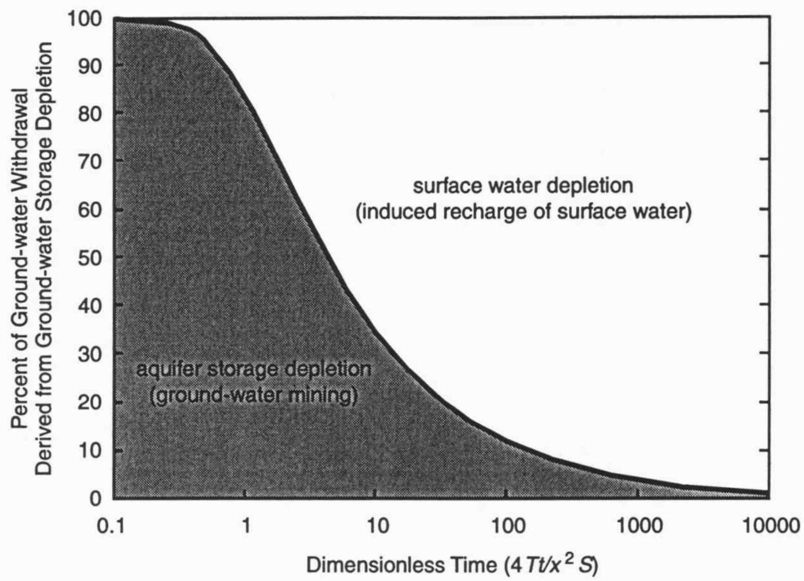

Fig. 3. Transition from reliance upon ground-water storage to induced recharge of surface water. *T* is transmissivity, *S* is storage, *x* is the distance from pumping well to stream, and *t* is time (adapted from Balleau, 1988).

basins the quantity of water in the aquifer governs the safe yield; in others, water quality is the limiting factor; in yet others, especially in confined aquifers with areas of recharge far away from pumping centers, the rate of flow towards the wells is the limiting factor. Changes in vegetation may affect surface infiltration and subsequent percolation to the water table. Clearly, no unique and constant value can be attached to safe yield.

The safe yield of an aquifer, in some instances, can be substantially augmented by engineering controls (ASCE, 1987). For example, more water can be made available through artificial recharge by spreading or injection wells, or by lowering ground-water levels to reduce evapotranspiration, to capture rejected recharge, or to capture surface water from streams. The amount of water production represented by "safe yield" is fixed at any point in time only in the sense that no more money may be available for engineering construction, or that other conditions (discussed above) remain unchanged, or that no more water may be legally obtained from any source (ASCE, 1987). Should these constraints be changed-for example, by the importation of water or the utilization of underground storage—safe yield could be increased.

The failures and unintended consequences of conventional and safe-yield approaches to water management provide some of the strongest incentives for retiring the concept. As the following examples show, such failures can have both local and regional consequences (Sophocleous et al., 1998).

- Ground-water pumping has dried up or threatened numerous reaches of baseflow-dependent streams, wetlands, and subirrigated land—with many examples found in Kansas along the fringes of the High Plains aquifer (some shown earlier), and in other states.
- Irrigation has contaminated the land in many areas. Increases in consumptive water use leave behind the salts dissolved in the water. The example of irrigation drainage water contaminating the ponds at Kesterson National Wildlife Refuge in California with toxic levels of selenium (NRC, 1989) is well known. Saline water from irrigation return flow into the Upper Arkansas River basin now threatens the ground-water resources of the alluvial and Ogallala aquifers in Kansas. The Kansas Geological Survey (Whittemore et al., 1999) is now embarked on a multi-year study to analyze the impact of Arkansas River salinity on the underlying alluvial and Ogallala aquifers in western

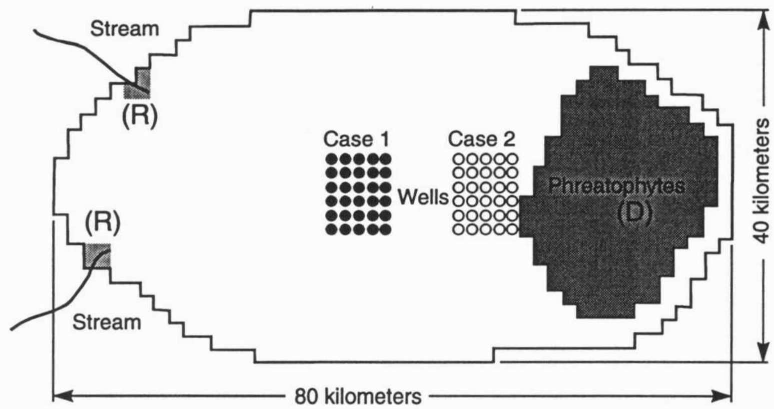

Fig. 4. Schematic map of an intermontane basin showing areas of recharge (R), Discharge (D), and two hypothetical water-development schemes, Case 1 and Case 2 (adapted from Bredehoeft, et al., 1982).

Kansas resulting from irrigation return flow in Colorado.

- Whole regional ecosystems change and disappear with large-scale water development—the Gulf of California has changed from an estuary to a marine lagoon as the Colorado River has been dried up. Nutrient runoff from the central US, including Kansas, has changed the ecology of the area surrounding the mouth of the Mississippi and led to the hypoxia problem in the Gulf of Mexico we witness today (Rabalais et al., 1991).

3. Developing a sound ground-water planning policy: some examples

As discussed previously in Section 2.1 on hydrologic principles, ground-water sources include aquifer storage and induced recharge of surface water. The timing of the change from storage depletion (or mining) to induced recharge from surface-water bodies is key to developing water-use policy (Balleau, 1988).

The shape of the transition or growth curve for an idealized, two-dimensional, homogeneous and isotropic system is shown in Fig. 3 in nondimensional form, based on Glover's (1974; Chapter 9) analytical solution and tabulation. In Fig. 3, the percent of ground-water withdrawal derived from ground-water storage is plotted on the *Y*-axis against dimensionless time (or normalized time, $t^* = \{4(T/S)/x^2\}t)$ on the *X*-axis. The general shape of the transition curve is retained in systems with apparently different boundaries and parametric values (Balleau, 1988). The rate at which dependence on ground-water storage (as shown at the left portion of the graph) converts to dependence on surface-water depletions (as shown on the right portion of the graph) is highly variable and is particular to each case. For example, if aquifer storage is 85% of the source of water after 1 month (or 1 year) of pumping, it will end up being only 5% of the water pumped coming from aquifer storage after 1000 months (or 1000 years) of pumping (Fig. 3).

The initial and final phases of the transition curve (Fig. 3), representing mining on the left and induced recharge on the right, are separated in time by a factor of nearly 10 000. As the example above showed, full reliance on indirect recharge takes an extremely long time. The distinct category of ground-water mining depends entirely upon the time frame. Initially, all ground-water developments mine water but ultimately they do not (Balleau, 1988). The eventual reduction in surface-water supply as a result of ground-water development, and the distinction between natural recharge and induced recharge complicates the administration of water rights.

Aquifer drawdown and surface-water depletion are two results of ground-water development that affect policy. Both are fundamentally related to pumping rate, aquifer diffusivity, location, and time of pumpage. The natural recharge rate is unrelated to

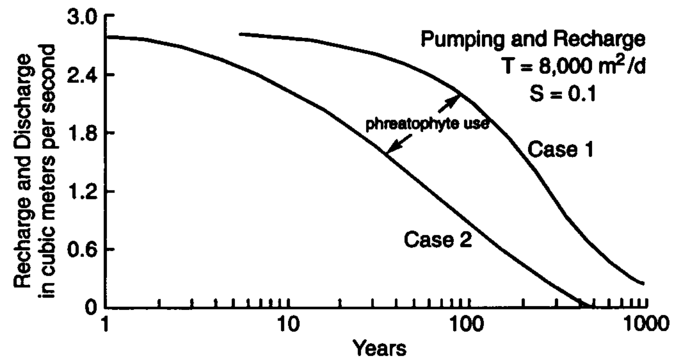

Fig. 5. Plot of the rate of recharge, pumping, and phreatophyte use versus time (adapted from Bredehoeft et al., 1982).

any of these parameters. Nonetheless, natural recharge is often used by policy makers to balance ground-water use, based ostensibly on a steady state (Balleau, 1988). As Balleau (1988) pointed out, public purposes are not served by adopting the attractive fallacy that the natural recharge rate represents a safe rate of yield.

To illustrate the influence of the dynamics of a ground-water system in response to development, Bredehoeft et al. (1982) chose a simple, yet realistic, system for analysis—a closed intermontane basin of the sort common in the western United States (Fig. 4). Under predevelopment conditions, the system is in equilibrium: phreatophyte evapotranspiration in the lower part of the basin (the natural discharge from the system) is equal to recharge from the two streams at the upper end. Pumping in the basin is assumed to equal the recharge. This system was simulated by a finite-difference approximation to the equations of ground-water flow (Bredehoeft et al., 1982) for one-thousand years. Stream recharge, phreatophyte-water use, pumping rate, and change in storage for the entire basin were graphed as functions of time. Two development schemes were examined: case 1, in which the pumping was more or less centered within the valley, and case 2, in which the pumping was adjacent to the phreatophyte area (Fig. 4).

The system does not reach a new equilibrium until the phreatophyte-water use (i.e. the natural discharge) is entirely salvaged or captured by pumping (Fig. 5). In other words, phreatophyte water use eventually approaches zero as the water table drops and plants die. In case 1, phreatophyte-water use is still approximately 10% of its initial value at year 1000 (Fig. 5). In case 2, it takes ~500 years for the phreatophyte-water use to be completely captured.

This example illustrates three important points (Bredehoeft et al., 1982). First, the rate at which the hydrologic system can be brought into equilibrium depends on the rate at which the discharge can be captured. Second, the placement of pumping wells changes the dynamic response and the rate at which natural discharge can be captured, and third, some ground water must be mined before the system can approach a new equilibrium. Steady state is reached only when pumping is balanced by capturing discharge and, in some cases, by a resulting increase in recharge. In many circumstances, the dynamics of the ground-water system are such that long periods of time are necessary before any kind of an equilibrium condition can develop. In some circumstances the system response is so slow that mining will continue well beyond any reasonable planning period.

A suitable hydrologic basis for a ground-water planning policy aimed at determining the magnitude of possible development would be a curve similar to the transition curve we saw earlier, coupled with a projected pattern of drawdown for the system under consideration. Since the 1980s, three-dimensional numerical models of the complete stream-aquifer hydrogeologic system have been used for water-rights purposes (Balleau, 1988). These models provide a predictive tool explaining the connection between well-field withdrawal and surface-water depletion at particular sites. Ground-water models are capable of generating the transition curve for any case by simulating the management or policy alternatives in terms of the sources of water from ground-water storage and

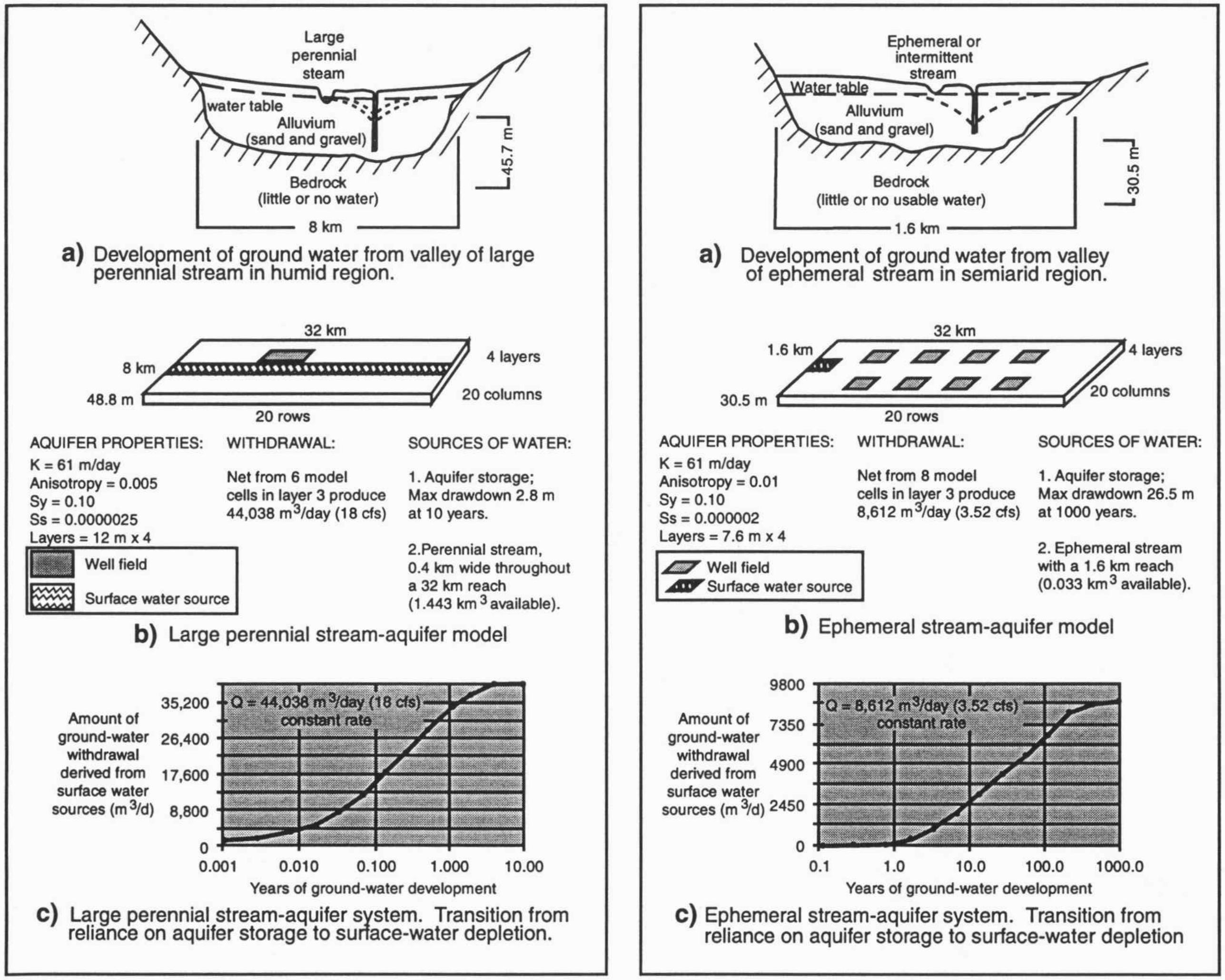

Fig. 6. Two example aquifer systems showing (a) their geometry, (b) the employed model input and (c) the resulting transition curves (adapted from Balleau and Mayer, 1988, and Lohman, 1972).

from surface-water depletion throughout the area of response. Specified withdrawal rates, well distribution, and drawdown of water levels to an economic or physical limit are used in the model for such projections (Balleau, 1988). However, a planning horizon must be defined to assess which phase of the transition curve will apply during the period of the management plan.

Lohman (1972) discussed safe yield and the sources of water derived from well fields using a series of five example aquifer types. His conceptual model was extended by Balleau and Mayer (1988) to illustrate quantitatively the rate of change of water sources in the types of systems that Lohman discussed. The three-dimensional aquifer model program MODFLOW of McDonald and Harbaugh (1988) was used to calculate the drawdown and depletion rates for the five example flow systems following Lohman's description. Two aquifer types are discussed briefly below: (1) a valley of large perennial stream in humid regions; and (2) a valley of an ephemeral stream in a semi-arid region. See Fig. 6a for illustration of the geometry of each aquifer system (Lohman, 1972). Additional input required for the three-dimensional simulations, particularly withdrawal rates and hydrogeologic properties, are illustrated in Fig. 6b (Balleau and Mayer, 1988). In each case, a well field was specified to produce at practical rates from each system. Withdrawal was simulated at a constant rate. Generally, the surface sources were simulated as an amount available to be captured from perennial streams, springs, or from reduction of evapotranspiration.

Calculated curves display the transition from full reliance on aquifer storage to full reliance on induced recharge of surface waters (Fig. 6c). These show the importance of selecting a suitable planning horizon when evaluating the effect of a ground-water withdrawal. The phase during which more than 98% of the withdrawals are derived from induced recharge ranges from 4 to 375 years in these two examples. The results suggest that a ground-water policy based either on equilibrium conditions or on a mining strategy should be thoroughly examined for its physical and economic effects through the years. Both arid and humid regions may require this type of information before the effects of a water plan are fully understood (Balleau and Mayer, 1988).

4. Expanding sustainability concepts: the broader view

Over the past several decades, the philosophy underlying management of water resources gradually has shifted from a deterministic world view based on the balance of nature to a recognition that nature is characterized by chance and randomness, and that natural systems are inherently variable, patchy, and often require disturbance to persist (Meyer, 1993). Stream ecosystems in particular depend on natural disturbances such as flooding. This new recognition means that we must manage for change and for complexity. Not only must we manage in the context of the ecosystem (rather than managing parts as though they were in isolation), but we must also use an adaptive management scheme that is responsive to changing environmental conditions (Meyer, 1993).

Managing in an ecosystem context (NRC, 1991) means that we have to think about the sustainability of the system—not just the fish, but the aquatic food chain; not just the trees, but the whole forest; not just the ground water, but the running streams, wetlands, and all of the plants and animals that depend on them (Sophocleous, 1997; Sophocleous et al., 1998). Such an approach is fraught with difficulty. We cannot use a natural system without altering it, and the more intensive the use, the greater the alteration. How much is too much? What are the central characteristics that must be preserved or sustained? And is there any way to answer these questions before it is too late? This is the crux of the sustainability problem-even if we care about the next generation, do we permit things that cannot be proven dangerous or forbid what cannot be proven safe? Science can never know all there is to know because science is a process and not an end point. Rather than allowing the unknown or uncertain to paralyze us, we must apply the best of what we know today, while providing sufficient management flexibility to allow for change and for what we don't yet know.

In outlining the current challenges for ecology, Meyer (1993) made the following perceptive comments, directly relevant to the water sustainability debate:

> "An additional component of management for change is managing in a probabilistic and

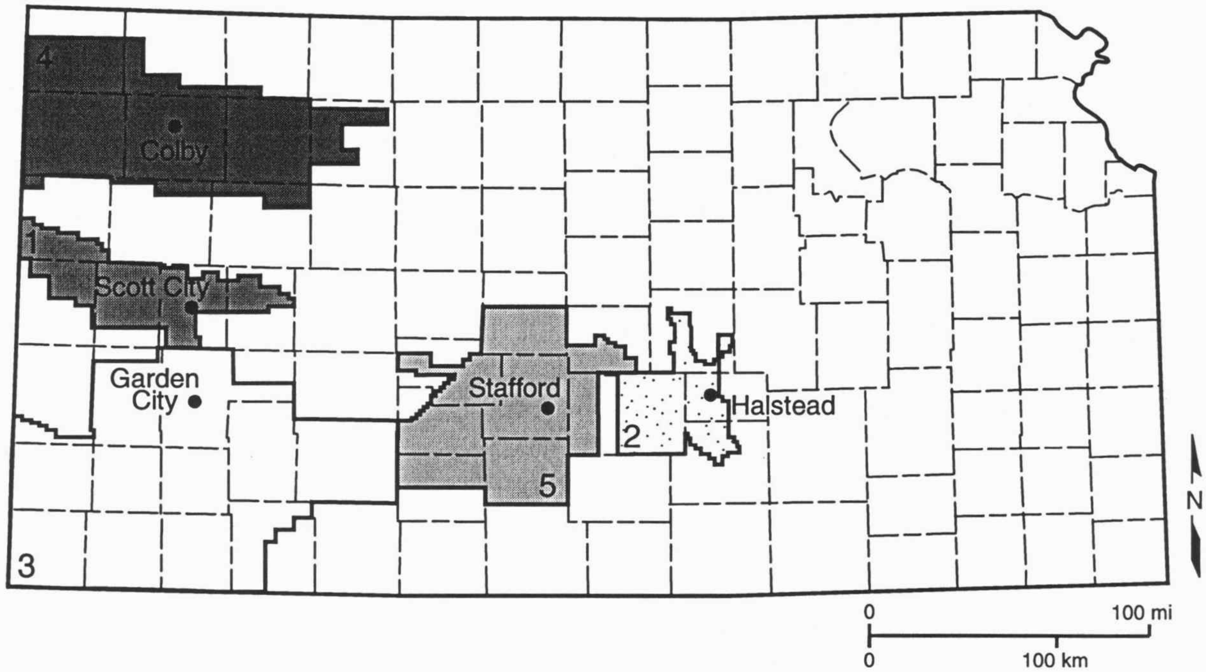

Fig. 7. Ground-water Management Districts (GMDs) in Kansas.

risk-assessment framework in which one recognizes the inherent unpredictability of nature... Rather than determining a fixed sustainable yield, the manager recognizes that yield should vary over time as environmental conditions vary. In the long term this produces a more sustainable yield. This type of management requires greater input of scientific understanding and continued monitoring than is currently practiced...[The evidence shows that] we have altered the hydrologic cycle as well as cycles of most elements; human activities seem to be affecting climate; biodiversity is declining rapidly. Events such as these require scientists and managers alike to think on a global scale...As human assaults on natural systems have accelerated over the past decade, so has the need for a more holistic concept of system management that has the goal of maintaining and restoring the ecological integrity of the resource rather than simply preserving water quantity or quality."

The need to manage ground-water resources as an integral part of overall available water resources and in recognition of their place in the equilibrium of the natural environment is better understood today by scientific experts and water-resource managers. *Integrated resource planning* has recently emerged as a tool for total water management, "assuring that water resources are managed for the greatest good of people and the environment and that all segments of society have a voice in the process" (AWWA, 1994). This concept of enlightened management, which in the past has eluded those directly or indirectly involved in the day-to-day management operations of ground water, is now taking hold in Kansas (Warren et al., 1995) and other states.

5. Kansas water-resources-management experience

In response to persistent ground-water-level declines, especially in western Kansas, the Kansas Legislature in 1972 passed the Kansas Ground Water Act authorizing the formation of local ground-water management districts (GMDs) to help

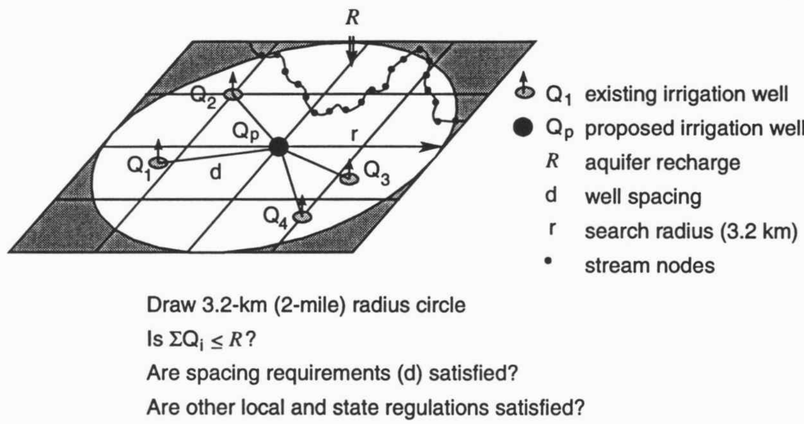

Fig. 8. Kansas "safe-yield" management policy.

control and direct the development and use of ground-water resources (Fig. 7). Since passage of the enabling act, five districts have been formed, of which the three western districts (1, 3, and 4; Fig. 7) overlie all or parts of the Ogallala aquifer. {The term High Plains aquifer is a more encompassing term, incorporating not only the Ogallala aquifer proper, covered by GMDs 3, 1, and 4, but also its eastern extensions in the Great Bend Prairie and Equus Beds regions, covered by GMDs 5 and 2, respectively (Fig. 7; Sophocleous, 1998b)}. The three western districts have the greatest number of large-capacity wells and the highest rate of water-level declines, in addition to having the least precipitation (ranging from west to east from less than 400 to 550 mm/year on average) and least ground-water recharge (generally less than 13 mm/year, Hansen, 1991). Because recharge rates are so low in western Kansas, so-called "safe-yield" policies, in which ground-water withdrawals are restricted to average recharge rates, have not been adopted as being too harmful to the region's economy. Thus, each of these districts has employed a plan that allows a part of the aquifer to be depleted (no more than 40%) over a period of 20–25 years (this is the so-called "planned-depletion" policy). This implies that the Ogallala is not a renewable resource, at least within a human generation. The rationale for the 20–25 year time span and for the 40% allowable depletion is as follows (Sophocleous, 2000). Given that loans were being made on approximately a 20–25 year term for irrigation system installations, a 20–25 year period was considered a reasonable planning period after which it was assumed the irrigation supply would be somewhat physically limited or perhaps legally restricted. Also, given that the aquifer had a relatively large amount of water in storage but a small amount of natural recharge, it was felt that 40% of the saturated thickness was a reasonable amount of depletion over the 20–25 year investment amortization period, and would essentially represent the economic life of the aquifer.

However, these western Kansas districts recognized that their long-term goal was to reduce the rate of water use in order to prolong the life of the aquifer and to assure future economic stability in the region. Towards this end, the Northwest Kansas GMD 4 implemented a so-called "zero depletion" policy in 1991 for new wells. This "zero depletion" policy limits the pumping of water from the aquifer for new wells so as not to exceed the estimated average amount of natural recharge. As a result, very few water rights are approved under this regulation. In fact, because of past over-appropriation, the western Kansas GMDs are mostly closed to further new appropriations. For a new appropriation to be approved, it has to satisfy the following two requirements (in addition to satisfying the above-mentioned "planned depletion" policy, as well as certain well-spacing requirements): (1) that the saturated thickness of the area of the new appropriation has been depleted by less than 15% since 1950; and (2) that such thickness is more than 12 m. The GMDs also took additional measures aimed at reducing water use as will be briefly outlined further below.

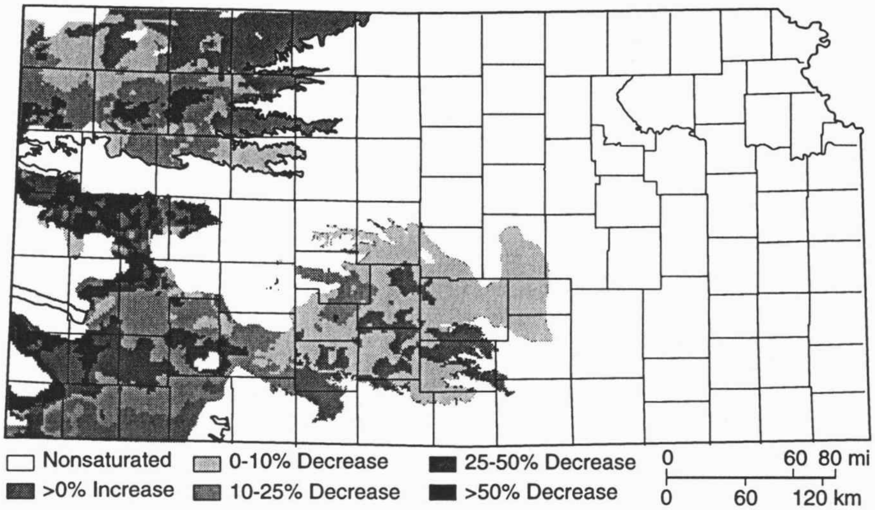

Fig. 9. Percent change in saturation thickness in the High Plains aquifer in Kansas (predevelopment to 1996).

The districts to the east (GMDs 2 and 5; Fig. 7), which have more precipitation (ranging from west to east from 580 to 810 mm/year on average) and thus more ground-water recharge, initially adopted a so-called "safe-yield" management policy to balance ground-water pumping with the average annual recharge. Under this policy, total appropriations in a 3.2-km-radius circle around the proposed diversion (such as an irrigation well) were limited to the long-term average annual recharge calculated for the circle (Fig. 8). Drawdown analysis for typical well and aquifer parameters in the High Plains aquifer in Kansas indicated that drawdown was limited beyond a radius of 3.2 km from a pumping well (Sophocleous, 2000). Thus, the quantity already appropriated within that 3.2-km circle plus the quantity proposed under the new application must not exceed the long-term average annual recharge (implying a renewable ground-water resource). (For a history and rationalization of these policies in Kansas, the reader is referred to Sophocleous, 2000).

This safe-yield policy has slowed the rate of ground-water decline, but it has not stopped ground-water declines. Both GMDs 2 and 5 experienced ground-water-level declines of more than 6 m in parts of their districts since establishment of the "safe-yield" policy in the mid-1970s. Ground-water pumping between predevelopment (circa 1940) and 1990 depleted significant portions of the High Plains aquifer and caused water-level declines of as much as 60 m at places in southwestern Kansas. Fig. 9 shows the declines in saturated thickness since predevelopment across western and central Kansas, where the darkest color indicates more than 50% decrease in saturated thickness. As a result of these declines, the Division of Water Resources (DWR; the water rights regulatory agency) of the Kansas Department of Agriculture has officially closed many areas of western and central Kansas to new ground-water development.

In addition, as a result of these ground-water-level declines, streamflows of western and central Kansas streams have been decreasing, especially since the mid-1970s. As a consequence, riparian vegetation has been progressively degrading in western and central Kansas (Spray, 1986), with numerous dead cottonwood and poplar trees visible across the countryside. This demonstrates that persistent ground-water declines affect sustainability of the resource long before the resource base is threatened with physical exhaustion, and that additional attributes of the resource, such as depth to water table, have a profound impact on the environment. In response to these streamflow declines, the Kansas Legislature passed the minimum instream flow law in 1984, which requires that minimum desirable streamflows (MDS) be maintained in different streams in Kansas. Although the establishment of MDS is a major step toward conservation of riverine habitat within the

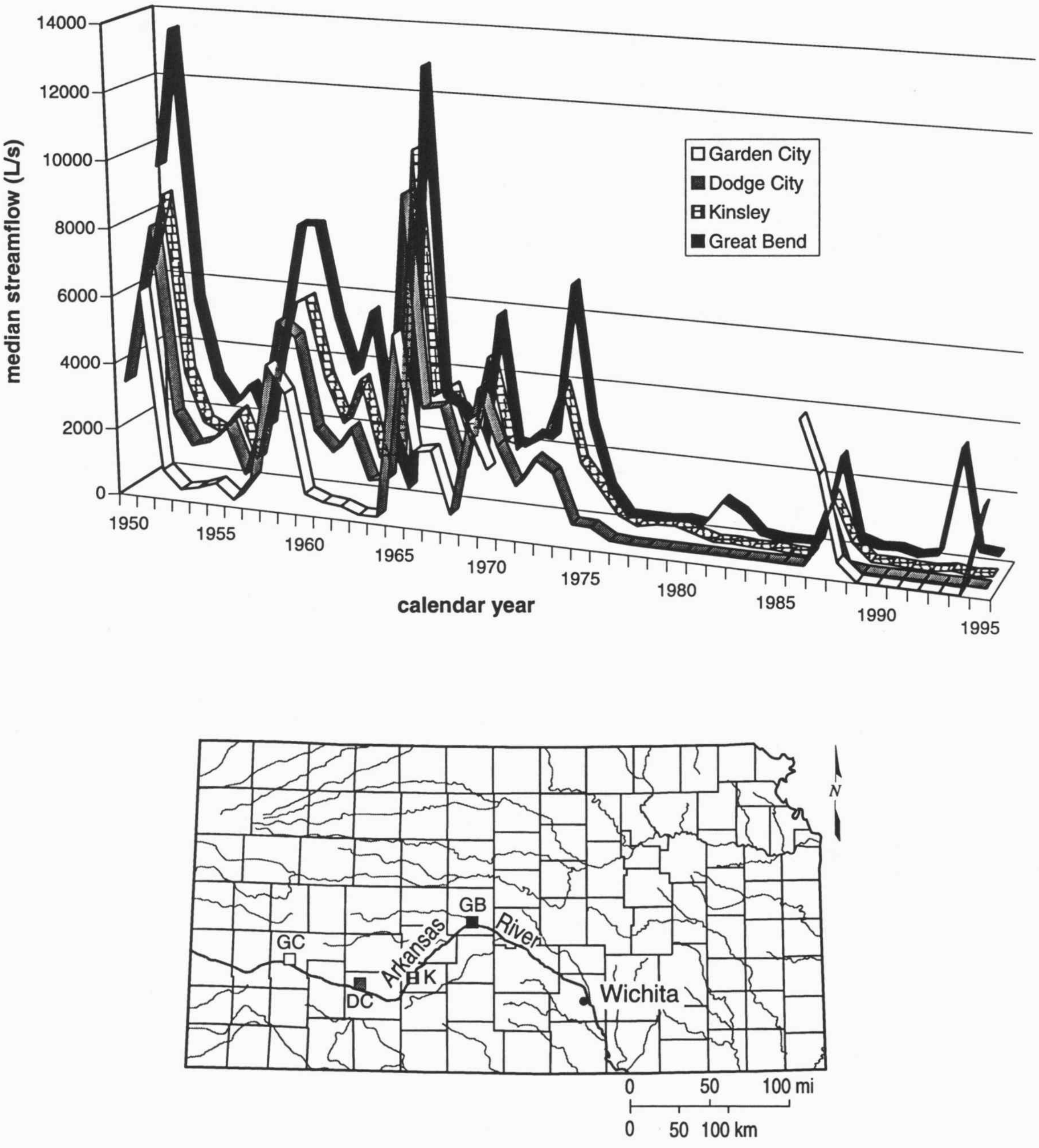

Fig. 10. Median annual discharge of the Arkansas River based on daily streamflow records from 1950 to 1995 at Garden City (GC), Dodge City (DC), Kinsley (K), and Great Bend (GB) stream gaging stations, and location map. (The Garden City station daily record from 1971 to 1985 is non-existent).

state, the trend in reduction of discharge since the mid-seventies, although reduced, appears to be continuing. Fig. 10 is a graph of median annual discharge in the Arkansas River, based on daily streamflow records for Garden City, Dodge City, Kinsley, and Great Bend for the period of 1950–1995. The pattern in reduction of surface discharge since the mid-1970 is clearly visible. As we showed earlier, maps comparing the perennial streams in Kansas in the 1960s to those of the 1990s show a marked decrease in kilometers of streamflow in the western third of the state.

The GMDs realized that the problem of controlling ground-water depletion is complex, involving not only hydrogeologic but also socioeconomic and legal considerations. The DWR and GMDs adopted a suite of management programs involving controls on new development, regulation of existing development, well-spacing requirements, annual water use reporting, water metering on all new non-domestic wells and on all wells in specially-designated areas, water-supply augmentation programs [including water conservation measures, water-use efficiency schemes, artificial recharge structures, participation of the western districts in an active weather modification program (Eklund et al., 1999), participation in recently proposed water banking schemes, and other programs], as well as public education and involvement programs. [For additional information on these programs the reader is referred to the GMD 4 web page (http://colby.ixks.com/~wbossert/); also for an overview of ground-water problems and management approaches to these problems in Kansas and other High Plains states, the reader is referred to Kromm and White (1992).]

As a result of continuing declines in ground-water levels and streamflow under their safe-yield management program, GMDs 2 and 5 recognized that some water provisions needed to be made in order to maintain some minimum desirable flow in the streams and satisfy wetland water requirements. Thus, in the early 1990s, these districts moved toward conjunctive stream-aquifer management by amending their safe-yield regulations to include baseflow (that is, the natural ground-water discharge to a stream) as ground-water withdrawals along with regular water-permit appropriations when evaluating a ground-water permit application. [Baseflow is estimated as the streamflow that is exceeded 90% of the time on a monthly basis, as a measure of dry-weather flow. (For a more detailed explanation and evaluation of these policies, the reader is referred to Sophocleous, 2000).]

The concept, shown in Fig. 8, is to prorate the baseflow to a series of phantom wells, known as "baseflow or stream nodes," which are shown as dark dots in the figure. These nodes are located on the stream centerline at 0.4-km intervals (the GMDs' well-spacing requirement), each having an annual quantity of water assigned to it equal to its prorata share of the estimated baseflow, which is considered its appropriation for "3.2-km circle" computations (Sophocleous, 2000). If there are such nodes in a 3.2-km circle, they are each treated as water rights for purposes of determining whether or not a new application should be approved. It is hoped that this new measure, together with the establishment of minimum desirable streamflow-standards, and the newly established total maximum daily load (TMDL) limits to achieve water quality standards on selected streams (http://www.kdhe.state.ks.us/tmdl/), will provide additional needed protection to the riverine-riparian ecosystem.

DWR and the Kansas Water Office (the state's water planning agency) have initiated a comprehensive basinwide-management program in areas of Kansas with significant water problems. A holistic and proactive approach, as well as close consultation and cooperation with the local districts, irrigators, and other interested parties are integral parts of this program. The Kansas Geological Survey assisted in the program's development by developing and applying integrated watershed and ground-water models (Perkins and Sophocleous, 1999; Sophocleous et al., 1999; Ramireddygari et al., 2000). [For a general overview of the approach and results of this methodology, the reader is referred to Sophocleous and Perkins (2000)]. The approach taken by DWR and the basin-working group was that of incentive-based alternatives to affect change in target, problem areas within the basin.

The City of Wichita has also developed an innovative Integrated Resource Planning program (Warren et al., 1995), which includes both conventional and non-conventional local water supplies to meet projected demands, such as capturing excess-flow river water and river bank storage water from the Little Arkansas River on an as-available basis. This water is being recharged and stored in the Equus Beds aquifer, just north of Wichita, Kansas to be recovered in times of drought. The plan established a priority of water use, whereby water that would normally flow through the area would be used first, saving slowly replenished water resources for times when the first-priority water is not available (Stous et al., 1999). [For additional information on this project, the reader is referred to the project web page, maintained by the US Geological Survey (http://www-ks.cr.usgs.gov/Kansas/equus/).]

The progressive evolution of Kansas water management, which incorporates local GMDs and their water-management programs, minimum-streamflow standards, the water use reporting and water metering programs, the use of modified safe-yield policies in some districts, the integrated resource planning by the City of Wichita, and the DWR subbasin water-resources-management program, as well as other programs, are all appropriate steps toward the attainment of sustainable development. Additional information on Kansas water management, policies, and agencies is provided in Sophocleous (1998a).

6. Concluding comments and outlook

In the past, the volume of recharge to an aquifer was accepted as the quantity of water that could be removed from an aquifer on a sustainable basis, the so-called safe yield. We now understand that the sustainable yield of an aquifer must be considerably less than recharge, if adequate amounts of water are to be available to sustain both the quantity and quality of streams, springs, wetlands, and ground-water-dependent ecosystems. Sustainable resource management is managing ground-water for both present and future generations, and providing adequate quantities of water for the environment. Quantifying what these environmental provisions are is presently an urgent research need. Ground-water management responses in areas of over-extraction must include bringing use back to sustainable or at least community-acceptable levels while exploring more sustainable options. In other areas, ground-water management needs to adapt to working within the finite limits set by the goal of sustainability. Wise management of water resources needs to be approached not only from the viewpoint of focussing on the volume of water available for sustainable use, but also from the impact of ground-water exploitation on the natural environment.

It is now recognized that a comprehensive and integrated approach to the management of ground-water resources is required if their quality and supply are to be sustained in the longer term, and other ecosystems dependent on ground water are to be protected. However, because of their interdependence, ground water cannot be managed separately from surface waters. To ensure sustainability of aquifers, it is imperative that water limits be established based on hydrologic principles of mass balance. Because of uncertainties and spatio-temporal variabilities of key controlling variables (such as recharge and other hydrologic-budget components), sustainability assessment should be understood as a dynamic and iterative process, requiring continued monitoring, analysis, prioritization, and revision. The progressive evolution of water management policies in the Kansas GMDs (Sophocleous, 2000) and the state in general, offer a real-world example of community-acceptable measures in the ongoing pursuit of the goal of water sustainability.

Management of natural resources has developed significantly during the past few decades. In particular, numerical modeling became an indispensable decision tool in ground-water management. Such models can generate the transition curve from storage depletion to induced recharge from surface-water bodies for the system under consideration, so that management plans and planning horizons can be thoroughly assessed. However, the reliability of such models suffers from the uncertainty of their input parameters. Because of the strong spatial and temporal variability of important primary variables in such models, the estimation of key parameters such as recharge will be a predominantly statistical undertaking. Therefore, quantification of risk and uncertainty will increasingly be of major importance to ground-water management. Present trends in the use of models for water-resource management purposes include greater use of more sophisticated models that increasingly integrate land, vegetation, climate, and water interactions. Such models also capitalize on recent technological improvements with the development of graphical user interfaces and decision-support systems, taking advantage of the continuing development of Geographic Information Systems (GIS) and visualization technologies. The design and implementation of such models has already been initiated in Kansas (Perkins and Sophocleous, 1999; Sophocleous et al., 1999; Ramireddygari et al., 2000; Sophocleous and Perkins, 2000) and elsewhere.

Local decision-making is considered the preferred route to water management as is indicated by the establishment of local GMDs in Kansas and elsewhere. Because local conditions vary significantly within the High Plains region, environmental differences affect water availability and use. Detailed water-management plans will necessarily be subregional to adequately adjust to local conditions. As Zwingle (1993) aptly stated, communities want to solve their problems, but not using rules that apply to somebody else.

The solution of regional and local water problems requires education, technical assistance, and supporting research. It is imperative that the community at large participates in policy formulations and in judgments of what is to be sustained. Strong public education and outreach programs are needed to improve understanding of the nature, complexity, and diversity of ground-water resources, and to emphasize how this understanding must form the basis for operating conditions and constraints. This is the only way to positively influence, for the long term, the attitudes of the various stakeholders involved. Pressure from the community for better management of our natural resources will be the main driving force for most changes.

As we confront the water problems of the present, armed with greater scientific and technological power than before, and with the benefit of hindsight, we have a better sense of the complexities inherent in our choices. This allows us to manage in a more strategic and integrated way, no longer committed to simplistic solutions but able to take a wise and balanced view of water resources as we strive to achieve sustainability in the management of our water resources.

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