WATER AND SCIENCE

PROCEEDINGS OF THE
NEW MEXICO WATER RESOURCES RESEARCH INSTITUTE SYMPOSIUM

Macey Center
New Mexico Institute of Mining and Technology
Socorro, New Mexico
February 15, 1985

New Mexico Water Resources Research Institute
New Mexico State University
Las Cruces, New Mexico

Proceedings Editor: Linda G. Harris
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PREFACE

It had been some time since anyone had focused strictly on the "science" side of water resources, so the standing room only crowd that met for one beautiful February day in Socorro, was an eager audience. The Water and Science Symposium was designed to give them an in-depth look at how science meticulously explores the "whys" of water resources and how scientists in turn use those facts to answer the larger questions in water resources.

The symposium began with lessons on how scientists can get their message across to Congress. Russell R. Brown, who is on the Senate Energy and Natural Resources Committee staff, presented a straightforward, practical approach on talking to Congress. He also provided insight into the types of scientific information that is most beneficial to policymakers.

Then the participants were taken on a hydrologic tour of water research, beginning with weather modification and snow surveys and ending with studies on ground water recharge. Bernard A. Silverman, of the U.S. Bureau of Reclamation, documented the fortunes and features of weather modification and described how the techniques fit into the scheme of water resources management.

Scientists then provided a detailed look at several approaches to water management. Peter J. Wierenga presented research on innovative techniques in drip and trickle irrigation. Robert B. Hulsman covered surge flow irrigation from an agricultural engineering approach. Researchers Bill Melton and Gregory Phillips talked about the plant development approach to water management. Melton described the techniques used in long-term plant breeding research, while Phillips talked about "instant" plants regenerated through cell culture research.

Geoscientists then talked about the difficulties in dealing with an underground resource--ground water. Daniel B. Stephens presented research findings on determining recharge in naturally arid terrains. Fred Phillips discussed his research on the chemical considerations in ground water recharge.

The symposium participants, by their attention and follow-up questions, demonstrated their interest in knowing how science is helping solve New Mexico's water resources problems. Special thanks should go to the Water Conference Advisory Committee for realizing the need for this forum and taking an active role in supporting it.

Thomas G. Bahr
Director

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Russell R. Brown
Stanley E. Cook
Robert B. Hulsman
Bill A. Melton
Fred Phillips
Gregory C. Phillips
Kyle E. Schilling
Bernard A. Silverman
Daniel B. Stephens
Edwin P. Weeks
Peter J. Wierenga

1985 Water and Science Symposium

Macey Center
New Mexico Institute of Mining
and Technology
Socorro, New Mexico

FRIDAY, FEBRUARY 15

8:00 - 8:45 Registration (Lower Lobby)

9:00 - 9:05 Welcome (Galena Room, Upper Level)
Thomas G. Bahr, WRRI

9:05 - 9:25 Between Science and Policy
Russell R. Brown, Staff,
Senate Committee on Energy
and Natural Resources,
Washington, D.C.

SESSION I: WATER AND THE WEATHER!

Moderator: Conrad Keyes, Department Head, Civil Engineering, New Mexico State University

9:25 - 9:45 Weather Modification
Bernard A. Silverman, Chief, Division of Atmospheric
Resources Research, Denver

9:45 - 9:55 Questions

9:55 - 10:15 Snow Survey Forecasting
Stanley Cook, Assistant State Conservation Engineer,
Soil Conservation Service,
Albuquerque

10:15 - 10:25 Questions

10:25 - 10:40 BREAK

10:40 - 11:00 Flow Forecasting
Abdulsattar R. Al-Dabagh,
Civil Engineering, New Mexico State University

11:00 - 11:10 Questions

SESSION II: WATER MANAGEMENT

Moderator: Robert R. Lansford, Professor, Agricultural Economics, New Mexico State University

11:10 - 11:30 Trickle Irrigation of Chile Peppers
Peter J. Wierenga, Professor,
Crop and Soil Sciences, New Mexico State University

11:30 - 11:40 Questions

11:50 - 1:15 LUNCH (Upper Lobby)

1:15 - 1:35 Surge Flow Irrigation
Robert B. Hulsman, Assistant Professor, Agricultural Engineering, New Mexico State University

1:35 - 1:45 Questions

1:45 - 2:05 Water Efficient Crop Development
Bill Melton, Professor,
Crop and Soil Sciences, New Mexico State University

2:05 - 2:15 Questions

2:15 - 2:35 Genetic Engineering for Drought Tolerance
Gregory C. Phillips, Assistant Professor, Horticulture, New Mexico State University

2:35 - 2:45 Questions

2:45 - 3:05 Water Management for Conservation
Kyle Schilling, Chief, Policy Studies Division, Institute of Water Research, U.S. Army Corps of Engineers,
Fort Belvoir, Va.

3:05 - 3:15 Questions

3:15 - 3:30 Break

SESSION III: GROUND WATER RECHARGE

Moderator: H. L. Case III, Assistant District Chief, U.S. Geological Survey, Albuquerque

3:30 - 3:50 Physical Considerations in Ground Water Recharge
Daniel B. Stephens, Associate Professor, Geoscience, New Mexico Institute of Mining and Technology

3:50 - 4:00 Questions

4:00 - 4:20 Chemical Considerations in Ground Water Recharge
Fred Phillips, Assistant Professor, Geoscience, New Mexico Institute of Mining and Technology

4:20 - 4:30 Questions

4:30 - 4:50 Artificial Recharge
E. P. Weeks, Hydrologist, Water Resources Division, U.S. Geological Survey, Denver

4:50 - 5:00 Questions

5:00 Closing Remarks
Thomas G. Bahr, WRRI

SPEAKER PREVIEW

1985 Water and Science Symposium

Abdulsattar R. Al-Dabagh is a graduate student in civil engineering at New Mexico State University. Previously, he worked for the Ministry of Irrigation for the Al-thar thar Reservoir project and for the Al-Latifia Irrigation and Drainage project in Iraq. The May 1985 doctoral candidate received an M.S. in civil engineering from Colorado State University and a B.S. in agricultural engineering from the University of Baghdad, Iraq.

Thomas G. Bahr has been director of the New Mexico Water Resources Research Institute since 1978. In 1982-83, he was director of the Office of Water Policy, which was established to address water issues related to Interior Department responsibilities. Before coming to New Mexico, he was director of the Institute of Water Research at Michigan State University. He holds degrees from Michigan State and the University of Idaho.

Russell R. Brown is on the professional staff of the U.S. Senate Subcommittee on Water and Power, Committee on Energy and Natural Resources. The subcommittee's jurisdiction includes irrigation and reclamation projects in the 17 western states, marketing power from federal hydroelectric projects, and energy development impacts on water resources, small power producers, and hydroelectric power. From 1968 to 1970, he was on the personal staff of the late Sen. Henry M. Jackson.

H. L. Case III is the assistant district chief, Water Resources Division, U.S. Geological Survey, in Albuquerque where he supervises water resources investigations in New Mexico. He has been with the USGS since 1973 and has had assignments as a hydrologist in Louisiana and South Dakota. He has a B.S. in geological sciences from the University of Texas and an M.S. in geology from Oklahoma State University.

Stanley E. Cook is the assistant state conservation engineer for the Soil Conservation Service (SCS). His 20 years in the SCS include positions as a field engineer, project engineer and area engineer in Montana, Idaho and New Mexico. He is a registered professional engineer in Montana and New Mexico. He has a bachelor's degree from Montana State University.

Robert B. Hulsman is an assistant professor of agricultural engineering at New Mexico State University specializing in irrigation and drainage systems. He came to NMSU in 1979 after receiving his Ph.D. in agricultural engineering from Utah State University. He also holds a master's degree from Utah State and a bachelor's degree from the University of Nebraska at Omaha. Hulsman is retired from the U.S. Air Force and for five years was in commercial aviation.

Conrad G. Keyes, Jr. is head of the civil engineering department at New Mexico State University. His research interests include weather modification, solar evaporation and geothermal applications. He is a registered professional engineer and certified weather modification operator. His professional memberships include the American Institute of Hydrology, the American Meteorological Society and the Weather Modification Society. The Roswell, New Mexico, native holds a B.S., an M.S. and a Ph.D. from NMSU, all in civil engineering.

Robert R. Lansford is professor of agricultural economics and agricultural business at New Mexico State University. He was project coordinator for the New Mexico state-level research on the High Plains Ogallala Aquifer Study. He is a delegate to the Universities Council on Water Resources, an alternate to the High Plains Study Council, and a member of the Great Plains Natural Resource Economics Committee and the Great Plains Council on Energy Committee. He holds degrees from the University of Minnesota and from NMSU.

Bill Melton is a professor in New Mexico State University's crop and soil sciences department. In his 17 years as an alfalfa breeder, he has written 173 publications on alfalfa breeding and production. He has received NMSU's Distinguished Research Award and Distinguished Graduate Teacher Award and Northrup King and Co.'s Distinguished Research Scientist Award. He also is a fellow with the American Society of Agronomy. He holds a B.S. from NMSU and a master's and doctorate from the University of Illinois.

Fred Phillips is assistant professor of hydrology at the New Mexico Institute of Mining and Technology. His research experience includes using isotopic methods for the study of ground water recharge and flow, identifying the origin of geothermal fluids in the Valles Cauldera of New Mexico, and studies of very old ground water in the Great Artesian Basin of Australia. He is a native Californian and a graduate of the University of California at Santa Cruz. He also holds an M.S. and a Ph.D. in hydrology from the University of Arizona.

Gregory C. Phillips is an assistant professor of horticulture at New Mexico State University specializing in plant tissue culture and cell genetics. Since 1983, he has served as interim director of the Plant Genetic Engineering Laboratory for Desert Adaptation at NMSU, one of the newly established centers for technical excellence participating in the state's Rio Grande Research Corridor. The Kentucky native holds a Ph.D. from the University of Kentucky in crop science with a major in plant breeding and genetics and a minor in plant physiology.

Kyle Schilling is chief of the Policy Studies Division, Institute for Water Resources, U.S. Army Corps of Engineers. He specializes in water resources management, river basin planning and water supply and conservation planning techniques. He also has directed a watershed planning party for SCS projects. The Pennsylvania native holds a B.S. in civil engineering from PENN State University. He also has done graduate work in civil engineering at the University of Nebraska.

Bernard A. Silverman is chief of the Division of Atmospheric Resources Research at the U.S. Bureau of Reclamation in Denver where he directs a national and international research program on precipitation enhancement technologies for extending and augmenting fresh water supplies. Silverman, who holds four meteorological patents, serves as the bureau's top expert in atmospheric sciences and weather modification. The New York native holds a B.S. in meteorology from the City College of New York and a master's and doctorate from the University of Chicago.

Daniel B. Stephens is an associate professor of hydrology and chairman of the geoscience department at the New Mexico Institute of Mining and Technology. He holds a B.S. with honors from Pennsylvania State University where he was named Outstanding Senior in the College of Earth and Mineral Sciences. He also holds an M.S. from Stanford University and a Ph.D. from the University of Arizona, both in hydrology. He is a member of the American Geophysical Union, the National Water Well Association and the Soil Science Society of America.

Edwin P. Weeks is chief of unsaturated field zone studies in the Water Resources Division (WRD) of the U.S. Geological Survey. His research includes studies on anisothermal vapor transport in unsaturated media and on methods for determining unsaturated zone flow properties. Other research in his nearly 27 years in the WRD include spreading and well injection tracer experiments in Texas and the effects of ground water development on streamflow in Wisconsin. He holds a B.S. in geological engineering from the Colorado School of Mines.

Peter J. Wierenga is a professor of crop and soil sciences at New Mexico State University. His research interests include irrigation management and trickle irrigation. In 1982 he received the Westhafer Award for Excellence in Research at NMSU. He also is the recipient of the Outstanding Research Award from the College of Agriculture, NMSU. Wierenga, who was born in Uithuizen, The Netherlands, received a B.S. and an M.S. from the Agricultural University, Wageningen, The Netherlands. He holds a Ph.D. from the University of California at Davis.

BETWEEN SCIENCE AND POLICY

Russell R. Brown
Professional Staff
Subcommittee on Water and Power
Committee on Energy and Natural Resources
United States Senate

I would like to express my sincere appreciation to Dr. Bahr for providing me with this opportunity to address the participants of the "Water and Science" Symposium sponsored by the New Mexico Water Resources Research Institute. I also would like to thank Dr. Benjamin S. Cooper, professional staff on the Senate Energy and Natural Resources Committee and also adjunct professor of physics at the American University, for his thoughtful discussions with me during the preparation of my remarks.

When Dr. Bahr first mentioned the symposium during a conversation last November, I was enthusiastic about getting out of cold Washington D.C. for a couple of days in the warm Southwest.

I also was enthusiastic about the invitation as it permits me to be with a different kind of people than those I usually associate with. It is exciting to converse with people who, just perhaps, might admit that they don't have the ultimate answers to all the world's problems.

To inform, or to influence? That is the decision all of you as members of the scientific community must make if you want to become involved with policy.

For the purpose of helping me discuss the relationship between science and policy, I will use two, very loose definitions. First, and I know this will raise some question, I will define "science" as a community consisting of those members of the physical sciences ranging from bench-work basic researchers to members of the engineering professions. And second, I will define "policy" or policy making as what happens where I work--the United States Senate. Policy making is usually expressed in the form of public laws or appropriation of funds--each ostensibly in the name of the public good. Of course, policy is made at various levels in our system of government from international and national to regional, state, and local levels. I chose the Senate, because that is where I work.

Science and policy share a common goal--the satisfaction of the public good. Science is traditionally described as a guest for Truth (with a capital "T"). A rational policy process would implement that truth in the name of the public good. But this is an imperfect world and not only is the discovered truth questioned, the communication of that truth by the scientific community to the policy makers is often suspect--as is the rationality of the policy process.

Science is expected to contribute to the satisfaction of very material basic needs: food, health, energy, shelter, and a benign environment. I would add to that list, protection from results of science itself and the unwanted and unintended side effects of applied technology such as pollution, hazardous waste, and so on.

The impact of science on policy is twofold: The first is accounted for by what science does best--discovery and verification, which lead to innovation, which leads to change. Scientific discovery and innovation have had more impact on public policy than any other single factor I can think of, except perhaps religion.

Members of the scientific community may often lament that they are not able to influence public policy. They may feel frustrated.

That may be true to the extent that they try to participate in the policy process. However, what they fail to recognize is how scientific and applied technology have shaped policy through discovery, implementation, and social change. We speak of a nuclear world and a computer society, the TV generation, and the green revolution. Related policy often is the result, response, or reaction to science.

The second impact of science on policy making is when science is called upon to offer advice. Historically, the scientific community was viewed as being able to supply the answer or solution to a problem. Some of you may have heard of Technocracy, Inc., a quasi-political party that enjoyed some popularity during the 1920s and 30s. The party was premised upon a government and social system controlled by scientific technicians.

Technocracy, Inc. was dependent upon the concept that science was disinterested, neutral and committed solely to its own impartial independent search for truth. When called upon, science would offer to the rational policy maker a solution or range of choices leading to the selection of a policy that logically would further the public good.

As we all know, science is only as impartial as the members of the scientific community. As for rational policy making, Technology, Inc. certainly is not represented in Congress. However, that is not to say that Congress does not search for the basis upon which to make rational policy decisions.

In the 1980s, Congress found itself dealing with complex issues based on technological choices. The triggering mechanism was the overriding concern with the environment and Congress was called upon to make judgement calls on subjects far removed from previous policy matters. Although the decision process remained the same, the subject matter dealt with the more complex questions of scientific knowledge and technology application. The adversarial and often compromising process that had served Congress so well in the past began to come under question. The process broke down when Congress faced the complexity of policy decisions for programmatic efforts for clean water, clean air, and problem specific efforts such as the supersonic transport or long-lived pesticides.

A technologically ignorant Congress found itself called upon to make hard decisions in the face of soft information and often in the context of restrictive time tables and deadlines. Congress looked to science to provide clear and concise directions for the establishment of policy but realized too, that the scientific community was subject to the same biases and foibles as Congress. Certainly, in the arena of the public hearing, you can find as many views as you want. Hear five experts and you will have 10 opinions. Congress wanted an unbiased advisory group--certainly something that does not normally surface during the hearing process. I would cite, for example, the most recent tobacco adventure and the relationship between smokeless tobacco and health hazards where you have scientists involved with public health.

Congress had no systematic way to get the detailed information it needed to study issues. So in 1972, Congress established a bipartisan agency called the Office of Technology Assessment (OTA). The assignment at OTA was to regularly advise Congress about scientific and technological developments having a bearing on national policy. Congress believed that OTA was to be the neutral, unbiased information source Congress needed in the policy making process.

The OTA has had a checkered career; it's occasionally referred to as the Office of Technology Arrestment or the Office of Technology Harrassment. However, the OTA has had a significant impact and has provided useful analysis to Congress on decisions relating to alcohol fuels, the synthetic fuels program, solar power satellites, the nuclear weapons program and so on. But OTA has also provided information that became lost or ignored when submerged in the political process--a prime example would be the OTA study on coal slurry pipelines.

In turn, policy directly impacts science. That impact may take two major forms. The first is the policy statement that commands action. Directives such as "Go forth and design a car that will get 28 miles a gallon", or "Land a man on the moon within such and such time," were policy dictated. However, when the policy statement was presented to Congress, it was often made in the absence of absolute scientific solutions. These directives reflect a great faith on the part of Congress in the scientific community's ability to fix a problem or find a solution. In my opinion, the scientific community has demonstrated a remarkable ability to meet these challenges.

On the other hand, there is the negative policy statement that says don't do something. This statement restricts or prohibits a direction of scientific research such as germ warfare or Sunday supplement genetics experiments. The latter reminds me of one of my favorite scenes from old black and white horror movies when the leader of a peasant mob, armed with wooden pitchforks and carrying torches, confronts the mad scientist and tells him he is trespassing into areas of knowledge that man was not meant to know.

The second direct major impact is that policy statement that strikes fear in the heart of the entire scientific community--"I am sorry, but there are no grant funds available." Since World War II, the impact of the federal government on science has been primarily through research funding. Most funding is goal oriented, but the federal government is also the principal source of funding of science for science's sake. The tremendous growth in federal funding following World War II peaked at about $23 billion in 1967. Funding declined a little and then held steady until 1985 when federal support reached $53.3 billion or about $20 billion of those constant dollars economists love to talk about. For fiscal year 1986, we have a budget request of $57.6 billion. This amount represents real growth since the low point in 1972 of about 28 percent or a 4 percent increase over 1985. This is not a bad increase considering the $200 billion plus deficits facing the federal government. In comparing the 1986 request to the 1985 request, many other federal programs are frozen or cutback. Research and development has a 4 percent real increase. Sounds good. But stop right there.

Whose growth is this? Where has the real growth in research and development funding occurred? The Department of Defense share--whether or not we use a constant dollar--has grown from 51 percent of the 1967 total to 70 percent of the 1985 total. In percentages, the National Aeronautics and Space Administration portion has declined and the share for what we will call science for science's sake has been almost flat.

We now have a real world policy statement--in the form of funding--which will impact science. You have it every year. You, as members of the scientific community must choose whether to inform or to influence. I detect enough interest in the audience to know that you will definitely try to influence them. I will not get into the question of whether you as members of the scientific community are above the mundane in search of that Truth (with a capital and "T"), and will lower yourselves to chase a buck. Frankly, you don't have a choice. You have to enter the policy process even if its from the standpoint of enlightened self-interest.

So how can you effectively enter into the policy process? Here I will make a judgement call that the procedure holds true whether it is an attempt to influence funding or policy directives. The process is the same. Being rational men and women of science, you probably would assume that the process of policy is rational also. Simply place your unbiased views before Congress and it will come to the same conclusion you have.

Unfortunately for you, the interests of Congress often lie elsewhere. Congressman George Brown, past chairman of the Subcommittee on Science, Research and Technology of the House Committee on Science and Technology, has succinctly stated Congress' view that: "There is little political mileage to be earned for supporting scientific research."

I will admit that members of the scientific community do receive great respect when testifying before congressional committees. The men and women of science do get the time and attention, but you are not all Carl Sagans or Edward Tellers. I would urge that you take to the challenge of influencing policy, the same set of tools that have been used by the scientific community in tackling any other problem.

Do a little backgrounding--a little basic research on the process itself. Find out with whom will you have to deal. First, Congress is generally composed of non-scientists--mostly lawyers with undergraduate degrees in the humanities. (I am not a lawyer, by the way.) Yet, they will be called upon to write, in this Congress, laws on issues such as energy, health, environment, and genetics. You can try to educate them as have others. In the third week in January, a most extraordinary event took place in Washington, D.C. The American scientific community, in an attempt to educate newly elected members of Congress, held a two-day seminar and invited the 43 newly elected members. Only six showed up for even part of the sessions. They were joined by five members returning for second terms. At most times, only one or two members were present. The only congressman who attended all of the sessions was an ex-history professor. The scientists were a Who's Who: Lewis Thomas, pioneer cancer researcher; Leon Lederman, physicist and head of Fermilab; Maxine Singer, molecular biologist at the National Cancer Institute; Joshua

Lederberg, Nobel laureate in genetics; John Tukey, statistician from Bell Labs and Princeton; and Robert Hirsch, former head of the federal fusion energy program and now with Arco Oil and Gas.

In summing up the poor attendance, former Representative James Symington said, "(A congressman) is an empty vessel who enjoys being empty and really doesn't care to be filled. I'm not talking about their throats or their treasuries. It's hard enough to get members (of Congress) to come to their own hearings." When faced with that kind of a response to an event sponsored by such prestigious organizations as the National Academy of Science, the American Association for the Advancement of Science, the American Chemical Society and the Institute for Electrical and Electronics Engineers, what can you do?

Face the fact, you will be a lobbyist, so take a few pages from the lobbyist's handbook. From the above incident, it is evident that it is difficult, if not impossible, to educate Congress en masse. You will have to use a rifle instead of a shotgun.

First find a member of Congress who thinks, for whatever reason, as you do. Do a little research on voting records and public statements. Then offer your support. Because he is already inclined to your views, he probably eats up whatever you say or offer.

After all, from his standpoint, you are his supporter and he will value a scientist in his corner. Your prestige will lend weight to his position. In turn, don't be dismayed if later on you find that your carefully crafted arguments and meticulous research are distorted or taken out of context. Such is the nature of the political policy making process.

You have now selected a champion. The nature of Congress is that in many circumstances, it only required one individual to have a profound inpact on policy. There are the obvious attributes of power and influence--a committee chairman, a senior member, a nationally recognized figure. But there is also shear tenacity as well as the aura of respected authority which surrounds an individual who is conversant with the background of an obscure or technologically complicated subject. It is up to you to provide the wherewithal for the development of that respected authority.

However, you must also realize the constraints that members of Congress, and therefore you, will have to operate under as part of the policy process.

I mentioned earlier that Congress is often called upon to make policy decisions based upon soft data. This condition is partly self-imposed and partly in response to the immediacy of problems as they are perceived by their constituency. There are cyclical patterns of legislative activity and inactivity with which you must conform if you are to influence the policy process. Looking at the ebb and flow of activity as Congress seeks to meet the deadline imposed by the budgetary process reminds me of a scene I witnessed a few years ago.

A co-worker and I, one evening after work, had adjourned to a bar on Capitol Hill for a short libation. We were seated in a corner of the bar when we noticed an impeccably dressed, attractive young lady-- who was unaccompanied--take a seat in the bar. As I recall, she was drinking white wine.

During the next hour or so, she was approached several times by young men, but each time with a demure smile she refused their advances. But, by this time, she had consumed several glasses of wine and had switched to a concoction that looked like a chocolate milkshake. There began a most interesting transformation as her immaculate coiffure assumed that of Broom Hilda in the comics, her eyes adopted the focus of Jack Elam, and she slumped onto the bar. At that moment, there appeared on the scene a man about my age, my shape, and with only a little more hair. There was a brief conversation and they left together.

The lesson to be learned: timing. Just as in that little scene, timing is crucial in the influence of the congressional policy process. You--or at least your information--must be there to have an impact. I recall a earnest request by a constituent to have funds for a certain project included as a part of an appropriations bill. The bill had in fact been approved by the Congress and sent to the president the week before. The train had left the station.

Just as you had to select your member target and time your input, so must you shape your information to suit the needs of the member and the circumstances of the policy process. Congressmen are notorious for being overscheduled and you should not be disappointed if the presentation which you had so laboriously prepared using visuals and multi-colored handouts is reduced to a two-minute conversation on an elevator. However, other access terminals to the policy process either through personal testimony or information supplied for a written record are often used by relevant committee staff, personal staff, and in public hearings. You must be prepared to use them all. You may even wish to have a layman review your written materials in anticipation of the non-technical audience. Assisting Congress is no different than trying to help anyone else. Make your case, but by all means be brief in your initial presentation. You will not generate further interest if you overwhelm your target; rarely does a congressman have the time to spend more than a minute or two reviewing background information in his initial exposure to a problem. Two well-thought-out pages can do wonders.

If possible, draw a relationship between your interest and the member's constituency. In that initial briefing paper or presentation, show how an issue is relevant to the people who elected the individual to public office. A quick example: a research group is interested in how to prevent saline ground water intrusion in wells drilled in western Kansas. This or a similar problem confronts many of the coastal urban areas in the eastern United States and those areas could benefit from the western Kansas experience. Let those easterners know what you are doing and cite the problems of their own districts in your briefing.

And finally, there is an "old boy" institutional network in the scientific/academic community that has infiltrated both the bureaucracy and Congress. You can't beat being able to pick up the phone and call someone who knows you, who may have some familiarity with the problem, and who, in fact, may be in a position to help. To the extent that you can work through your professional associations, do so. But it is likely that a time will come when you will be at odds with your peers as to policy, or at least in competition with them.

As scientists, you face a two-headed challenge. The pursuit of knowledge and a quest for truth in the eighteenth century tradition, and the contemporary twentieth century reality of $200 billion deficits. You do not have a choice, you must become involved with the policy process.

I hope this converstion has given you some insight into that process and encourages you to become active participants.

WEATHER MODIFICATION

Bernard A. Silverman
Chief, Division of Atmospheric Resources Research
Bureau of Reclamation

Introduction

I appreciate this opportunity to appear before you and discuss the subject of weather modification. I am especially pleased that the subject of weather modification shares the agenda with other water management techniques. Indeed, precipitation management is a water resource tool to be managed on a year-round basis as any other component of the total water management system. Precipitation is a renewable atmospheric resource that should be properly managed to better serve society's needs.

Unfortunately, too many potential users and policymakers view weather modification only as a drought-relief measure. Funding for research and operational programs increase during drought periods, apparently with the expectation that water deficits that took years to develop will be quickly replenished. Weather modification is often invoked as a desperation measure, perpetuating the "hydro-illogical" cycle (figure 1). This is encouraged, in part, by the quick reaction time and relatively low cost of weather modification operations in contrast to other potential drought-relief measures, so weather modification serves as an inexpensive means of showing the public that something is being done about the situation. However, apathy in the hydro-illogical cycle must be replaced by constructive planning and preparation for drought to lessen its impact. Weather modification can and should play an important role in such a water management system by augmenting and recharging water supplies whenever the opportunities arise and the situation warrants.

Cloud seeding is but one of several resource management tools available to help meet critical water needs. It does not preclude

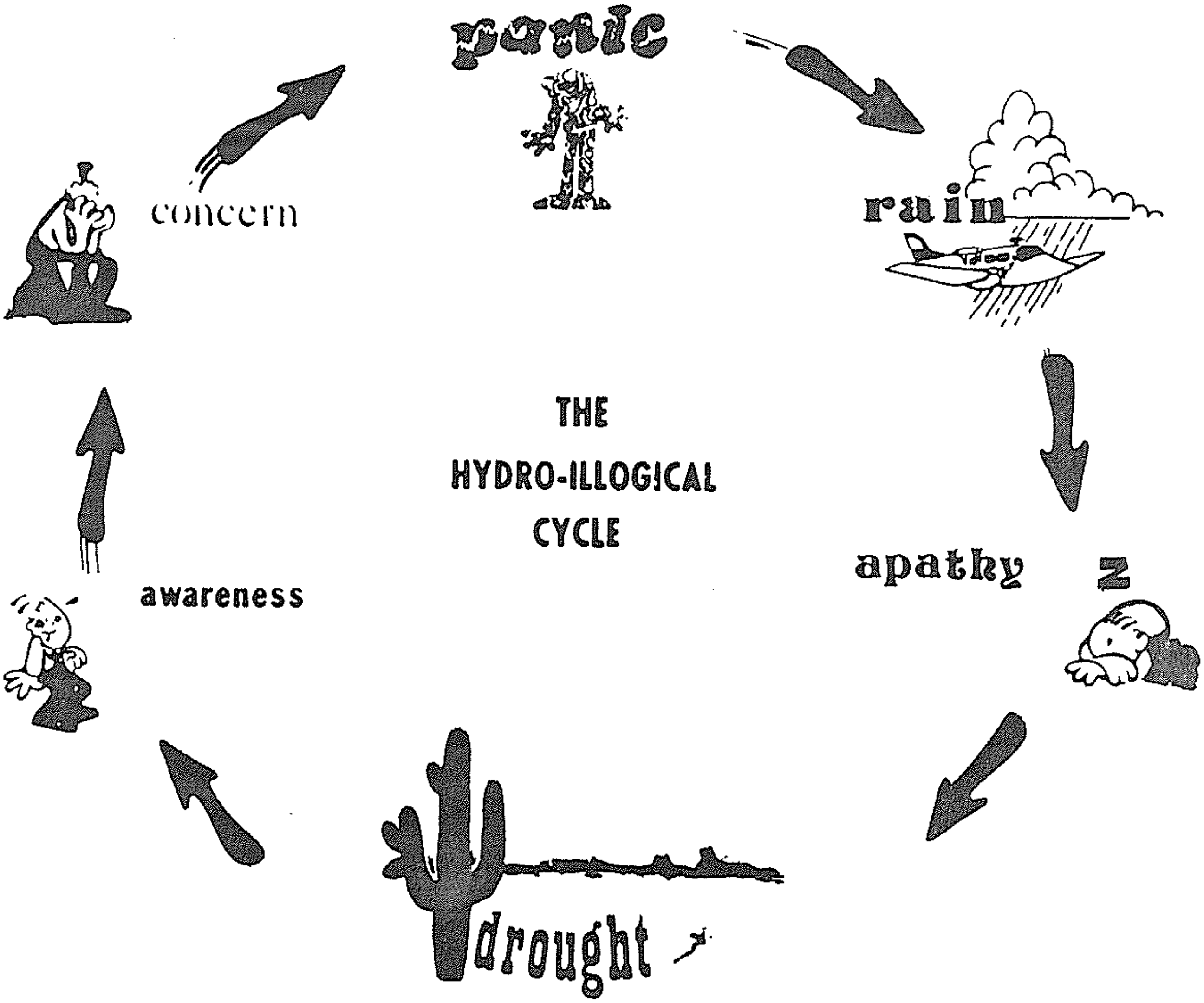

FIGURE 1. THE HYDRO-ILLOGICAL CYCLE.

continued planning and development of other water management alternatives, nor does it lessen the commitment to improve water conservation practices. However, the cloud seeding alternative does have many unique and attractive features. Currently, it appears to be the most cost-effective means of securing additional water. Cloud seeding does not require major, permanent construction and large-fixed operation and maintenance costs. Moreover, a decision to employ cloud seeding is reversible on a year-to-year, even storm-to-storm, basis within a season, should local hydrology, weather patterns or public interests so dictate.

Today I will briefly review the status of weather modification and highlight the recent worldwide and national activity in the application of weather modification.

State-of-the-Science

Assessments of the state-of-the-science of weather modification vary depending on the risk level assumed which, in turn, depends on the standards of their authors and/or on the audiences for which they are intended. It is no wonder then that the assessments published by the American Meteorological Society and the World Meteorological Organization tend to be conservative, while the assessment published by the Weather Modification Association is more optimistic. The former organizations apply the rigorous standards of scientists, while the latter applies those of the commercial operators it represents.

Users of weather modification must and do apply standards that are commensurate with the risk levels that are common to their businesses. The risk levels of users such as farmers tend to be considerably higher than those of scientists. The need for more rain and less hail has created a demand for cloud seeding even in the face of sometimes outspoken scientific skepticism. Thus, while the research community is laboring to place weather modification on a secure scientific foundation, people with major weather interests at stake are applying current knowledge and investing in operational cloud seeding. These users and their supporters are attempting to reap the benefits of an emerging technology believing that the scientific risks and costs are small in comparison to the benefits to be gained.

All parties, including the public, must realize that we cannot be totally sure about the outcome of cloud seeding with our current knowledge. The best we can do is to find situations where cloud seeding can be done within risk levels acceptable to the individual user to achieve the desired outcome. Some techniques to achieve such results are now available for use, and more can be expected in the future.

Weather modification has the potential for improving atmospheric conditions for the benefit of society. The accumulating evidence indicates that weather modification shows promise for increasing water supplies, reducing hail and wind damage, reducing transportation delays, and reducing the loss of life and property associated with weather hazards. The most comprehensive review of the state of knowledge and potential of weather modification was performed in 1978 by the Weather Modification Advisory Board. This board of distinguished scientists and community leaders was appointed by the Secretary of Commerce to make recommendations concerning a national policy and program of research and development in weather modification pursuant to Public Law 94-490. Its 1978 report, "The Management of Weather Resources", cited the following capabilities as evidence of the potential for realizing the benefits of weather modification in the near future:

1. Supercooled fog and stratus can be seeded to improve visibility.
2. Holes can be opened in winter stratus clouds to increase the amount of solar radiation that reaches the ground.
3. Snowpack, and thus the spring runoff, can be increased by seeding winter-time clouds rising over some mountain barriers.
4. Rainfall is increased in Israel by seeding winter cumulus clouds; seeding convective rain bands in winter cyclonic storms over California (the nearest United States analog to the successful Israel experimental) also suggests positive results.
5. Rain can be induced from some types of summer cumulus clouds, and their precipitation apparently can be increased by intensive seeding to increase the size of the clouds ("dynamic seeding").

6. Hail suppression is attempted in many countries, with claims of up to 80 percent success in the Soviet Union. United States experiments have provided no convincing evidence, but evaluations of several projects suggest that hail damage from some kinds of storms can be reduced.
7. There is no evidence that increases in rain or snow in one area decreases them in nearby areas.

The advisory board concluded that a usable technology for significantly enhancing rain and snow and ameliorating some weather damage is scientifically possible and within sight. They expressed the view that prudent steps should be taken as soon as possible to strengthen investigations of these possibilities and recommended a 20-year program of action to achieve it. The centerpiece of this program was the development of cloud seeding to make more rain and snow in the right places at the right times. In particular, they focused on winter snowpack augmentation stating that:

> In terms of scientific and technological underpinning, and in consideration of probable high economic value, it is the judgment of this Board that seeding winter orographic storms to increase the amount of snow in the high mountainous watersheds of the West is the most advanced--and closest to significant, broad-scale operational use--of all cloud seeding possibilities. A successful confirmatory experiment--including, of course, provision for assessing the seeding results--must be completed before large-scale seeding of winter orographic storms is considered to be an acceptable tool, available to water resource decisionmakers.

The advisory board recommended that the federal government should develop a coherent, long-term research and development program and organize seriously for the effort, which they indicated should be a national commitment. Despite several legislative and executive initiatives, the board's recommendations have not been implemented, nor are they likely to be in the near future without participation and cost sharing by the prospective beneficiaries of the technology.

Review of Weather Modification Activities

The federal research programs in weather modification are dedicated to developing reliable and acceptable technologies that are of benefit to society. The federal appropriation in support of weather modification totals $9.7 million in fiscal year 1985, a little more than half of what it was five years earlier. These funds are, at this time, entirely devoted to research and development of precipitation enhancement techniques in three federal agencies-the BOR (Bureau of Reclamation), NOAA (National Oceanic and Atmospheric Administration), and NSF (National Science Foundation). The BOR's line item appropriation of $6.6 million supports a continuing program of research and development of precipitation enhancement technologies to augment the fresh water supplies of the nation. The BOR also has primary responsibility for site specific applications of developed technologies and technology transfer of precipitation enhancement methodology through cooperation with state and local agencies. The bureau's field activities are now focused on development of winter snowpack augmentation techniques for increasing streamflow in the high mountain basins of the West. NOAA is supporting more fundamental research on precipitation enhancement effectiveness in connection with programs in North Dakota, Utah, Nevada, and Illinois through a congressional "write-in" of $2.6 million. The NSF funding of $500,000 is supporting fundamental research that is relevant to precipitation enhancement through its Grants program.

Up to 1981, anyone intending to engage in any weather modification activity in the United States was required to report that activity to the Secretary of Commerce in accordance with Public Law 29-205 enacted in 1971. NOAA published summaries of these activities. The reporting requirement was dropped after 1981, so the summary of weather modification activities reported in 1981 was the last one published. Similarly, the World Meteorological Organization maintains a register of experiments and operations in weather modification carried out within member countries. Data are gathered by means of voluntary responses to a questionnaire and, as such, is not complete. The most recent register of national weather modification projects was issued in 1982. An examination of these national weather modification projects was issued in 1982. An examination of these national and international summaries of weather modification activities reveals interesting information on the extent, purposes, locations, sponsors, techniques, target areas, seeding agents, seeding durations, etc. associated with these activities. The summaries also show trends in these activities over the years and around the world.

Such data for the years 1981 and 1982 are presented in tables 1 through 8, and figure 2. These data are by and large self-explanatory; however, a few points are worth emphasizing. Activity in weather modification is quite extensive both nationally and internationally and is primarily focused on precipitation enhancement of augment water resources and on hail suppression to protect growing crops. Activity dates back to 1952 with some projects being operated continuously for more than 30 years (figure 2). Weather modification activity peaked in the United States in 1977 as a result of the severe drought in the West. It declined thereafter and has been generally constant since 1979. Internationally, on the other hand, weather modification activity has been increasing since 1977. Recent increases in activity and interest are probably due to the severe droughts in Africa and South America. Sponsors of weather modification activity include nations, states and user groups such as water districts, utilities, etc. As the worldwide need for water and food increases, it is likely that activity in weather modification will tend to increase, with the increase being punctuated by spurts associated with the occurrence of droughts.

Concluding Remarks

Demands for water increase daily. The population continues to grow, along with attendant needs for water, food, fiber, and energy production. Many water users use the latest techniques to stretch available water, but demands are sure to increase and these measures will help, but will not eliminate the problem. There may be no one best solution to solve water shortages, instead, a combination of practices

Table 1A. UNITED STATES WEATHER MODIFICATION ACTIVITY DATA (NOAA)

ITEM	YEAR				
	1977	1978	1979	1980	1981
NUMBER OF ACTIVITIES	90	61	49	49	46
FEDERALLY SPONSORED	11	13	10	9	8
NONFEDERALLY SPONSORED	79	48	39	40	38
STATES WITH ACTIVITIES	23	19	19	20	18
TOTAL TARGET AREA (MI^2)	270,690	235,519	123,880	119,333	81,986

Table 1B. UNITED STATES WEATHER MODIFICATION ACTIVITY DATA
(NOAA)

ITEM	1977	1978	1979	1980	1981
MODIFICATION DAYS	2,603	1,688	1,238	1,515	1,336
HOURS OF OPERATION					
AIR	3,309	2,649	2,398	1,640	1,914
GROUND	77,320	78,140	15,605	24,081	40,913
SEEDING MATERIAL USED					
DRY ICE (Kg)	48,077	19,389	12,463	42,140	8,913
SILVER IODIDE (Kg)	1,412	1,493	902	923	885
LIQUID PROPANE (Gal)	12,295	17,728	11,077	13,819	7,715
POLYELECTROLYTE (Kg)	2,353	1,575	641	270	574

Table 2. WEATHER MODIFICATION ACTIVITIES IN THE
UNITED STATES (1981)
(NOAA)

PURPOSE		NUMBER OF ACTIVITIES
PRECIPITATION ENHANCEMENT		34
HAIL SUPPRESSION		7
FOG CLEARING		7
RESEARCH		5
	TOTAL	53*

*46 SEPARATE ACTIVITIES

Table 3. SPONSORS OF WEATHER MODIFICATION ACTIVITIES IN THE UNITED STATES (1981) (NOAA)

	SPONSORS	NUMBER OF ACTIVITIES
FEDERAL	3	8
NONFEDERAL	41	38
COMMERICAL	0	0
WATER DISTRICTS	11	11
UNIVERSITIES	1	1
UTILITIES	4	5
STATES	4	6
CITIES	1	1
AIRLINES	10	4
PRIVATE	1	1
RESORTS	3	3
COMMUNITIES	6	6

Table 4. WEATHER MODIFICATION ACTIVITIES IN THE UNITED STATES BY STATE AND AREA (1981) (NOAA)

STATE		NUMBER OF ACTIVITIES	AREA (MI^2)
ALASKA		3	103
CALIFORNIA		10	7,906
COLORADO		2	2,600
FLORIDA		1	5,000
IDAHO		5	1,032
KANSAS		1	10,815
LOUISIANA		1	1,295
NEBRASKA		1	1,152
NEW YORK		1	100
NEVADA		4	6,060
NORTH DAKOTA		3	13,586
OKLAHOMA		5	3,950
OREGON		1	10
SOUTH DAKOTA		1	2,682
TEXAS		1	3,500
UTAH		4	20,510
WASHINGTON		3	595
WYOMING		3	1,090
TOTAL	18	50*	81,986 (2.2%)

*FOUR PROJECTS WERE MULTISTATE

Table 5. WORLDWIDE WEATHER MODIFICATION ACTIVITY
(WORLD METEOROLOGICAL ORGANIZATION)

YEAR	NUMBER OF COUNTRIES
1977	17
1978	17
1979	23
1980	27
1981	28
1982	26

Table 6. WEATHER MODIFICATION INTERESTS IN 1982
(WORLD METEOROLOGICAL ORGANIZATION)

	NUMBER OF COUNTRIES	
	ACTIVE	INTERESTED
PRECIPITATION ENHANCEMENT (COLD CLOUDS)	14	14
PRECIPITATION ENHANCEMENT (WARM CLOUDS)	9	10
HAIL SUPPRESSION	10	18
FOG CLEARING	5	11
LIGHTNING SUPPRESSION	1	5
TROPICAL CYCLONE MODERATION	3	4
CLOUD CLEARING	3	4

Table 7. MAJOR WEATHER MODIFICATION PROGRAMS IN 1982 (WORLD METEOROLOGICAL ORGANIZATION)

TYPE	COUNTRIES
PRECIP. ENHANCEMENT (COLD CLOUDS)	CANADA, ISRAEL, MEXICO, SENEGAL, USA, USSR, ZIMBABWE
PRECIP. ENHANCEMENT (WARM CLOUDS)	BRAZIL, THAILAND
HAIL SUPPRESSION	BULGARIA, CANADA, FRANCE, SWITZERLAND, USA, USSR
FOG CLEARING	NORWAY, THAILAND, USA, USSR
LIGHTNING SUPPRESSION	USSR
TROPICAL CYCLONE MODERATION	PHILIPPINES, USA, USSR
CLOUD CLEARING	CUBA, USA, USSR

Table 8. WEATHER MODIFICATION ACTIVITY DATA (1981)

	WORLD	US**	USSR**	MEXICO**
NUMBER OF ACTIVITIES	102	46	12	9
MODIFICATION DAYS	3913 (1-340)*	1223	515	616
MODIFICATION AREA (KM^2)	2,430,756 (0.3 - 900,000)*	222,563 (2.3/16.1)+	77,473 (0.35/3.5)+	321,509 (16.2/158.4)+
PRECIPITATION AUGMENTATION AREA	1,326,324	220,422	10,000	321,509
HAIL SUPPRESSION AREA	360,550	103,809	67,473	0

* RANGE

\+ PERCENT OF TOTAL AREA/PERCENT OF HARVESTED AREA

** THE US, USSR AND MEXICO HAVE THE MOST ACTIVITIES IN THE WORLD

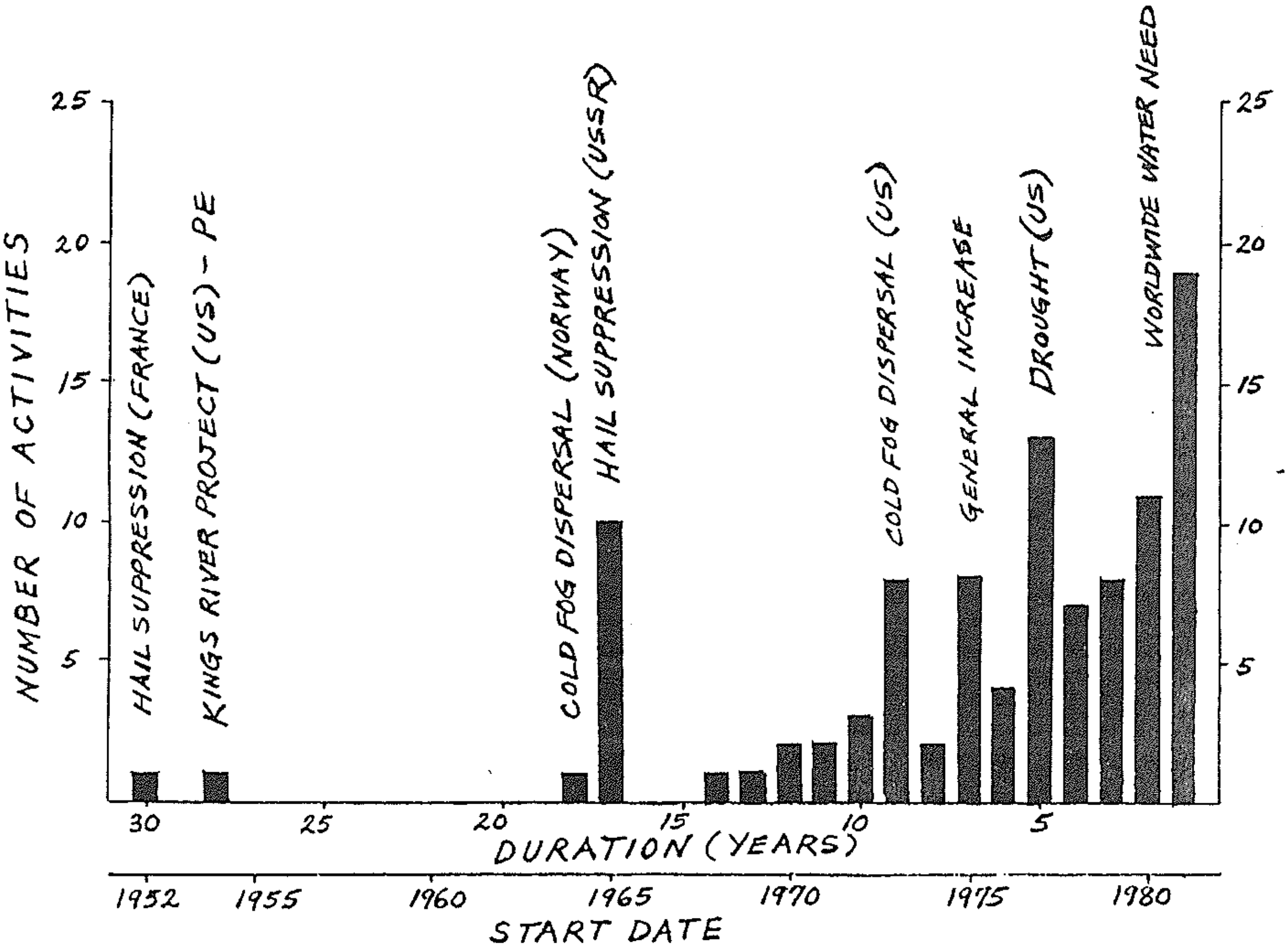

FIGURE 2. THE HISTORY OF WEATHER MODIFICATION ACTIVITIES EXISTING IN 1981.

may be desirable. I believe that innovative techniques like cloud seeding can play an important part in solving this problem. When the technology is developed, cloud seeding is expected to provide increases in precipitation of about 10 to 30 percent. While the percentage may seem small, the added amounts of water could be quite important as our growing population pushes the environment to the limits of its carrying capacity.

The atmosphere is a great public resource; citizens, scientists, public officials, and water users can and should work together to manage this valuable resource wisely. Planning and studies are needed now to avoid the water crisis and shortages that are forecast to occur by the end of this century. Time, money, and effort devoted to cloud seeding research now can be seen as investments that will yield future benefits when the technology is developed.

Benjamin Franklin in the eighteenth century said, in all his wisdom, that "Nobody misses the water until the well runs dry." I hope we will have the foresight to prove that statement wrong.

SNOW SURVEYS

Stanley E. Cook
Assistant State Conservation Engineer
Soil Conservation Service

In any language, and by any name, our plain old American snow can be either a joy or a nuisance. But to those who live and work in the West, it's much more than just snow--it's frozen water. Water that clings to mountains, nestles amongst trees during the winter, and slowly melts every spring to become a resource without which we can't support our agriculture, our cities, our industries or our recreation facilities.

In the West nearly three-fourths of our water comes from the winter snow, so knowing how much water is in the snowpack is terribly important. For this reason, the Soil Conservation Service (SCS), cooperating with many other agencies, industries and conservation districts is charged with the job of measuring the snowpack each winter and with forecasting the water supply for the coming summer. Monthly forecasts are made for each watershed by using a complicated formula based on past measurements, measured streamflow, character of the snowpack, soil moisture, and several other significant factors. The end result is a water supply forecast that triggers water conserving or water use decisions by many water managers.

Among those served by water supply forecasts are farmers and ranchers who, in water short years, may decide to plant fewer acres, switch to crops that need less water, or change to a more efficient irrigation system. Reservoir managers need water supply forecasts to develop a management plan for early release of stored water if the forecast calls for above average snowmelt. Otherwise, flood-prone land downstream might be covered with water. And in case of below average snow melt forecasts, reservoir managers may need to reduce winter and early spring outflow, or they will not have their reservoirs filled when farmers start to irrigate. Multi-purpose reservoir operators must also plan for power generation and fishery management. These operators must also plan for enough water for recreation areas at reservoir edges and for protecting downstream waterflow nesting areas from too much water during the critical nesting period. Each year reservoir managers use water supply forecasts to develop a management plan that allows for the greatest possible beneficial use of the coming year's water. As a result of rapid homesite development in western foothills and mountains, many builders failed to design buildings with the ability to hold the heavy winter snow load. The result: many damaged or collapsed roofs. Now, snow measurement data collected over many years are being used to prepare snow load maps--maps that can be used by architects, engineers and building inspectors to assure realistic roof and structural designs.

Highway maintenance and route selection in the mountains must consider the cost of snow removal, as well as avalanche hazard. Here again, snow survey information is valuable for planning and efficient operation, and for motorist safety.

As outdoor winter recreation mushrooms, competition by various groups increases. Snowmobiles need marked trails for their fun. Cross country skiers need trails, too, but not where they compete with fast moving power machines and their drivers. And downhill skiers have still other needs. They all need snow, they all need room to maneuver. Snow survey data are used to choose trail routes as well as to get some idea of probable snow cover at different times of the year, plus the number of skiing days expected.

Snow survey data is valuable to big game managers. Snow depth affects the movement of big game animals to lower elevation winter ranges. Snow survey information also allows managers to provide natural forage during the critical winter and early spring periods when each animal must dig through snow on wintering ranges to reach its food supply. Knowing what current snow conditions prevail, including depth and snow hardness, affects each animal's chances of survival and can help explain fluctuations in wildlife population.

Snow surveys also lend themselves to a pollution watch. Snow samples containing airborne pollutants swept out of the atmosphere and concentrated in the mountain snowpack easily can be collected and analyzed. Downwind from cities and industries, these particles could exceed maximum limits for drinking water or other important uses.

Collecting snow data to make forecasts started in 1905 when Dr. James E. Church, professor of the classics, Reno, Nevada, set out to prove the relation between snowpack and summer water supply. He was extremely successful. In the 20s and 30s his techniques were improved until the science of snow surveying and the art of water supply forecasting were gradually accepted and standardized throughout the West.

Snow survey sampling is hard work. Once each month, teams of snow surveyors trek high into the mountain watersheds to snow courses. Skiis, snowshoes and snowmobiles are their transportation. The snow surveyor's backpack contains sections of hollow aluminum tubing that can be coupled end to end depending on snow depth. At the site, the sections are coupled together and the sharp edged tube is driven down through the deep snow to the ground below. The snow surveyor takes 10 of these readings from each snow course. At each spot, he measures snow depth and carefully weighs each sample to determine how much water the snow contains. Some extremely remote courses, and some that are hazardous to reach, are read by flying over them with an airplane or helicopter. However, at these aerial measuring sites, water content can't be measured, only snow depth.

All the measurement data, when compared with past years, give a means of forecasting how much water the snowpack will yield when it melts in the spring and summer. Water supply forecasts are released each month during the spring so water users can plan ahead.

During the past 10 or 15 years, new sophistication and many new technologies have been developed to make forecasts faster and more accurate. The first new development was the pressure pillow. Placed on the ground at a snow course, this 20-square-foot stainless steel pillow is filled with non-freezing fluids. As snow piles on the top, the increasing pressure of the weight can be transformed into electrical energy by a device called a transducer, which when hooked to a radio transmitter at a remote snow course can transmit snow water content information to the forcaster's office in an instant.

The newest system of all is a snow telemetry network system called SNOTEL. At a snow course site, a radio transmitter/receiver is powered by solar batteries. On command--anytime during the night or day--temperature, snow water content, and total precipitation information can be collected from snow courses. Command signals from a survey office can be relayed through one of two central stations at Boise, Idaho, or Ogden, Utah. Transmitters at these sites direct a signal skyward. The signal bounces earthward off ionized trails--the sand-sized remains of meteors that burned when they entered the earth's atmosphere--and activates the receiver at the remote mountain snow course. In an instant the remote site transmitter comes on the air and sends back its current readings through the same fleeting ionized trail link-up. It is no longer necessary to get readings only once a month. Readings can now be made several times a day. The result is improved accuracy and the ability to monitor a snow pack that may be melting so rapidly there is danger of local downstream floodings. Competition for water in the West is increasing. Agricultural needs compete with the needs of growing towns and cities. The growing demand for power competes with the demand for expanding recreation uses. These competing needs means that accurate snowpack data and accurate water supply forecasts are high on the priority list of water conserving skills--skills that are much needed in the West.

FLOW FORECASTING

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The hydrologist is frequently required to estimate monthly, seasonal, or annual volumes of flow. Such estimates may be needed for operational purposes or to provide a data base for evaluating reservoir storage requirements. Therefore, forecasting river flow is very important in a water resources system. Flow forecasting is essential for determining optimal policies for the use of the available water and operation of the water resources component.

What is forecasting? Forecasting is by definition the probable future behavior of a phenomenon. The confidence assigned to the forecast depends upon the nature of the phenomenon studied and the adequacy of the model used to appropriate the process. Hydrological phenomena depend upon several uncertain factors that may cause substantial differences between observed and predicted values.

Flow Forecasting Techniques

The tools of river forecasting include rainfall runoff relations, unit hydrographs, routing methods, recession curves and stage discharge relations. In brief, I will go over the basic idea of these tools.

Rainfall/Runoff Relation: To determine this relationship, we correlate storm rainfall, basin conditions, storm duration, and resulting storm runoff "average depths". Those rainfall-runoff relations are used to estimate the amount of water expected to appear in the streams (figure 1).

Unit Hydrograph: The rainfall/runoff relation provide us an estimate of volume of water that will run off for a given storm. The unit hydrograph is used in order to determine the distribution of the water with respect to time (figure 2).

Stream Flow Routing: The next step is to predict the movement and change in shape of flood wave as it moves downstream, particularly to determine the shape of flood wave from one station to another station (figure 3). A lot of routing methods are available ranging from complex storage

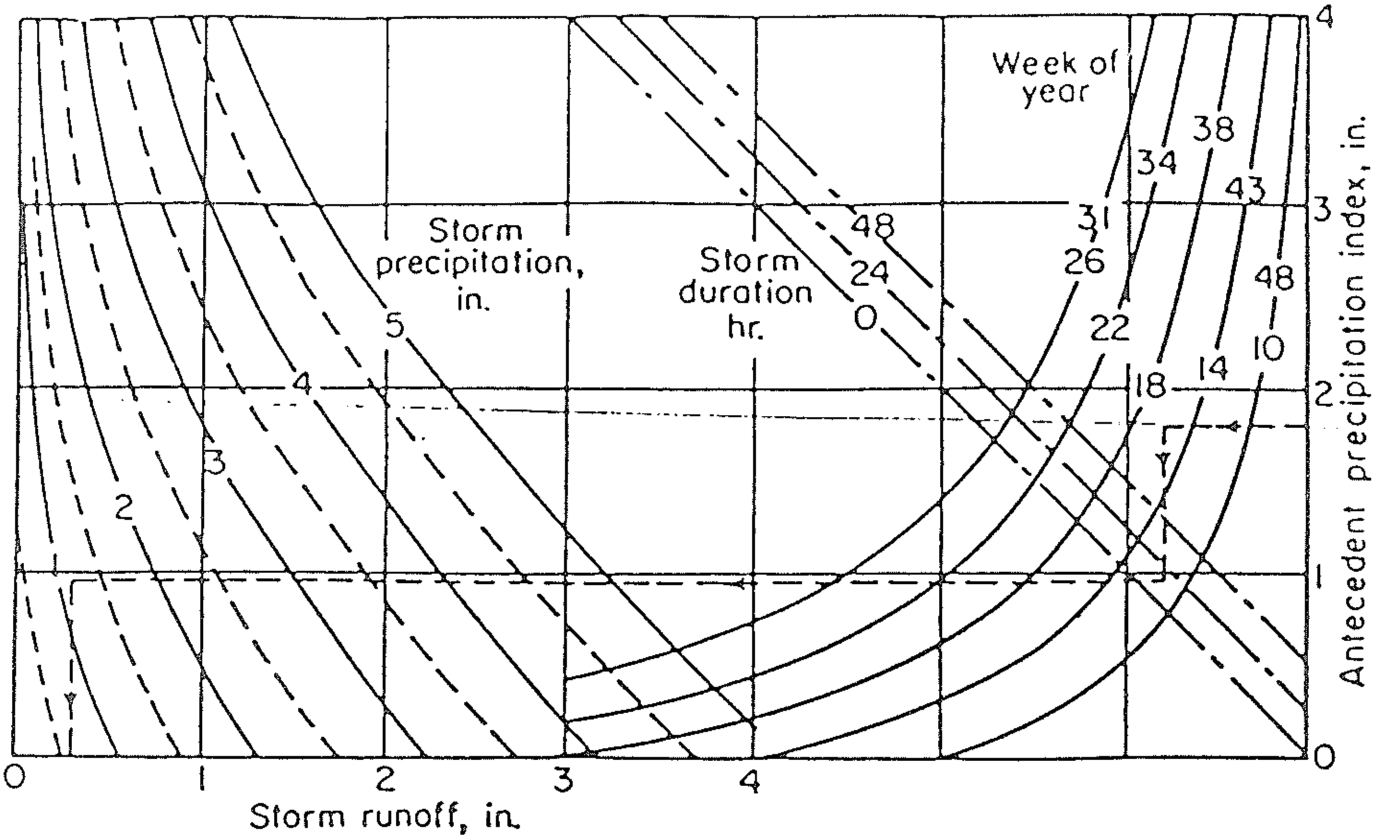


Figure 1. Rainfall-runoff relation.

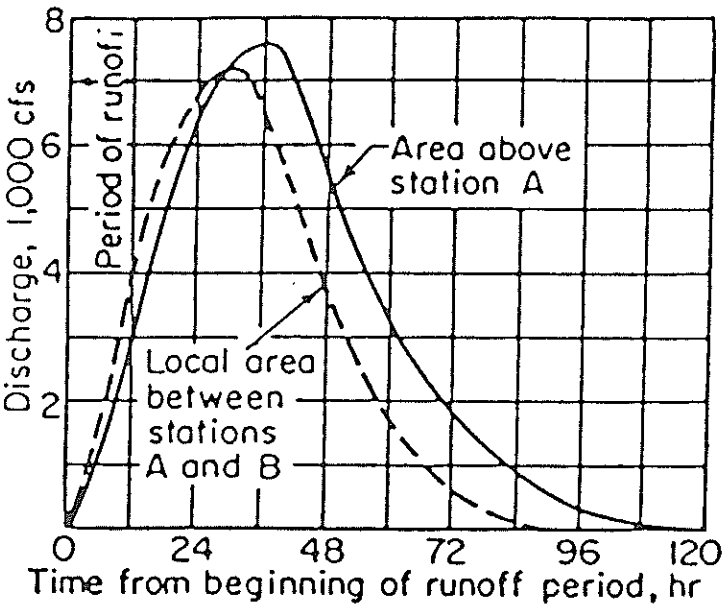
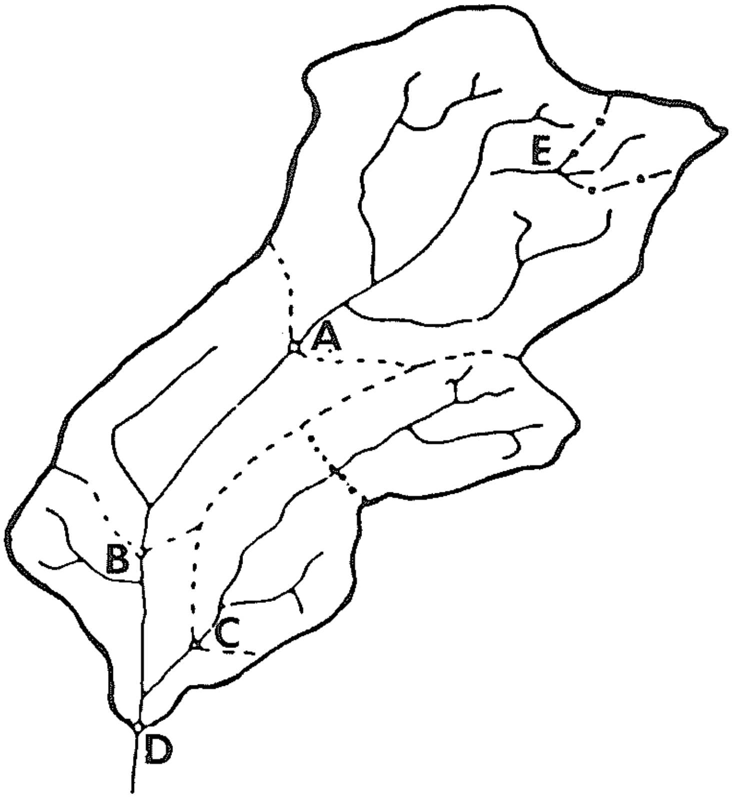


Figure 2. Twelve-hour unit hydrographs.



Fiqure 3. River basin map.

function to simple procedures. For example, the Muskingum method (figure 4) is used to determine the time distribution of this water at a forecast point. The stage discharge relation is then used to convert these flows to stages (figure 5).

Time Series Analysis: The purpose of this approach is to build astochastic models for discrete time series in order to be used in an important area of application. The objectives are:

1. To derive models possessing maximum simplicity.
2. To derive models possessing minimum number of parameters.

Obtaining such models is important because:

1. They may tell us something about the nature of the system generating the time series.
2. They can be used for obtaining optimal forecasts of future values of the series.
3. They can be used to derive optimal control policies showing how available water which is under one control, should be manipulated so as to minimize disturbances in some dependent variable.

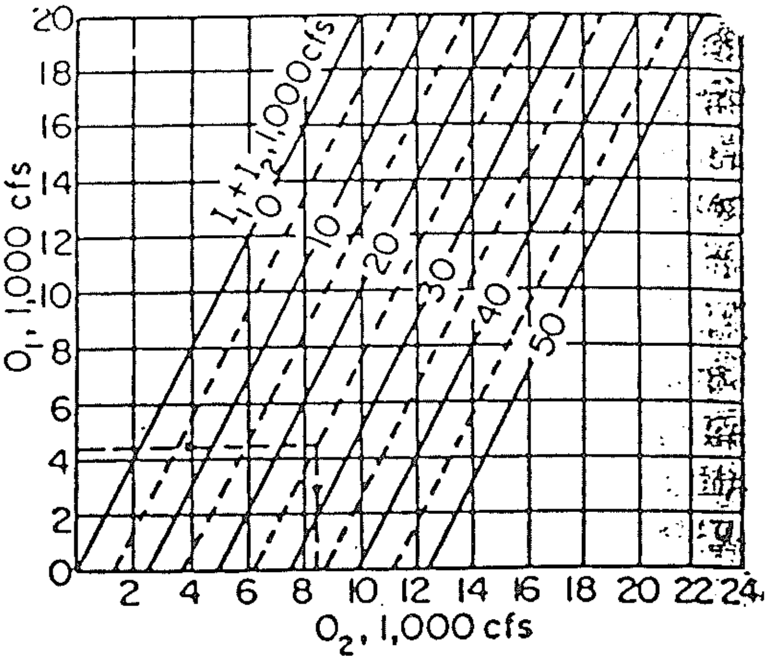
Case Study of the Rio Grande

The Rio Grande is a vital source of water to the people of New Mexico. The river flow is supplied primarily by snow melt runoff from the mountains of southern Colorado and northern New Mexico. The flow allocated throughout the basin is limited by three international treaties between the United States and Mexico and several compacts among Colorado, New Mexico and Texas. Therefore, flow forecasting techniques are needed to wisely manage the flow to make the best use of this limited resource.

The purpose of this study is to develop a set of monthly flow forecasting models for three key measurement sites in northern New Mexico and southern Colorado.

Historical Background

The Rio Grande system is composed of two major rivers, the Rio Grande and the Rio Chama. The Rio Grande is the third longest river in the United States. The river originates in the San Juan Mountains in



$K = 18$ hr; $X = 0$; routing period Δt = 12 hr.

Figure 4. Muskingum routing diagram.

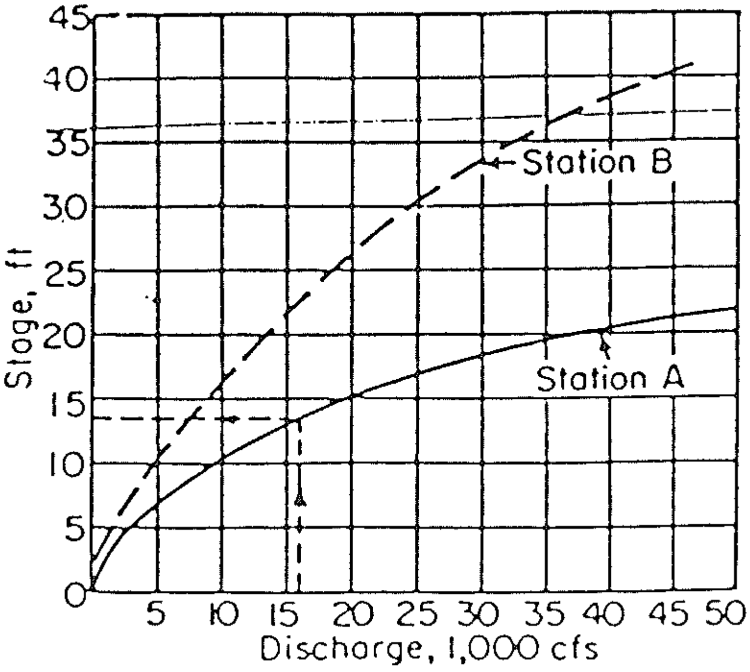


Figure 5. Stage-discharge relations.

southern Colorado and flows through New Mexico and Texas before emptying into the Gulf of Mexico. The Rio Grande flows in a southeasterly direction through Del Norte, Monte Vista and Alamosa, then turns south into New Mexico near Lobatos. At Lobatos the river enters the Rio Grande Canyon, which is 50 miles long and 1,200 feet deep. The river then enters Espanola Valley, which is 25 miles long and flanked on the west by the Jemez Mountains and on the east by the Sangre de Cristo Mountains.

The Rio Chama, which orginates in southern Colorado, on its New Mexico route passes through El Vado and Abiquiu reservoirs before converging with the Rio Grande. The Rio Chama flows through terrain that varies from a narrow valley above Rio Brazos, to wide fertile mesas for the portion between Rio Brazos and Rio Nutrios, then through Continuous Canyon to Abiquiu Dam. Finally, the river flows through a wide valley until it joins the Rio Grande in the Espanola Valley.

Methodology

The three gauging stations selected for this study (Rio Grande at Lobatos in Colorado, Rio Chama at Lapuente in New Mexico, Rio Grande at Otowi Bridge in New Mexico) were selected because:

1. Each station represents incoming flow of the rivers which is mostly from snow melt.
2. Each station's historical records are available.
3. Each station represents watersheds with no significant manmade influence.

The monthly flow data for a period of 30 years is used to identify the stochastic model at each selected station in terms of seasonal mixed autoregressive integrated moving average models (ARIMA), which can be defined as:

$$z_t = \phi_1 z_{t-1} + \phi_2 z_{t-2} + \cdots + \phi_p z_{t-p} + q_t - \theta_1 q_{t-1} - \theta_2 q_{t-2} - \cdots - \theta_q q_{t-q}$$

where z_t is the value of the process at time t, $\phi_1, \phi_2 \ldots \phi_p$ are the coefficients of the autoregressive part, $\theta_1, \theta_2 \ldots \theta_q$ are the coefficients of the moving average part, a_t is the white noise assumed to be normally distributed with zero mean and constant variance, and p, q are the orders of the autoregressive and the moving average respectively.

The ARIMA modeling procedure can be conveniently classified into three stages. The first is the identification stage, where one selects a tentative model through the examination of sample autocorrelation function (ACF) and partial autocorrelation function (PACF). Then the process proceeds to estimate the parameter values of the model and specific statistics are used to test if the parameters are statistically significant. Finally, the residuals of the temporary model are tested for adequate fit. This testing procedure will reveal any modeling specification errors. Then the model will be used to forecast for leading time and these forecasted values will be compared with the time values of these periods.

Analysis and Conclusions

The time series at each selected station was log-transformed in order to remove the existed trend and smooth out the series in the following manner:

$\tilde{z}_t = \log (z_t + r)$ where $r > o$ for all t.

The sample ACF and PACF for the original flow series indicated that the series is not stationary. Therefore the series must be differenced in terms of yearly and seasonal periodicity. This was done as

$$\nabla \tilde{z}_t = \tilde{z}_t - \tilde{z}_{t - 1}$$

and

$$\nabla \tilde{z}_t = \tilde{z}_t - \tilde{z}_{t - 12}$$

for yearly and seasonal periodicity respectively. The ACF and PACF of the differenced series are shown in figures 6, 7, 8 and 9. The ACF at Lobatos station shows that the values of ACF at log 12 is highly significant (ie. Fall outside the confidence limit of two standard error), while the PACF shows that it has significant values at log 12, log 24, log 36 and log 56 and they are decreasing. Furthermore, the ARIMA model may contain a moving average of the first order and a moving average of the first order for the regular and seasonal parts, respectively (0, 1, d)(a, 1, 1).

For the case of the Lupuente gaging station, the ACF shows that t has significant values at log 2 and log 12 and the rest are not significant.

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                                  DATA LISTING
                                ARIMA PROCEDURE

                       NAME OF VARIABLE       =  X
                       PERIODS OF DIFFERENCING=  1,12.

                       MEAN OF WORKING SERIES=0.00373721
                       STANDARD DEVIATION    =   0.88207
                       NUMBER OF OBSERVATIONS=       356

                                AUTOCORRELATIONS

LAG COVARIANCE CORRELATION -1 9 8 7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 8 9 1         STD
  0   0.778048     1.00000 |                    |********************|         0
  1  0.0855816     0.11000 |                  . |**                  | 0.0529999
  2 0.00905818     0.01164 |                  . | .                  | 0.0536373
  3  -0.105941    -0.13616 |                 ***| .                  | 0.0536444
  4  -0.110202    -0.14164 |                 ***| .                  | 0.0546066
  5 -0.0868373    -0.11161 |                  **| .                  |  0.055629
  6 -0.0505069    -0.06491 |                  .*| .                  | 0.0562545
  7 -.00031317    -0.00040 |                  . | .                  | 0.0564645
  8  0.0510914     0.06567 |                  . |*.                  | 0.0564645
  9  0.0836881     0.10756 |                  . |**                  | 0.0566786
 10  0.0693887     0.08918 |                  . |**                  | 0.0572491
 11  0.0136345     0.01752 |                  . | .                  | 0.0576381
 12  -0.324183    -0.41666 |            ********| .                  |  0.057653
 13 -0.0923883    -0.11874 |                 .**|  .                 | 0.0655682
 14  -0.076717    -0.09860 |                 .**|  .                 | 0.0661695
 15   0.011269     0.01448 |                 .  |  .                 |  0.066581
 16 -.00464326    -0.00597 |                 .  |  .                 | 0.0665898
 17    0.10258     0.13184 |                 .  |***                 | 0.0665913
 18  0.0769971     0.09896 |                 .  |**.                 | 0.0673206
 19  0.0498512     0.06407 |                 .  |* .                 |  0.067728
 20 -0.0336245    -0.04322 |                 . *|  .                 |  0.067898
 21  -0.037641    -0.04838 |                 . *|  .                 | 0.0679753
 22  -0.103325    -0.13280 |                 ***|  .                 | 0.0680719
 23 -0.0551512    -0.07088 |                 . *|  .                 | 0.0687958
 24  -0.072036    -0.09259 |                 .**|  .                 | 0.0690007
 25  0.0183552     0.02359 |                 .  |  .                 | 0.0693487
 26  0.0748049     0.09614 |                 .  |**.                 | 0.0693713
 27  0.0558154     0.07174 |                 .  |* .                 | 0.0697446
 28  0.0881071     0.11324 |                 .  |**.                 | 0.0699515
 29 -0.0478258    -0.06147 |                 . *|  .                 | 0.0704646
 30 -0.0137347    -0.01765 |                 .  |  .                 | 0.0706151
 31 -0.0595286    -0.07651 |                 .**|  .                 | 0.0706275
 32  0.0613623     0.07887 |                 .  |**.                 | 0.0708599
 33  0.0110695     0.01423 |                 .  |  .                 |  0.071106
 34  0.0477922     0.06143 |                 .  |* .                 |  0.071114
 35  0.0228709     0.02940 |                 .  |* .                 | 0.0712629
 36 0.00417096     0.00536 |                 .  |  .                 |  0.071297
 37  0.0172269     0.02214 |                 .  |  .                 | 0.0712981
 38 -0.0376218    -0.04835 |                 . *|  .                 | 0.0713174
 39 -.00392717    -0.00505 |                 .  |  .                 | 0.0714094
 40 -0.0258528    -0.03323 |                 . *|  .                 | 0.0714104
 41 -0.0121113    -0.01557 |                 .  |  .                 | 0.0714539
 42 -0.0103636    -0.01332 |                 .  |  .                 | 0.0714634
 43  0.0235181     0.03023 |                 .  |* .                 | 0.0714704
 44  0.0008964     0.00115 |                 .  |  .                 | 0.0715063
 45  0.0229781     0.02953 |                 .  |* .                 | 0.0715063
 46  0.0250063     0.03214 |                 .  |* .                 | 0.0715406
 47 -.00650852    -0.00837 |                 .  |  .                 | 0.0715811
 48  0.0197769     0.02542 |                 .  |* .                 | 0.0715839
 49 -0.0160614    -0.02064 |                 .  |  .                 | 0.0716092
 50 -0.0346983    -0.04460 |                 . *|  .                 | 0.0716259
 51 -0.0678373    -0.08719 |                 .**|  .                 | 0.0717039
 52 -0.0230675    -0.02965 |                 . *|  .                 | 0.0720011
 53  0.0592414     0.07614 |                 .  |**.                 | 0.0720354
 54 -0.0182639    -0.02347 |                 .  |  .                 | 0.0722611
 55   0.046155     0.05932 |                 .  |* .                 | 0.0722825
 56 -0.0494941    -0.06361 |                 . *|  .                 | 0.0724191
 57 -0.0891746    -0.11461 |                 .**|  .                 | 0.0725759
 58 -0.0074398    -0.00956 |                 .  |  .                 | 0.0730826
 59  0.0306116     0.03934 |                 .  |* .                 | 0.0730861
 60  0.0889285     0.11430 |                 .  |**.                 | 0.0731455
                           '   MARKS TWO STANDARD ERRORS
```

Figure 6. Lobatos.

DATA LISTING

PARTIAL AUTOCORRELATIONS

```
LAG CORRELATION -1 9 8 7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 8 9 1
  1     0.11000  |                 . |**                 |
  2    -0.00046  |                 . | .                 |
  3    -0.13908  |                ***| .                 |
  4    -0.11513  |                 **| .                 |
  5    -0.08568  |                 **| .                 |
  6    -0.06435  |                 .*| .                 |
  7    -0.02200  |                 . | .                 |
  8     0.02867  |                 . |*.                 |
  9     0.06327  |                 . |*.                 |
 10     0.05145  |                 . |*.                 |
 11     0.00442  |                 . | .                 |
 12    -0.41838  |           ********| .                 |
 13    -0.02079  |                 . | .                 |
 14    -0.05415  |                 .*| .                 |
 15    -0.05659  |                 .*| .                 |
 16    -0.12002  |                 **| .                 |
 17     0.05310  |                 . |*.                 |
 18     0.00069  |                 . | .                 |
 19    -0.01153  |                 . | .                 |
 20    -0.06566  |                 .*| .                 |
 21     0.01610  |                 . | .                 |
 22    -0.07040  |                 .*| .                 |
 23    -0.02411  |                 . | .                 |
 24    -0.32824  |            *******| .                 |
 25    -0.03479  |                 .*| .                 |
 26    -0.01248  |                 . | .                 |
 27    -0.04548  |                 .*| .                 |
 28    -0.05939  |                 .*| .                 |
 29    -0.05698  |                 .*| .                 |
 30     0.01446  |                 . | .                 |
 31    -0.05087  |                 .*| .                 |
 32     0.06013  |                 . |*.                 |
 33     0.01462  |                 . | .                 |
 34    -0.02010  |                 . | .                 |
 35    -0.01638  |                 . | .                 |
 36    -0.26896  |              *****| .                 |
 37    -0.01036  |                 . | .                 |
 38    -0.06786  |                 .*| .                 |
 39     0.01462  |                 . | .                 |
 40    -0.03779  |                 .*| .                 |
 41    -0.06277  |                 .*| .                 |
 42    -0.00556  |                 . | .                 |
 43    -0.04976  |                 .*| .                 |
 44     0.04199  |                 . |*.                 |
 45     0.00632  |                 . | .                 |
 46     0.04122  |                 . |*.                 |
 47    -0.02595  |                 .*| .                 |
 48    -0.12277  |                 **| .                 |
 49    -0.02232  |                 . | .                 |
 50    -0.10513  |                 **| .                 |
 51    -0.10368  |                 **| .                 |
 52    -0.03926  |                 .*| .                 |
 53     0.03432  |                 . |*.                 |
 54    -0.09668  |                 **| .                 |
 55     0.02462  |                 . | .                 |
 56    -0.06606  |                 .*| .                 |
 57    -0.16214  |                ***| .                 |
 58     0.00703  |                 . | .                 |
 59     0.01450  |                 . | .                 |
 60     0.02133  |                 . | .                 |
```

Figure 7. Lobatos.

```
                                  DATA LISTING
                                ARIMA PROCEDURE

                       NAME OF VARIABLE       =  X
                       PERIODS OF DIFFERENCING=  1,12

                       MEAN OF WORKING SERIES=    0
                       STANDARD DEVIATION    =  0.835777
                       NUMBER OF OBSERVATIONS=       297


                                AUTOCORRELATIONS

LAG COVARIANCE CORRELATION -1 9 8 7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 8 9 1         STD
  0   0.698524     1.00000 |                    |********************|          0
  1 -.00813203    -0.01164 |                  . | .                  |  0.0580259
  2  -0.169912    -0.24324 |               *****| .                  |  0.0580337
  3 -0.0597589    -0.08555 |                  **| .                  |  0.0613706
  4 -0.0900956    -0.12898 |                 ***| .                  |  0.0617708
  5  0.0538723     0.07712 |                 .  |**.                 |  0.0626711
  6 -0.0407191    -0.05829 |                 . *|  .                 |  0.0629898
  7 -0.0264687    -0.03789 |                 . *|  .                 |  0.0631712
  8   0.101717     0.14562 |                 .  |***                 |  0.0632477
  9 0.00766645     0.01098 |                 .  |  .                 |  0.0643666
 10  0.0343368     0.04916 |                 .  |* .                 |  0.0643729
 11  0.0286739     0.04105 |                 .  |* .                 |  0.0644991
 12  -0.285355    -0.40851 |            ********|  .                 |   0.064587
 13 -0.0209888    -0.03005 |                 . *|  .                 |  0.0727686
 14  0.0873279     0.12502 |                 .  |***                 |  0.0728104
 15  0.0352136     0.05041 |                 .  |* .                 |  0.0735296
 16 -0.0255491    -0.03658 |                 . *|  .                 |  0.0736458
 17 0.00295887     0.00424 |                 .  |  .                 |   0.073707
 18  0.0800295     0.11457 |                 .  |**.                 |  0.0737078
 19  0.0174393     0.02497 |                 .  |  .                 |   0.074305
 20 -0.0815311    -0.11672 |                 .**|  .                 |  0.0743332
 21  -0.063238    -0.09053 |                 .**|  .                 |  0.0749478
 22  0.0525119     0.07518 |                 .  |**.                 |  0.0753151
 23 -.00615972    -0.00882 |                 .  |  .                 |  0.0755673
 24 -0.0800886    -0.11465 |                 .**|  .                 |  0.0755708
 25  0.0261061     0.03737 |                 .  |* .                 |  0.0761542
 26  0.0616185     0.08821 |                 .  |**.                 |  0.0762159
 27  0.0525074     0.07517 |                 .  |**.                 |  0.0765589
 28  0.0471275     0.06747 |                 .  |* .                 |   0.076807
 29  -0.090423    -0.12945 |                 ***|  .                 |  0.0770063
 30 -0.0462735    -0.06624 |                 . *|  .                 |  0.0777355
 31 -0.0185319    -0.02653 |                 . *|  .                 |  0.0779254
 32  0.0953401     0.13649 |                 .  |***                 |  0.0779558
 33  0.0607358     0.08695 |                 .  |**.                 |  0.0787563
 34 -0.0752132    -0.10767 |                 .**|  .                 |  0.0790788
 35  0.0184141     0.02636 |                 .  |* .                 |  0.0795709
 36  0.0344535     0.04932 |                 .  |* .                 |  0.0796003
 37 -.00994327    -0.01423 |                 .  |  .                 |  0.0797032
 38 -0.0876643    -0.12550 |                 ***|  .                 |  0.0797117
 39 -0.0673007    -0.09635 |                 .**|  .                 |  0.0803742
 40  0.0445651     0.06380 |                 .  |* .                 |  0.0807622
 41  0.0562587     0.08054 |                 .  |**.                 |  0.0809317
 42 -0.0158875    -0.02274 |                 .  |  .                 |  0.0812011
 43  0.0307206     0.04398 |                 .  |* .                 |  0.0812226
 44 -0.0359039    -0.05140 |                 . *|  .                 |  0.0813027
 45  0.0212556     0.03043 |                 .  |* .                 |   0.081412
 46  0.0287701     0.04119 |                 .  |* .                 |  0.0814503
 47 -0.0565504    -0.08096 |                 .**|  .                 |  0.0815204
 48 -0.0107278    -0.01536 |                 .  |  .                 |  0.0817907
 49  0.0057672     0.00826 |                 .  |  .                 |  0.0818004
 50  0.0718115     0.10280 |                 .  |**.                 |  0.0818032
 51  0.0403947     0.05783 |                 .  |* .                 |   0.082237
 52 -0.0649543    -0.09299 |                 .**|  .                 |  0.0823738
 53 0.00686087     0.00982 |                 .  |  .                 |  0.0827265
 54  0.0410574     0.05878 |                 .  |* .                 |  0.0827304
 55 .000905046     0.00130 |                 .  |  .                 |  0.0828709
 56 -0.0800183    -0.11455 |                 .**|  .                 |   0.082871
 57 -0.0445081    -0.06372 |                 . *|  .                 |  0.0834025
 58  0.0705672     0.10102 |                 .  |**.                 |  0.0835662
 59  0.0503403     0.07207 |                 .  |* .                 |  0.0839764
 60  0.0274632     0.03932 |                 .  |* .                 |  0.0841844
                              MARKS TWO STANDARD ERRORS
```

Figure 8. Lapuente.

```
                          DATA LISTING

                    PARTIAL AUTOCORRELATIONS

LAG CORRELATION -1 9 8 7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 8 9 1
  1     -0.01164 |                 . | .                 |
  2     -0.24341 |              *****| .                 |
  3     -0.09771 |                 **| .                 |
  4     -0.20710 |               ****| .                 |
  5      0.01816 |                 . | .                 |
  6     -0.16875 |                ***| .                 |
  7     -0.06045 |                 .*| .                 |
  8      0.06614 |                 . |*.                 |
  9     -0.00865 |                 . | .                 |
 10      0.07941 |                 . |**                 |
 11      0.08039 |                 . |**                 |
 12     -0.38212 |           ********| .                 |
 13     -0.04112 |                 .*| .                 |
 14     -0.06321 |                 .*| .                 |
 15     -0.03819 |                 .*| .                 |
 16     -0.20720 |               ****| .                 |
 17      0.06111 |                 . |*.                 |
 18     -0.00887 |                 . | .                 |
 19     -0.00818 |                 . | .                 |
 20     -0.03427 |                 .*| .                 |
 21     -0.06643 |                 .*| .                 |
 22      0.04766 |                 . |*.                 |
 23     -0.03155 |                 .*| .                 |
 24     -0.35097 |            *******| .                 |
 25     -0.06271 |                 .*| .                 |
 26     -0.01390 |                 . | .                 |
 27      0.03752 |                 . |*.                 |
 28     -0.05154 |                 .*| .                 |
 29     -0.05684 |                 .*| .                 |
 30     -0.01136 |                 . | .                 |
 31     -0.05206 |                 .*| .                 |
 32      0.12463 |                 . |**                 |
 33     -0.07184 |                 .*| .                 |
 34     -0.01419 |                 . | .                 |
 35      0.06361 |                 . |*.                 |
 36     -0.20928 |               ****| .                 |
 37     -0.05159 |                 .*| .                 |
 38     -0.10670 |                 **| .                 |
 39     -0.04625 |                 .*| .                 |
 40     -0.05260 |                 .*| .                 |
 41     -0.08164 |                 **| .                 |
 42     -0.08122 |                 **| .                 |
 43     -0.01929 |                 . | .                 |
 44      0.01792 |                 . | .                 |
 45     -0.01824 |                 . | .                 |
 46     -0.03416 |                 .*| .                 |
 47     -0.00529 |                 . | .                 |
 48     -0.18028 |               ****| .                 |
 49     -0.02678 |                 .*| .                 |
 50     -0.04897 |                 .*| .                 |
 51     -0.01637 |                 . | .                 |
 52     -0.05482 |                 .*| .                 |
 53      0.00996 |                 . | .                 |
 54     -0.03046 |                 .*| .                 |
 55      0.06119 |                 . |*.                 |
 56     -0.08330 |                 **| .                 |
 57     -0.00484 |                 . | .                 |
 58      0.00082 |                 . | .                 |
 59      0.01633 |                 . | .                 |
 60     -0.08599 |                 **| .                 |
```

Figure 9. Lapuente.

And the PACF shows significant values at log 2, log 12 and log 24 of a decaying form. Therefore, the ARIMA model a contain a moving average of the second order and a moving average of the first order for the regular seasonal parts, respectively (0, 1, 2)(0, 1, 1).

At this stage, those two models were fitted to the series and the parameters were estimated using the method of maximum likelihood. Then the models were varified and used to forecast for a leading time of two years. Figure 10 shows the observed values compared to the forecasted values with and without updating the model parameters. It is clear from the graph that the forecasted values after updating the parameter are very close to the real value.

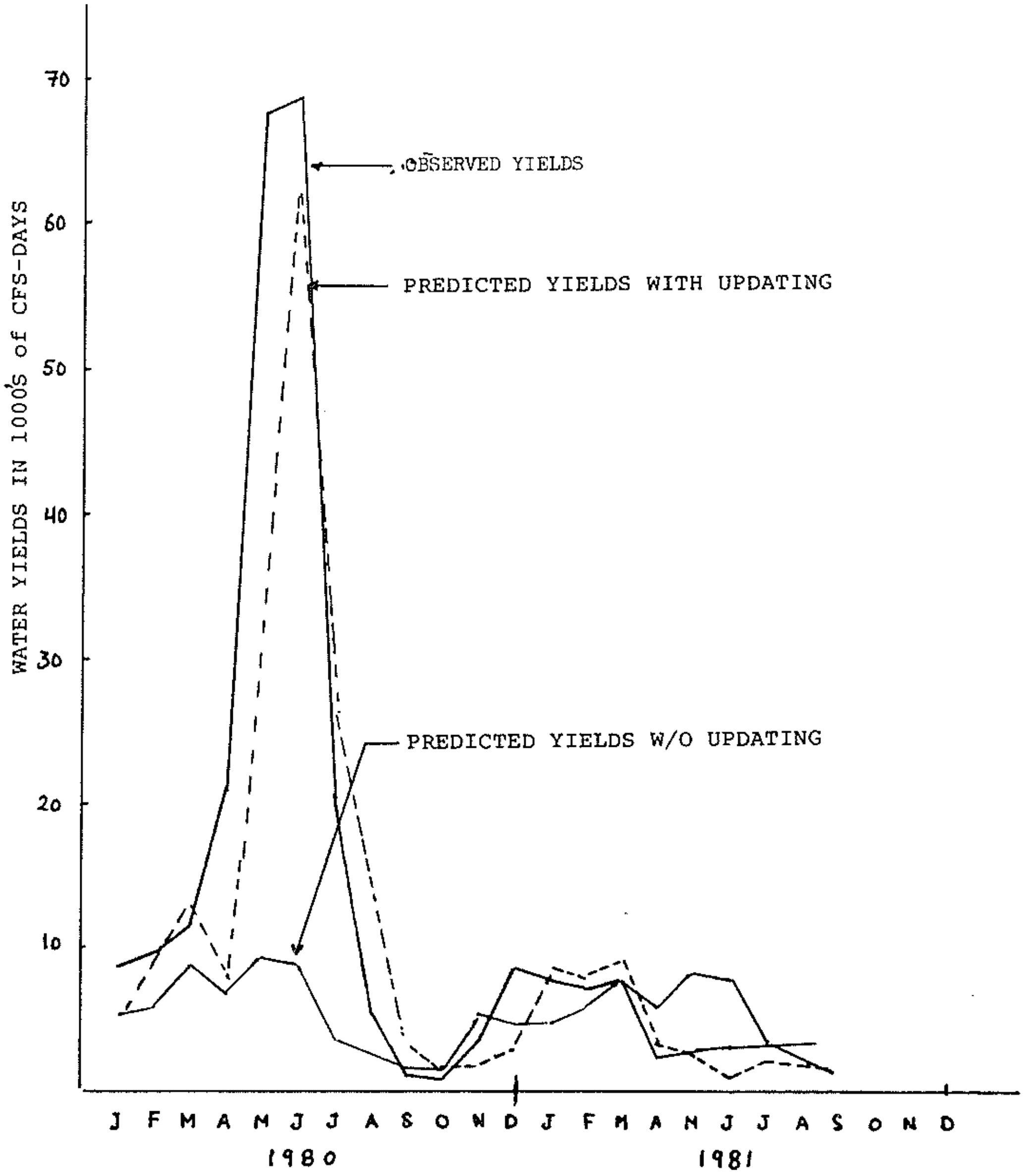

Figure 10. Rio Grande at Lobatos. Predicted and observed yields.

TRICKLE IRRIGATION OF CHILE PEPPERS

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New Mexico State University

Introduction

Trickle irrigation refers to water transported through plastic pipes or tubes, which are perforated or have emitters, and delivered close to the plant root system at a precisely controlled rate. The pipes or tubes can be placed above ground or below ground. The perforations or emitters are placed at regular distances along the plastic tubing, and are generally between 6 inches and 24 inches apart for row crops. For tree crops, several emitters per tree may be installed depending on the age and size of the tree.

Trickle irrigation has been used for fruit and nut trees, for grapes, and for vegetable and field crops. The system is particularly suitable for high value crops such as grapes, strawberries, avocados and peaches, but it is also used for field crops such as cotton and sugar cane.

With support from the New Mexico Interstate Stream Commission and the New Mexico Water Resources Research Institute, we have studied the use of trickle irrigation of chile peppers at New Mexico State University (NMSU) for more than eight years. During this eight-year period we have gained much experience with trickle irrigation, and have learned a great deal about the effects of trickle irrigated water on yield and quality, chile pepper nutrient requirements, salt distribution, planting dates and on other agronomic practices. During the last years of the experiment, the effects of double row versus single row planting was investigated. In addition, we investigated whether it would be possible to use the trickle tubing more than one year in a row, if we left the tubing in the ground and planted the new crop over the old row. The results of this study can be found in more detail in the bulletins, journal articles and theses referenced at the end of this paper.

Methods and Materials

The study was conducted on a 3 ha field at NMSU's Plant Science Research Center. Standard practices were used to prepare the land for planting except that there was no preirrigation. Trickle lines (Bi-Wall II Irrigation Tubing, Reed Irrigations Systems, California; and Chapin Twin Wall, Watermatics, Watertown, New York) were installed at 5 cm below the surface of each row using a converted cotton planter. The emitter spacing was 30 cm. Water was supplied from a nearby well through a header line that ran through the center of the field. The average electrical conductivity of the irrigation water was 1.24 mmhos/cm. Phosphorus fertilizer was applied by sidedressing, while nitrogen was applied by injecting urea (30 percent N) directly into the main header line.

The main treatment consisted of applying various amounts of irrigation water. The treatments received from 60 to 140 percent of the water applied to control plots (Wierenga 1983). The control plots were irrigated on the basis of tensiometer readings, or on the basis of pan evaporation data. The amounts of water applied to the plots were determined with water meters. Climatological data were recorded at a weather station adjacent to the field plots. Salt distributions around the trickle lines and data on the long term accumulation of salts in the soil irrigated by the trickle system were determined by sampling the soil and determining its salinity in the laboratory (Hibner 1982). The feasibility of multiyear use of trickle tubing was investigated in one experiment by chopping the plants during the fall or winter following each growing season and planting on the same row the next spring. The plots were not tilled between successive crops. Weeds were controlled by applying herbicides. In this experiment, chile peppers were grown the first year followed by cotton the second and third years.

Results and Discussion

Yield and water use. Table 1 shows the green chile yields for the years 1977 to 1983. These same data are shown in figure 1 (also Wierenga and Hendrickx 1985). Yields are plotted as a function of water applied.

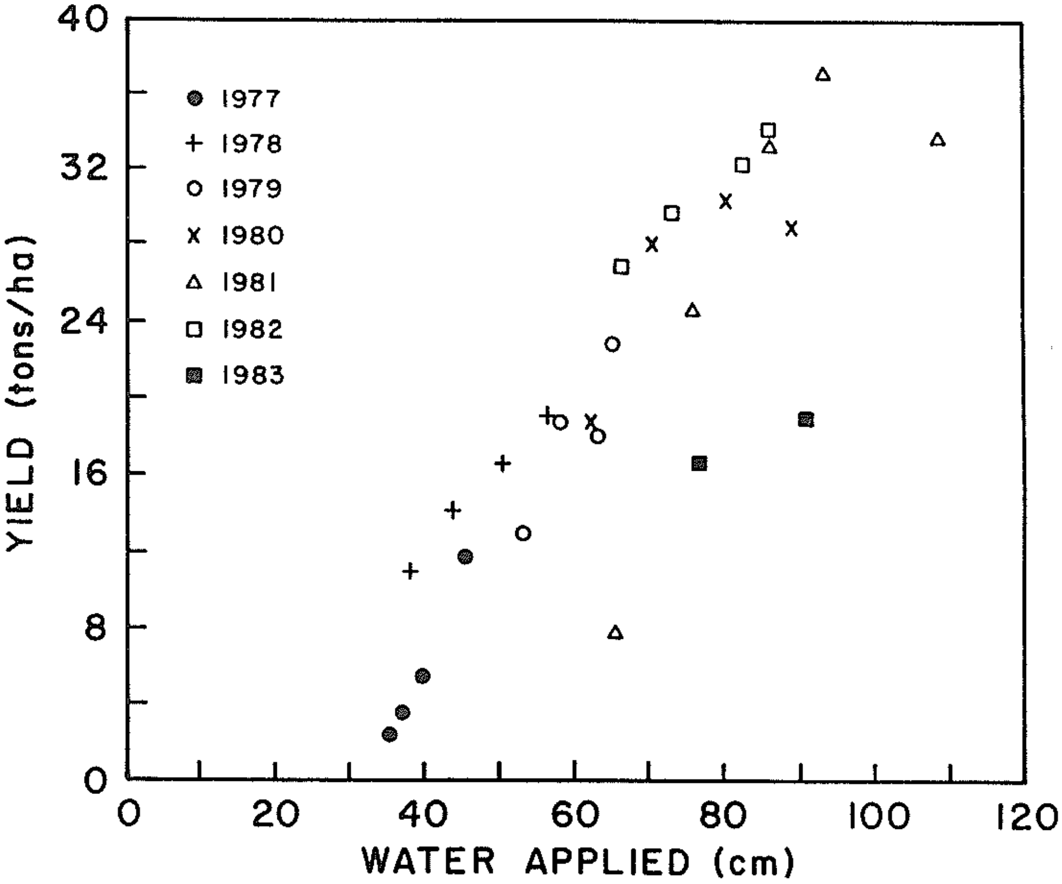

Figure 1. Yield of green chile versus water applied (rainfall included) for the years 1977-1983 with a single row per bid.

Table 1. Green chile yields[a] as influenced by irrigation treatment.

Treatment % of control	Water applied[b]	Yield (t/ha)
	---cm---	
	1977	
60	35.2	2.5
70	37.2	3.7
80	39.5	5.6
100	45.1	11.8
	1978	
80	38.1	11.0
100	44.2	14.2
120	50.3	16.3
140	56.4	19.1
	1979	
80	53.1	13.0
100	57.9	18.8
120	63.0	18.1
140	65.0	22.8
	1980	
80	62.1	18.8
100	70.1	28.1
120	79.9	30.2
140	88.6	28.9
	1981	
60	66.3	7.8
80	75.9	24.6
100	86.1	33.2
120	93.6	37.2
140	109.0	33.6
	1982	
80	64.9	27.4
100	71.9	29.9
120	81.6	31.9
140	85.2	34.0
	1983	
70	76.1	16.7
100	89.6	18.8

[a] The 1981 yields include yields from the first harvest on 13 August and from the second harvest on 13 September. The 100% treatments are the control treatments.

[b] Includes 10.3 cm rain in 1977, 3.6 cm rain in 1978, 14.3 cm rain in 1979, 9.8 cm rain in 1980, 12.8 cm rain in 1981, 9.4 cm rain in 1982, and 7.0 cm rain in 1983.

Clearly, the greeen chile yields increase with increasing amounts of water applied, up to a point. In 1980 and 1981, the highest yields were obtained when plots received 20 percent more water than the control (100 percent) treatment. However, yields on the test plots started to decrease when they received 40 percent more water to the control treatments. From the data in figure 1 and based on a statistical treatment of these data (Wierenga and Hendrickx 1985), it appears that highest yields of green chile are obtained when 80 to 95 cm water (31 to 37 inches) is applied through the trickle system. However, the optimum amount of water varies from year to year, largely as a result of weather conditions an or crop cover. Thus, in years of high evaporative demand and for double row chile, the amount of water applied may be higher than that shown in table 1. The amount of water applied to the chile in this study is considerably less than that generally applied to flood irrigated chile. Although no formal comparison was made of water use of trickle versus flood irrigated chile, an informal survey of flood irrigated chile fields in the Mesilla Valley (W. E. Cox, personal communication 1981) showed that, based on an estimated 4 inches of water per irrigation, the amount of water applied to 20, supposedly well-managed, fields varied between 48 and 56 inches. The actual amounts are probably larger, because most irrigations tend to be greater than 4 inches. Thus, flood irrigated green chile appears to need 50 to 55 percent more water than trickle irrigated chile.

Salinity. Soil samples were taken with a 5 cm diameter hydraulic soil probe at 10 cm depth intervals to a depth of 50 cm from the top of the bed and the furrow bottom, respectively. Samples were taken before the 1977 growing season (dated 1976), after the 1977 growing season, and after each subsequent growing season. During 1979, chile was grown on an adjacent field and samples were taken in the fallow field. More detailed sampling was done to determine the salt distribution around trickle lines at various times during the growing season. The samples resulting from this more detailed sampling procedure were analyzed for both chloride and total salt. Chloride ions move quite readily in soils and thus present a clearer picture of salt movement following irrigation than does total salts.

Table 2 shows the average chloride and average salinity levels (expressed in electrical conductivity of the saturation extracts) for the period 1976 through 1981 (Hibner 1982). What these data show is that there was very little salt buildup over the course of this experiment. In 1981, one-half of the field was flood irrigated while the other half was kept under trickle irrigation. The average chloride and conductivity values for the flood irrigated half of the field were 7.2 meq/l and 2.7 mmhos/cm, respectively. Thus, with one year of flood irrigation, salinity levels were at or below where they were at the beginning of the trickle irrigation experiment.

An example of the salt distribution found around a trickle line is presented in figure 2. The numbers in this figure indicate salt concentrations in mmhos/cm of the saturation extracts. The figure shows low salt concentrations around the trickle line where most of the roots are concentrated (Al-Khafaf 1977), and higher salt levels at the top and shoulders of the furrow. This pattern was found to be typical for most of the growing season, except that under the wetter irrigation regimes, the low salt area around the drip line tended to be larger. Furthermore, as the plants grew larger, the salts near the top of the furrow tended to diminish and salts tended to move into the furrows between the plant rows. This movement may also be the explanation for the relatively minor increases in soil salinity observed in table 2 because as salts are moved to the center, in between plant rows, any rain in July or August would move the salts to the subsoil.

Fertilizer use. The fertilizer experiment was conducted in 1980. Nitrogen was applied at rates of 0, 112 and 224 kg N/ha in 10 equal increments at 10-day intervals with the first injection on May 10 and the last on August 8. Phosphorus treatments consisted of 0, 56 and 112 kg P/ha, added as orthophosphoric acid (Panpruik et al. 1982).

Plant tissue analysis showed that the levels of NO_3-N in chile leaves and petioles responded significantly to N rate, and decreased as the plant approached maturity. It appears from this and previous studies

Table 2. General means of electrical conductivity and chloride concentration in the saturation extracted for the period 1976 through 1981.

Year	Chloride meq/l	Conductivity mmhos/cm
1976	7.4	2.5
1977	10.0	3.1
1978	10.7	3.3
1979	9.2	3.3
1980	11.6	2.3
1984	8.9	2.7

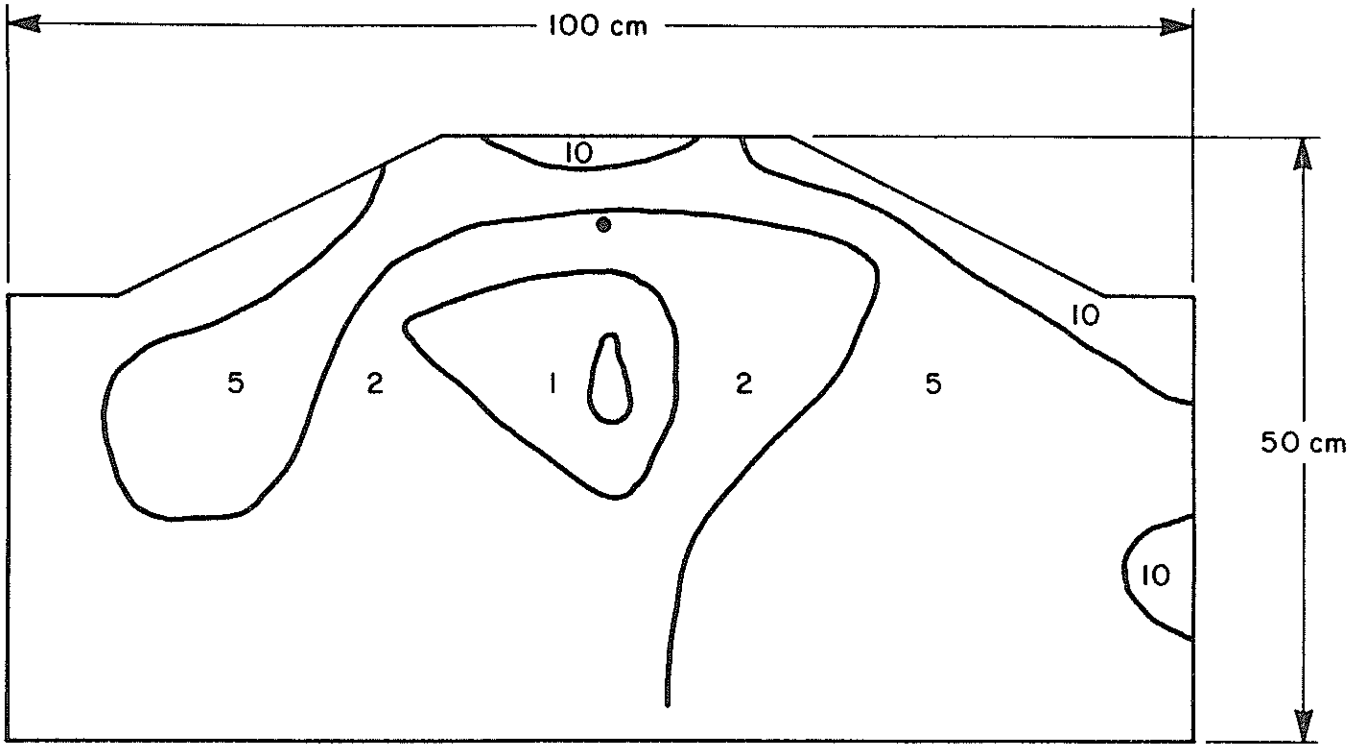

Figure 2. Salt distribution around trickle line on May 27, 1977. The numbers indicate the salt concentration in mmhos/cm. The trickle line is located near the center top of the low salinity area.

that a NO_3-N content of 1000 ppm should be maintained in the leaves of chile peppers grown in the Mesilla Valley and that the corresponding level in the leaf petioles should be 4000 ppm. Increasing levels of phosphorus did not affect P content of the leaves and petioles. Increasing levels of nitrogen or phosphorus fertilization had no effect on green chile yields. The lack of yield response to nitrogen or phosphorus fertilization in 1980 may have been due to high initial concentrations in the soil. Based on visual observations, we found that in most years, 140 lbs/acre N applied through the trickle lines was necessary to obtain adequate yields.

Planting date. Chile peppers in southern New Mexico are generally planted around March 20. We speculated that by using trickle irrigation we could delay planting for a few weeks, reasoning that trickle irrigation provides a more favorable environment for seed germination and growth. An experiment was conducted in 1981 in which chile peppers were planted on six dates, 10 days apart, starting March 10. Measurements were made of soil temperature, rate of emergence, leaf area development, flowering and final green chile yields.

Figure 3 shows the number of days to 75 percent emergence for the various planting dates. There is a clear relationship between planting date and rate of emergence. As planting is delayed, the soil gets warmer, and it takes less time for chile to emerge. From a statistical analysis of the data, we found that for every 10 day's delay in seeding there was a five-day decrease in the number of days to 75 percent emergence (Post 1982).

Figure 4 shows the yields of green and red chile obtained for the six planting dates. The highest green chile yield was obtained for the March 30 planting date. Thus, planting on or before March 30 appears most favorable for trickle irrigated chile. Red pod yields did not appear to be as strongly affected by planting date, which may be due to the longer growing season for red chile.

Multiyear use of trickle tubing. In 1981, cotton was planted in one-half of a 4-acre field that had been planted in drip irrigated chile in 1980.

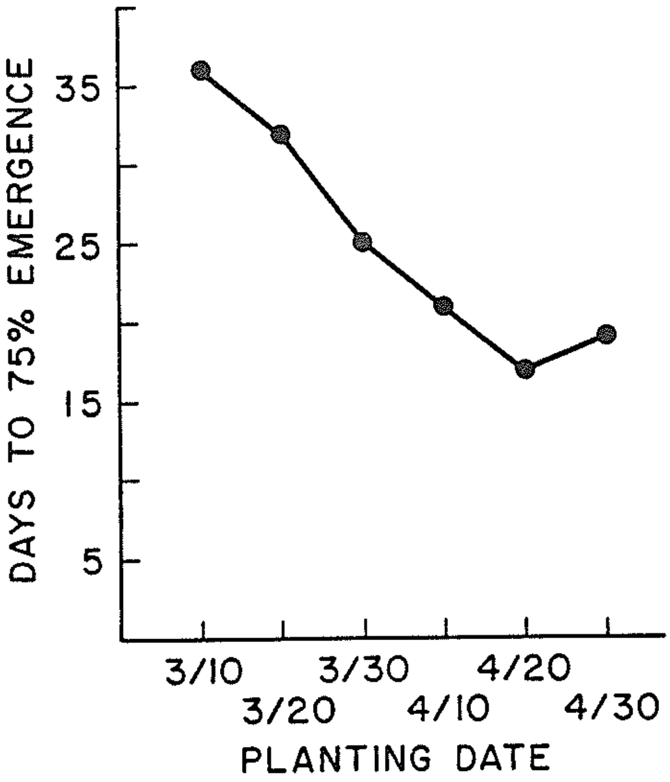

Figure 3. Days to 75 percent emergence versus planting date.

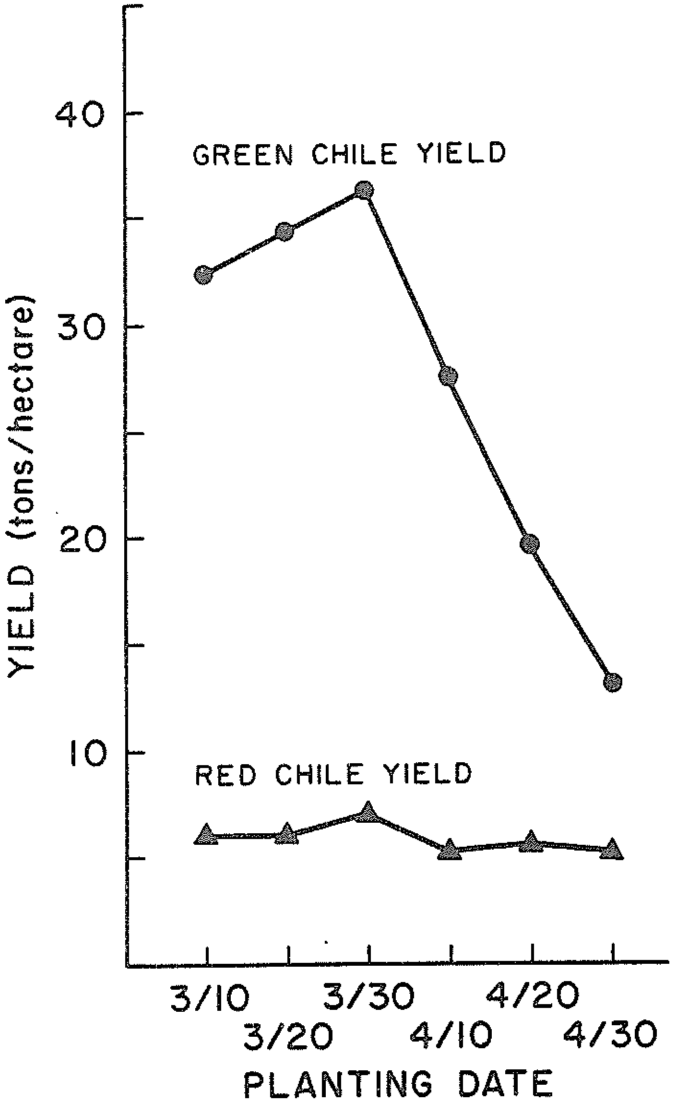

Figure 4. Green and red pod yield (metric tons/hectare) for all six planting dates.

The other half also was planted with cotton but flood irrigated. The chile stalks left from the 1980 growing season were chopped and cotton was planted directly in the untilled soil, without preirrigation. The flood irrigated field was treated as is common in the Mesilla Valley. Assuming there was enough carryover from the 1980 chile crop, we applied no fertilizers to the trickle cotton. Weed control was done with herbicides and some hand hoeing. The total amount of water applied to the cotton through the trickle lines in 1981 was 21 inches. The flood irrigated plot received 31 inches. In 1982, cotton was again planted on the 2-acre trickle irrigated field, using the same tubing, and again without land preparation or cultivation except for chopping of the cotton stalks remaining from the previous season. The amount of water applied to the trickle irrigated cotton in 1982 was 24 inches. Cotton yields in 1981 were 2.2 and 1.9 bales/acre of lint cotton from the trickle irrigated and flood irrigated plots, respectively. In 1982, the cotton yield was 1.4 bales/acre from the trickle irrigated field. Thus, in this three-year experiment we obtained an excellent yield of chile peppers the first year, an above average yield of cotton the second year, and an average cotton yield the third year. These results show that trickle tubing can be used three years in a row. During the third year many emitters were plugged and the water distribution over the field was not ideal. Yet an average yield was obtained at minimal costs.

Conclusions

Perhaps the most important aspect of this study on trickle irrigation is the prospect of combining trickle irrigation with minimum tillage and reduced fertilizer application rates. Installing trickle irrigation systems is relatively expensive. However, if the use of such a system can be combined with minimum tillage in a three-year rotation and reduced fertilizer and water use while maintaining adequate yields, one might have an economical viable farming system.

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SURGE FLOW IRRIGATION

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Introduction

Surge flow irrigation, a new concept in surface irrigation, requires that water be applied to a field surface in a series of on/off pulses. These pulses, called "hydraulic surges", thus the name "surge flow", are generally independent water applications whose sum is designed to satisfy the antecedent soil moisture deficit. Initial studies have shown that surge flow has the potential to significantly improve the performance and versatility of surface irrigation systems.

Background

The concept of surge flow irrigation originated in 1978 when Drs. Glen E. Stringham and Jack Keller, Utah State University, were attempting to develop an automated furrow cutback system. The typically irrigated furrow loses large volumes of runoff water at the end of each furrow. Flow control techniques are used to reduce furrow inflow stream sizes when the water reaches the distant end of the furrow. Common practices are to manually throttle flow-control valves, or use smaller diameter syphon tubes, to achieve this. The Utah researchers were attempting to achieve a cutback mode with an automated system using gated pipe with valves at each gate. They concluded that some irrigation valves could be more effectively operated in an open/closed mode, rather than in fully open or partially open modes, to obtain the desired cutback flow (Stringham and Keller 1979). Automated valves were cycled on and off in a manner that achieved a "time-averaged" cutback flow without changing the instantaneous discharge of the valves. The results showed that water advance rates down furrows with cycled inflow streams were about 30 - 40 percent faster than with continuous inflow streams.

The Utah group believed that the implications of these findings, and the effects they could have on surface irrigation, were of such magnitude that the development of this technology should be accelerated. This belief lead to the establishment of a technical committee on surge flow irrigation and the founding of Western Regional Project W-163, Surge Flow Irrigation, in August 1981. Ten western states are now doing surge flow irrigation related research. Questions pertaining to the hydraulics and mechanics of surge flow irrigation are being addressed by this group. New Mexico State University (NMSU) is represented on the regional project by Dr. Robert B. Hulsman, Department of Agricultural Engineering. The contribution to the region, and to the state of New Mexico by NMSU, is in the area of closed border irrigation and the benefits as may be derived from surge flow irrigation.

Current Research

Current research projects include investigation of soil infiltration characteristics under the various flow regimes of surge flow. These characteristics include the changing infiltration rate of the soil with numerous wet and dry advances during each irrigation. Also being investigated are the results of operating the systems using different cycle times and cycle ratios. The terms "cycle time" and "cycle ratio" are defined as the total inflow stream on-time plus the stream off-time and the ratio of the inflow stream on-time to the cycle time respectively. The development of automatic valves and electronic controller systems has progressed to the point where industry is actively involved with producing hardware specifically designed for surge flow irrigation. Soil chemists and physicists also are investigating soil properties relative to surge flow.

System Layout

A typical automated surge flow irrigation system is shown in figure 1. The main water supply to the system is from an underground pipeline, although it could be from a canal. A micro-processor controller operates two alfalfa valves and two T-gate valves that cycle water to two of the four closed borders. Three different irrigation conditions, row crops, broadcast crops and a bare soil surface, are presented in the figure. Borders #1 and #2 are irrigated by the upper set of control valves.

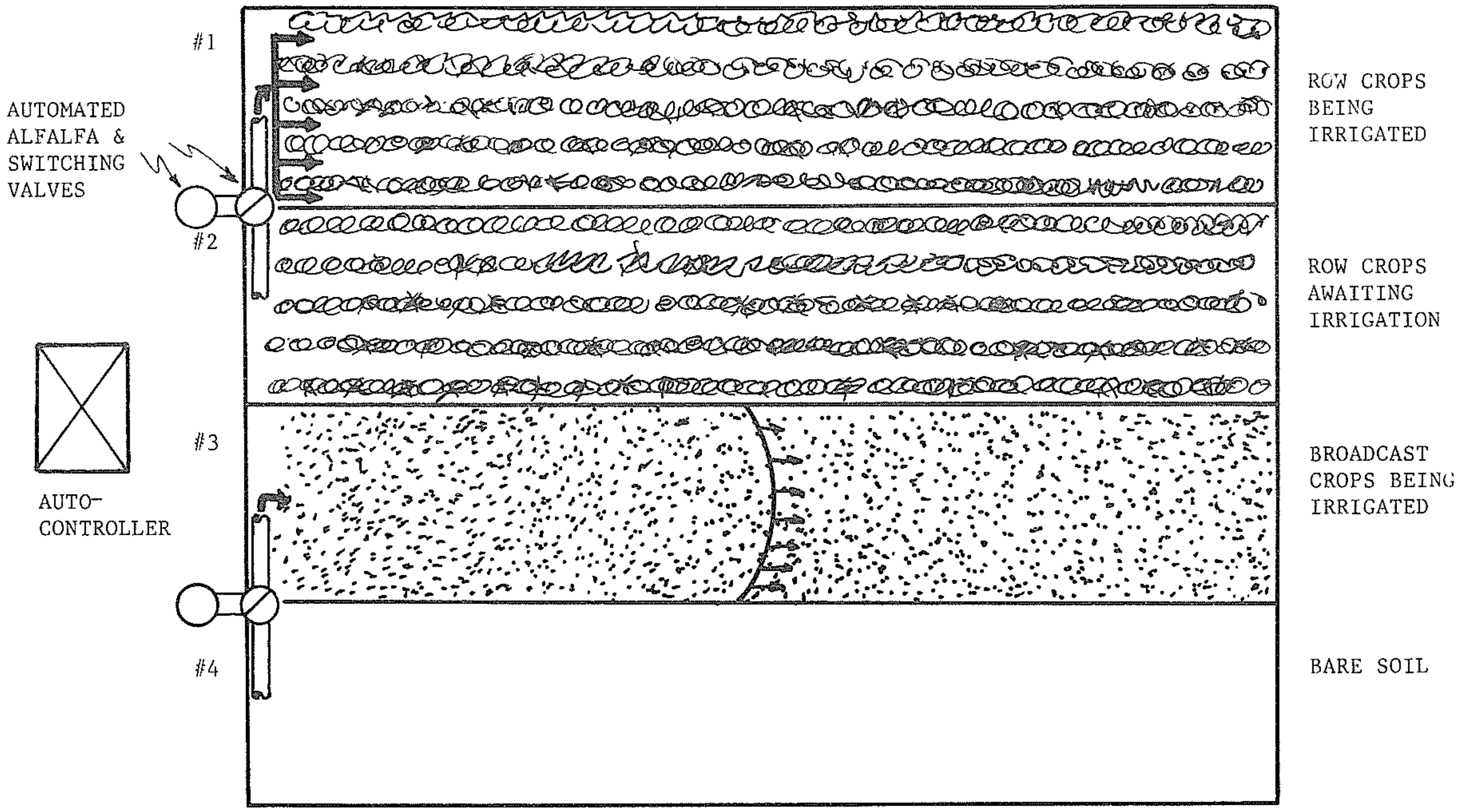

Fig. 1. A typical automated surge flow irrigation system with four borders, auto-controller, automatic valves and field cultivation practices of row crops, broadcast crops and a bare soil surface.

While one border is being irrigated, the water in the other is both moving down the border and is being infiltrated. When border #1 has completed its surge on-cycle, and all the water in border #2 has infiltrated, the suppy water will be diverted to border #2. The water in border #1 will continue to move down the border, and infiltrate, until the next water surge event. The stream of water passes between the rows causing an increase in the time for water to advance down the border. The reasons for the increase in advance times are attributed to the difference in soil surface conditions because of cropping practices. Border crops are usually either drilled, as with small grains, broadcast, as with alfalfa or pasture, or planted in rows. Crops drilled across the border offer a greater resistance to flow than those drilled down the border. Broadcast crops offer even greater resistance to flow. Crops planted on furrows are not normally located in the flow stream and therefore offer no impediment to flow, other than soil surface roughness. Border #3 is a broadcast crop, also being surge flow irrigated. The major difference between border #1 and #3 is that the resistance to flow is much greater, therefore the time required for the flowing stream to move a given distance down the border will be longer. Border #4, a bare soil, offers the least resistance to flow because no crops are currently growing in this border. This condition would exist only when a border is being pre-irrigated.

Research Results

Tests in Utah indicate the volume of water required to wet an entire furrow length was 33 percent less than that required using a continuous flow stream (Stringham and Keller 1979). Other tests in Utah also indicate the average advance time for continuous flow in furrows exceeded 400 minutes, whereas the average time for surge flow was about 130 minutes (Allen 1980) for the same furrow lengths, a decrease of 67 percent.

Tests conducted in Washington in 1982 indicate that advance times were approximately equal for surge flow as compared with continuous flow. However, the volume of water needed for surge flow was half as much as for continuous flow (Regional project paper, W-163, 1982).

Preliminary tests for 36 graded border irrigations in New Mexico indicate advance times were greater, in all cases, for surge flow irrigations over comparable borders using continuous flow. A cycle ratio of 0.5 appears to be the most beneficial in reducing surge flow advance times (figures 2 and 3). Regional investigators also have found this to be best for furrow irrigations. Surge flow is also very convenient because it will enable the switching of water flow from one border to another without having to program controllers to schedule around uneven off and on stream flow times.

Although the advance time were greater, the volume of water applied to surge flow borders was less than for continuous flow borders using the same inflow rate. The largest volume difference between surge and continuous flow appears to be associated with a cycle ratio of 5.0.

A 34.2 percent water savings was recorded on a laser level border, using a 0.5 cycle ratio, and 27.4 percent less on a graded border using the same ratio and growing the same type crop (figure 2). Another graded alfalfa border used 25.1 percent less water than a comparable continuous flow border using a cycle ratio of 0.5 (figure 3). Other cycle ratios produced water volume savings but less dramatically as shown by the higher inflow stream sizes for alfalfa (figure 3).

Considerably more research into the relationships of cycle times, cycle ratios, and inflow stream size versus flow hydraulics is needed before the effects of the surge flow phenomena may be assessed for border irrigation.

Disscussion

Some of the inherent imperfections of conventional surface irrigation may be overcome by increasing by as much as two or three times the advance distance down a field for a given volume of water. Overly deep percolation of water at the head of the field, in order to achieve a full irrigation of the root zone at the end of the field, can be eliminated. The difference between the intake opportunity times at the head and the end of the field are reduced and the resultant water distribution over

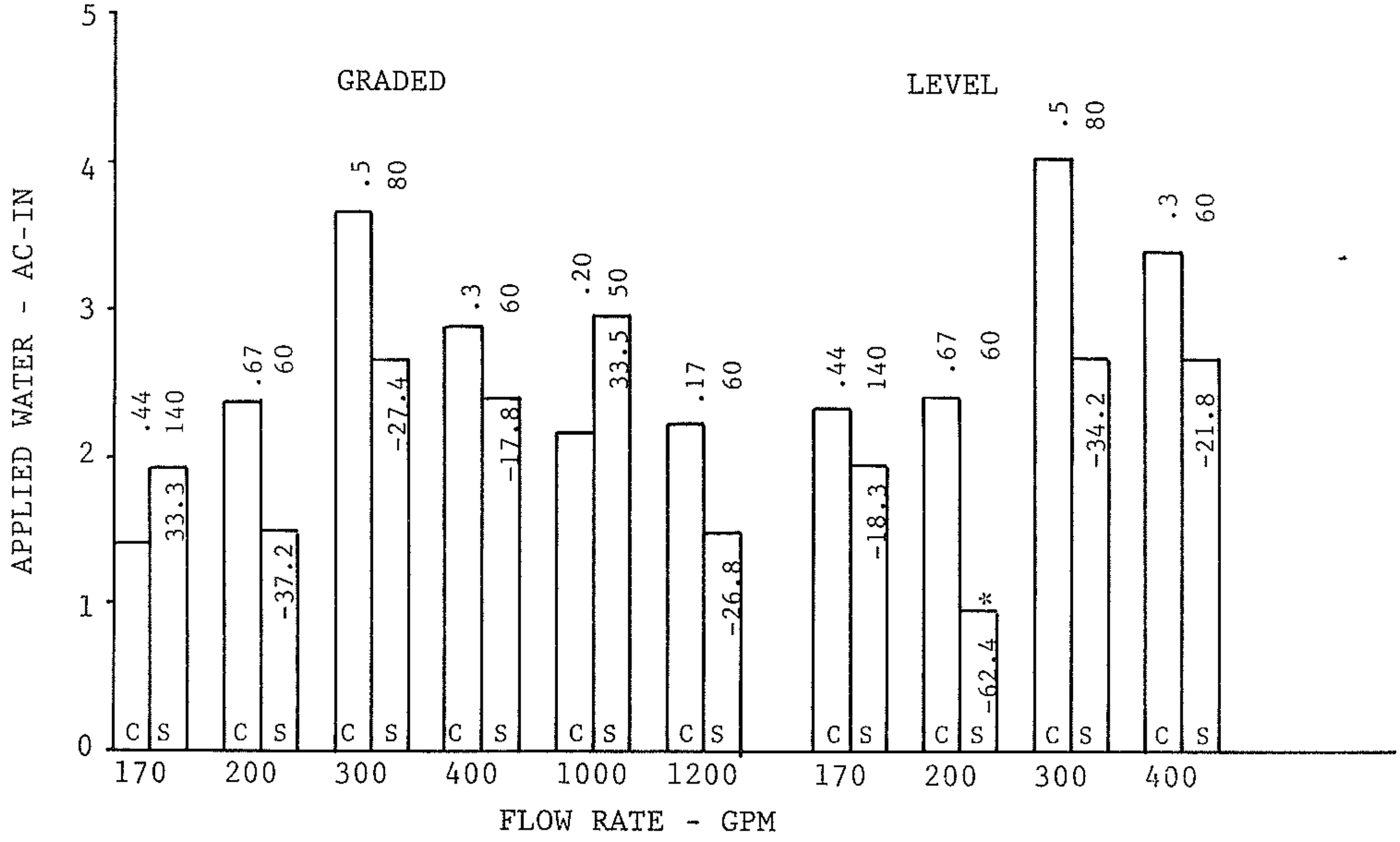

Fig. 2. Total water used for continuous (C) flow and surge (S) flow irrigation on borders of barley. Cycle ratios and cycle times are shown at the top of each bar. Percent difference of water volume used for surge flow over continuous flow is shown within the bar.

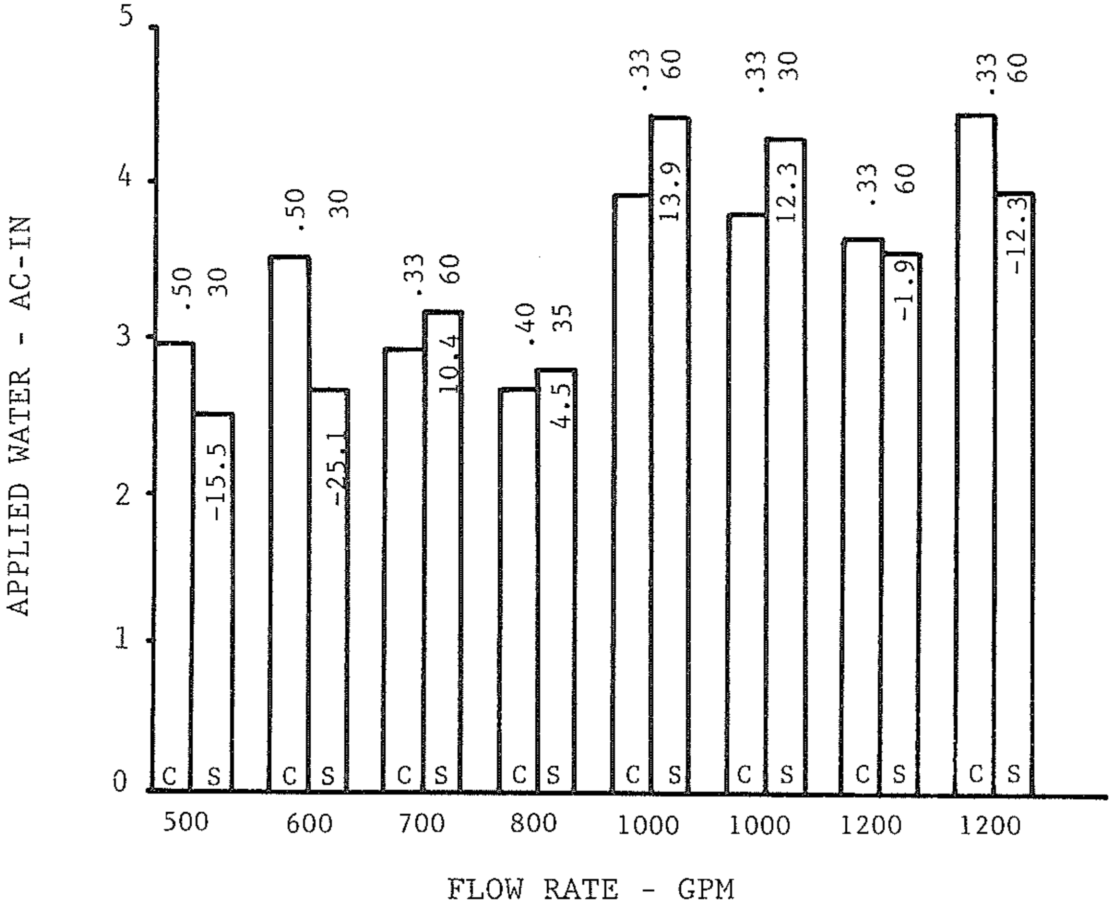

Fig. 3. Total water used for continuous (C) flow and surge (S) flow irrigation on borders of alfalfa. Cycle ratios and cycle times are shown at the top of each bar. Percent difference of water volume used for surge flow over continuous flow is shown within the bar.

the field is much better (Bishop et al. 1981).

Surge irrigation is a practice with the potential of increasing surface irrigation efficiencies to levels usually associated with sprinkle or trickle irrigation. Because surge irrigation involves automation and does not require water pressurization, it affords the immediate advantage of labor and energy savings. Other advantages include increased yields, higher income, and savings in fertilizer and herbicide use. A disadvantage is the higher initial cost of an automated system. These systems are expected to cost must less than other automated systems, however.

The ease by which surge flow can be automated could lead to the eventual replacement of high water and energy consuming irrigation systems currently in use in many areas of the state.

Existing irrigation scheduling computer software (Hulsman and Hohn 1984, Hulsman 1985a, Hulsman 1985b) easily can be used to schedule irrigation frequency and amounts for crops irrigated with surge flow systems. Automated systems of this type also could have micro-processors that read computer scheduling commands and activate the irrigation system without direct management input, other than to program the computers.

Significant improvements in irrigation efficiencies are critical to future growth in New Mexico agriculture. Competitive pressures from urban, industrial and other demands already are causing transfers of water from the agricultural sector. These water transfers are accompanied by a reduction in irrigated acreage because of a very limited water supply (U.S. Department of the Interior 1976).

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DEVELOPMENT OF WATER EFFICIENT CROP CULTIVARS

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Development of drought resistant cultivars, or plants with increased water-use efficiency, are age-old objectives in plant breeding that have not been very productive. The only accomplishments have been the identification of cultivars that perform better than others under water-stress conditions through widespread testing programs. This improved performance is most often due to an escape mechanism, such as early maturity, which limits yield potential under more optimum conditions. The research into drought resistance has generally taken two directions:

1. With major crops--the idetification of resistance mechanisms; or
2. Development of miscellaneous crops that grow under limited moisture conditions.

Volumes of research have been published on factors thought to be associated with drought resistance. The usefulness of the findings are limited by: (1) confounding of cause and/or effect factors; (2) the fact that no one mechanism is responsible for drought resistance in all environments and germplasms; (3) by costs and manpower associated with obtaining measurements; and (4) lack of determinations of heritability.

The research on miscellaneous crops is most often limited by a lack of a marketable commodity and producer acceptance even though the plants may grow with less moisture. Some of the miscellaneous crops are such efficient scavengers of soil moisture that they decrease their own growth over time and deplete soil moisture to a degree that other crops cannot follow until after a moisture recharge period.

The plant breeding effort is further complicated by stress environments reducing the ability to detect genetic variability and increasing specificity of adaptation.

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Despite these negative factors, a plant breeding program to improve the productivity of alfalfa under less than optimum moisture conditions was initiated at New Mexico State University. Alfalfa has a high water requirement, but is also considered to be drought resistant because of its ability to go dormant during periods of stress and because of its deep and extensive root system. Alfalfa is a cross-pollinated polyploid that provides more potential genetic variability than expected with most major crops. Alfalfa, the most important cash crop in New Mexico, is grown on the largest irrigated acreage. Thus, savings in even small amounts of irrigation water could be significant with water-use efficient alfalfa. Potentially, alfalfa acreage could be expanded into dryland areas now occupied by wheat and grain sorghum. The perennial nature of alfalfa impedes the breeding program in that evaluations must be conducted over a period of several years. The involvement of limited irrigation removes the problems associated with the unpredictability of natural rainfall and allows definition of target environments. The moisture environments for these studies were defined as 16 to 20 (high stress), 36 to 40 (intermediate stress), and 30 to 80 (optimum) acre-inches of water per year. Initial efforts scheduled irrigations uniformly over the entire growing season which runs from February to November.

The initial efforts involved field studies to identify cultivar and germplasm sources with potential to improve production under limited irrigation conditions and to establish expected yield levels on which to base future studies. Three types of plant responses were noted: 1) entries that performed well at low rates of irrigation but decreased in relative performance as rates of irrigation increased; 2) entries that increased in relative performance with increased irrigation; and 3) entries that performed well at all levels of irrigation. At the low rate of irrigation, Zia, San Jon Dawson, Lahontan, Turkistan, and NC83-2 were the highest yielding entries. As the intermediate rate of irrigation, the best entries were Zia, Labontan, Mesilla, NC83-2, and Vangard. When stress levels were extremely high, C-3 was a good performer, but did not show yield potential in more optimum environments. Forage yields were reduced 65-70 percent and 5-25 percent at the low and intermediate rates of irrigation when compared to the high rate of irrigation.

The second process was the development of screening procedures to identify genotypes with the capability of improved performance with less than optimum moisture. The requirements of the screening procedure were that it: 1) be non-destructive of plants; 2) be able to handle extremely large plant populations in a minimum time with low manpower inputs; 3) result in a large selection differential; and 4) produce heritable results in the same environment. Final evaluation will be field yield trial results under controlled irrigation. Fifteen to 20 potential screening procedures were evaluated with only five selected for progeny evaluation. The field stress test resulted in a first cycle population that exceeded the yield of its specific check by 41 percent at the low rate of irrigation. The first cycle population also was similar or slightly higher in yield than its check at the intermediate and high rates of irrigation. The first cycle population produced by the PEG (polyethylene glycol) producedure exceeded the yield of its specific check by 16 percent at the intermediate level of irrigation but performed poorly at the low rate of irrigation. Populations from the field capacity pots and wilt procedures yielded less than their checks at all rates of irrigation. Selected population from the drought box procedures yielded from 15 percent less to 14 percent more than the check cultivar. Second cycle selected populations were produced by subjecting the first cycle populations to the selection procedure by which they were initiated, and intercrossing the selected plants. At a low rate of irrigation, additional gains were obtained from the drought boxes and the PEG procedures. At the intermediate level of irrigation, additional second cycle gains were obtained from the drought box procedure. Second cycle seed was not available when this test was planted from the field stress procedure. However, 9-D11A, a first cycle field stress population, was the highest yielding entry in the test.

These results have established that performance with less than optimum levels of irrigation is a heritable trait and can be improved by plant breeding procedures. Three effective selection procedures and several desirable germplasm sources have been identified.

The goal of producing new cultivars under optimum conditions with a third less irrigation water is obviously a definite possibility. The next step is to match irrigation management procedures with improved plant populations to maximize productivity.

GENETIC ENGINEERING FOR DROUGHT TOLERANCE

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It is well known that much of the available water in states such as New Mexico--about 85 percent--is diverted to irrigated agriculture. However, urban growth and industrialization are making greater and greater demands on the available water, especially high-quality water, in arid and semiarid regions. Significant advances in recent years in the development and application of improved irrigation systems and water management practices have provided important opportunities to conserve water and help reduce some of the water quality problems associated with irrigated agriculture. Another important way in which to conserve our water resources is to utilize economic crop plant varieties and cultivars that make reduced demands on irrigation water supplies, or that can utilize lower quality water. At New Mexico State University, Dr. Bill Melton has made efforts to develop a water use efficient alfalfa variety. Alfalfa is New Mexico's leading cash crop and most significant water user among local crops. He and his colleagues have utilized conventional breeding approaches to improve water use efficiency in alfalfa. Although these approaches are proven and significant progress has been made, it is generally difficult and time consuming to breed crop varieties with enhanced water use efficiency. Novel genetic engineering technologies offer the potential to speed the efficient breeding of crop varieties. In the broadest sense of the term, genetic engineering includes the conventional breeding techniques. In more popular usage, however, genetic engineering refers to a number of emerging genetic tools based on laboratory techniques. I intend to describe one of these laboratory-based approaches as a possible new tool to supplement conventional breeding and improvement of crop plants for enhanced water use efficiency and/or water stress tolerance.

The Theoretical Basis of Cellular Selection

The conventional breeder typically is able to grow about 1,000 plants on a acre of land and often must maintain them for an entire growing season in order to perform one cycle of selection. Thus, the breeder deals with thousands of selection units, and then applies some appropriate selection pressure resulting in, say, the best 10 percent of the individuals being saved to produce the next generation for another cycle of selection. Generally, several cycles of selection are required in an improvement program. The cellular geneticist is able to grow about one billion cells of a plant in one or a few liter of nutrient media in the laboratory. These cells generally divide within days to produce the next generation. Many selection pressures can be imagined which could be incorporated readily into the nutrient medium or provided within the environment. Thus, the potential power of the cellular selection tool resides in the fact that millions, if not billions, of selection units can be screened in a small space in a matter of weeks or months. That is, cellular selection could permit the screening of larger numbers of units with more stringent selection pressures, potentially allowing the breeder to accomplish in the period of a year what otherwise would require several years.

The state-of-the-art technology of plant cell and tissue culture have been reviewed recently in edited columes by Street (1977), Reinert and Bajaj (1974), Vasil (1980), Thrope (1981), Tomes et al. (1982) and Vasil et al. (1982). The tremendous potential of the usefulness of cellular selection techniques in plant genetic engineering has been demonstrated in several independent efforts. These efforts have resulted in the selection for genetic alteration of such traits as amino acid overproduction, disease resistance, herbicide tolerance, antibiotic resistance and salt tolerance. Current evidence indicates that when plant tissues and cells are grown in the unorganized state as callus or cell suspension cultures, the rates of genetic mutation chromosomal rearrangement and somatic recombination increase. Genetic variability therefore accumulates in such cultures over time. Selection pressures are devised, then, to sort out those variants of interest. Most agriculturally useful variants are resistance mutants, that is, they are selected on the basis of being resistant to some normally lethal or debilitating condition. Often, the selection pressure is introduced to cell cultures in a series of increasing levels of stringency, which allows for surviving cells after each phase of selection to be present in adequate cell density to proliferate. Minimum cell density must be balanced against the stringency of selection to prevent epigenetic or non-heritable escapes from being proliferated. Cells surviving the most stringent level of selection are grown out and plants are regenerated from them, usually achieved through manipulation of hormones and/or nutrients provided in the culture medium. Progeny tests of plants regenerated from selected cells are viewed as essential. By demonstrating a heritable basis for altered traits, these tests establish the usefulness of cellular selection schemes to plant improvement. The range of genetic variation resulting from cells in culture overlaps extensively with traditionally obtained phenotypes. However, there have been examples cited that may represent novel phenotypes as well. Therefore, there are strong indications that cellular selection approaches represent a very powerful genetic tool to the breeder.

Prior Efforts to Select for Water Stress Tolerance at the Cell Level

Bressan et al. (1981) made the first well-documented effort to evaluate cultured plant cells under simulated water stress using increasing concentrations of high molecular weight PEG (polyethylene glycol, a non-penetrating osmoticum) as a selection pressure. Cherry tomato cells placed in culture exhibited a 14-fold greater increase in growth under stress conditions following selection, compared to cells never previously exposed to PEG (-11 bars). The increased resistance was stable under sustained stress, but was lost upon transfer back to nonstress conditions. Plants could not be regenerated from selected cells. This is not surprising because there have been few other reports of regeneration of plants from tomato cells. These investigators could not determine whether true genetic selection of variant cells within the initial population, or physiological adaptation of the cells to the simulated water stress (epigenetic change), had occurred. They suggested that a combination of these two mechanisms were likely to be involved. They further noted that the selected cells also exhibited an increased tolerance to NaCl stress compared to control cells. Heyser and Nabors (1981) determined that tobacco cells selected for increased tolerance to NaCl exhibited osmotic adjustment. These two observations indicate there may be a potentially common mechanism of cell adaptation under these two selective conditions. In the leater case, plants were regenerated from selected cells and the plants exhibited a genetic basis for the cell adaptation to NaCl stress, but water use was not evaluated.

Clearly, the initial report on cellular selection under simulated water stress offers encouragement, but at the same time points out the very early, pioneering nature of this area of research. In a recent review of water and salt stress tolerance in cultured cells, Handa et al. (1982) concluded that "...selection by exposure to (PEG or salt induced) stress is unable to discriminate between the innately tolerant and intolerant types within the population..." using current cellular selection procedures. However, they considered that a mixed population could nevertheless yield salt tolerant plants consistent with reported literature. They go on to state "...that understanding the nature of the selection mechanisms is particularly germaine in obtaining variant cells which possess agriculturally useful traits." They did not indicate how this could be accomplished except to suggest that perhaps biochemical assays of key metabolites or enzymes may be a better measure of cellular tolerance than growth or survival per se under stress. This raises the fundamental question of how to validate a cellular selection approach to be assured of deriving variants of a particular type.

In Vivo - In Vitro Correlations as a Means to Validation of Cellular Selection Approaches

Several fundamental questions need to be addressed in order to develop a cellular selection procedure to aid in the improvement of crop plants for water use efficiency. First, what selection conditions are required at the cellular level to distinctly separate water stress tolerant (or water use efficient) from intolerant (or inefficient) cells in mixed populations? Second, is there a genetic basis for cell adaptation in culture to induced water stress? And third, can plants be regenerated from cells selected in this manner that will be useful in plant breeding programs? Current research efforts in our laboratory are focused on the first major question posed above. It seems reasonable to use whole plants that possess the desirable characteristic as a standard by which to measure cellular performance. The availability of genetically related populations, which differ in respect to this single characteristic (primarily), would offer a paradigm for the study of cells in a mixed population in terms of distinguishing between cell types. In other words, correlation of cellular responses with known responses of whole plant populations would offer a means to validate the cellular selection approach.

The materials are available to address this issue. Dr. Melton and his colleagues at NMSU have developed alfalfa populations that differ in their ability to utilize water efficiency under field production conditions. They have made those materials available for this pursuit. Such materials are essential to answer the first question posed above, in that plants with known genetic differences for performance under limiting water in the field can then be used to establish whether these genetic differences are expressed at the cellular level under simulated water stress (e.g., using PEG). If so, there is a firm basis for performing cellular selection for improvement of water use efficiency along the lines of Bressan and colleagues. If not, the screening and/or assay procedures will have to be modified in a manner such that the known genetic differences are expressed at the cellular level in predicted ways. It is my thesis that whole plant-cell correlations for genetic expression of targeted performance characteristics are essential to the development of useful cellular selection approaches.

It is relevant to note from Dr. Melton that the more efficient plants in the field survive no better than the control plants in the absence of water. This finding indicates that growth or survival per se is not the distinguishing feature of water use efficiency, at least in this case. Rather, he observes that efficient plants do one or both of two things: 1) start growing again (break dormancy) more quickly in the presence of water, while controls do not break dormancy much before the water disappears again; or 2) grow at a much faster rate than controls in the presence of water. This observation argues that a time-course study of growth following removal of stress may be an appropriate means to distinguish efficient from inefficient cell types.

Thus, there are at least three possible approaches to address the issue of validation of a cellular selection scheme through in vitro in vivo correlation studies. First, and simplest, is the application of PEG or some other osmotic agent to the known differentially responding alfalfas in tissue culture to determine whether these materials respond in the predicted differential manner under stress at the cell level. A second approach would be an assay or combination of assays that biochemically differentiate these materials in the predicted manner under stress at the cell level. Third, a growth or biochemical assay may differentiate these materials in the predicted manner at the cell level upon removal of the induced stress.

Preliminary results from our laboratory have indicated that the application of -11 bars PEG to tissue cultures of these model alfalfa populations, using growth and survival as the index for screening, does not elicit a perfect correlation to the whole plant predictions. Materials from one genetic background do show reasonable correlation to the whole plant response, but materials from another genetic background do not. The application of salt or mannitol as osmotic agents also failed to elicit the expected responses. The conclusion is that simple growth under PEG induced stress is not adequate to distinguish between innately stress tolerant and intolerant cell types in a mixed population. It was important in this case to have two genetic backgrounds to test the hypothesis in order to avoid a mistaken conclusion. Current activities in our laboratory are focused on key metabolites and enzymes as biochemical selection indices both under stress and upon removal of stress in the tissue cultures. Of particular interest are amino acids, polyamines and their biosynthetic enzymes (Galston 1983).

Future Directions

We anticipate that an additional 12-18 months of research will allow us either to validate a cellular selection scheme based on in vitro in vivo correlation studies, or to have gathered sufficient information to state why cellular selection for enhanced water use efficiency is not feasible.

We are optimistic, despite certain logistical problems, that a positive solution to this issue will be obtained. Assuming success is forthcoming, the materials and technologies are available to address the other two fundamental questions posed earlier in this paper; 1) whether there is a genetic basis for cell adaptation in culture resulting in greater water use efficiency; and 2) whether plants can be regenerated from selected cells so that they will be useful in plant breeding programs.

Numerous scientists have worked out the procedures for regenerating alfalfa plants from cultured cells. This process is under genetic control and only a proportion of plants in many populations are competent to complete the regeneration process. Our laboratory has screened nondormant and semidormant alfalfas adapted to New Mexico and the southwestern United States for genotypes that regenerate plants from cultured cells (Phillips 1981). Useful regenerator lines among these materials and the optimal conditions for regeneration have been identified. Cellular selection aimed at improvement of forage quality has been carried out in alfalfa (Reisch et al. 1981, Reisch and Bingham 1981). The putatively validated cellular selection scheme for enhanced water use efficiency can then be challenged by actually carrying out a cell selection program with these local regenerator materials. Progeny of plants regenerated from selected cells can be evaluated to determine whether a genetic basis exists for any observed enhancement of water use efficiency. Moreover, such materials can be directly compared with materials selected under field stress conditions (i.e., Dr. Melton's materials) to determine their usefulness in a breeding program. This comparison also will generate an estimate of actual genetic gain or breeding progress achieved through a single cycle of cellular selection, which will give the breeder an intelligent means to predict the value of incorporating the cellular selection program. This comparison also will generate an estimate of actual genetic gain or breeding progress achieved through a single cycle of cellular selection, which will give the breeder an intelligent means to predict the value of incorporating the cellular selection tool into an ongoing breeding program. It is doubtful that such a tool will be very helpful to the alfalfa breeders at NMSU because the time invested in developing their present populations may have yielded suitable materials that could no longer benefit by cellular selection. However, if the cellular selection tool is proved valuable in the alfalfa model system, it will be a powerful tool indeed for incorporation into the breeding programs aimed at other important crops in New Mexico and elsewhere.

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WATER MANAGEMENT AND CONSERVATION

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The restructuring of the nation's water management institutions is evidence of the uncertainty our nationwide management perspective. The demise of the Water Resources Council, proposals for agency consolidation, and a new focus on cost sharing and financing for federal projects are causing a redefinition of traditional federal, state and local roles. In addition, there is an obvious shift away from an attitude of development as the only solution to supply problems toward improved management and conservation for better, more efficient service from existing development. Although some major projects will continue to be built, it appears that the era of major water development projects is drawing to a close.

Over the last half century, the composition and magnitude of our nation's water use has changed. Technological change, economic development and population growth have placed greater demands on the resource. Along with the development of irrigated agriculture, the past 50 years have been characterized by the growth of domestic and related uses and the expansion of central supply and delivery systems to serve them. We cannot rely on further development alone to meet all demands, however, because many sources are now nearly completely developed.

The need for overall budgetary retrenchment also has grown with the size of the federal deficit. There are more competing demands for the federal dollar, including funds needed for the operation, maintenance, repair, rehabilitation and/or modification of existing projects. Except for major port and waterway improvements and flood control reservoirs, new water development project proposals have been relatively limited in scope and unable to command widespread public and institutional support.

During the past decade, project cost sharing and financing also has been subjected to severe scrutiny and divisive debate. The National

Water Commission's milestone report in 1973 recommended a series of cost sharing policy changes. The Carter administration completed the "Section 80" study of cost sharing authorized by the Water Resources Development Act of 1974 and consequently proposed that the benefits of certain projects, a "hit list", be re-evaluated. The Carter administration also proposed that, in addition to sponsors fulfilling traditional requirements for land rights and project operation, states finance "up front" 5 to 10 percent of project costs, depending on the nature of the outputs. These proposals generated a great deal of controversy, and no consensus on cost sharing and financing was achieved. The era of turmoil, characterized by a gradual loss of a consensus among the executive and legislative branches on water priorities and federal responsibilities, has been accompanied by a halt in the congressional authorization process for new water projects.

Among the 106 on-going construction projects in the corps' FY 1985 civil works budget (147 projects in FY 1983), only six were begun after 1979. Meanwhile, 200 projects involving $13 billion await authorization and projects involving $16 billion are authorized and await funding.

The abilities of local governments, the states and the nation to meet critical water needs will be sorely tested in the years to come. Huge population shifts are placing stress on the nation's older, more developed, but water-short, region to provide water from an already heavily allocated resource. By the year 2000, the states in the water-short Sunbelt will have to accommodate the needs of 39 percent of the nation's population. Central to an understanding of national (and for that matter, international) domestic water questions is the preoccupation with present and emerging water problems in urban areas. Exponential growth of water needs and qualitative aspects of natural resources development have coalesced to create a background of urgency vis-a-vis urban water problems. Competition among agricultural, industrial and domestic uses for often inadequate supplies is increasing and ground water overdraft and quality problems already are a reality in some regions.

This competition for the limited resource is seriously impinging on the ability to supply water for all uses in some regions of the country. Droughts in the Northeast from 1961-1966, in the West from 1976-1978, the nationwide fears of drought early in 1981, and persistent rumors of climate change are reminders of the variability of the hydrologic cycle. This variation also brings the related threats of supply interruption, desertification and economic and social losses. During the drought of the 1960s, 14 million of the 50 million residents of the northeastern United States were restricted in their water use. Recent state of Pennsylvania studies indicate that for the lower Susquehana and Delaware River basins, the 1966 drought was a once in 50-year event and that the drought of 1980-1981 in southeast Pennsylvania was only a once in a 5-10 year event. Yet, preliminary indications are that 44 percent of 120 sample water systems in this region experienced shortages in 1980-1981, whereas two-thirds of those experiencing shortages had no shortage in 1966.

Many domestic water users in the nation's rural areas depend on single or limited supply sources that are subject to drought. In some regions of the country mandatory conservation is becoming the rule, not the exception. Real time adaptation to domestic water shortage emergencies often takes on a different perspective than preplanned technical responses. Local politicians and decision makers often deal with drought disasters from a different risk acceptance perspective and are increasingly willing to enter into the technician's realm in these matters. Public and local decision makers as well as some researchers' perceptions of climate variability and associated risk may also be changing given the highly variable weather patterns of recent years. In addition, there may be some technical justification to adjust emergency response organization and practice to the uncertain possibility of increasingly extreme weather.

Major areas of needed investment also exist in the rehabilitation and replacement of distribution and treatment systems, and the development of new sources. Numerous newspapers and magazine articles and reports have focused on the problems as unique to either older cities located in a particular region of the country, generally the Northeast. Yet, the studies supporting the Urban Water Supply Subcommittee work did not find these problems limited to the Northeast. Another study of more than 50 western U.S. cities found that more than 40 percent of their water was unaccounted for or lost. The technology used in water supply systems has changed little since the turn of the century. New tools have been developed in other industries (aerospace, computers, nuclear, petroleum), which could improve how water systems are built and operated. Research is needed to place such tools in the hands of practicing engineers and operators. The rehabilitation and repair of physical facilities needed to continue serving existing populations and the new facilities needed to serve future populations are both increasingly difficult to finance. Public works investment has been declining nationally for many years. Capital investment in water supply has declined relatively more than for most public works and many communities barely cover debt retirement and routine operations. Although these constraints vary across the nation, no region is exempt from domestic water problems.

I will not dwell on agricultural water use, as you have already heard a great deal about it from the other speakers. The development of irrigated farming in the West has had considerable impact on the agricultural economy of the United States. Water is often the limiting resource in agricultural production. Too much or too little--and the timing of that excess or scarcity--increases the farmer's cost of production and degrades the nation's stock of land and water resources. Ground water along with surface water is an important source of irrigation water. Ground water accounts for more than 40 percent of irrigation withdrawals in the 17 western states. The proportion is much higher in the High Plains Ogallala aquifer region.

The possibilities for demand management and shifts in use cause some observers to conclude that marginal changes in agricultural water use can "solve" other water supply needs such as domestic with some regional dislocations. Within a mixed strategy context of development, improved management, conservation and shifts in uses, domestic water demands and problems are increasing. Focused attention on this issue is needed. The two major water related concerns of the nation--water supply and water quality--have been repeatedly examined. Yet, changing socio-demographic conditions as well as shifting, planning and management practices and financing conditions invalidate much past work and previous institutional models for development. At the same time, a series of events such as droughts, water shortages, infrastructure decay, ground water depletion and water contamination have aggravated or are expected to increase persistent water resources problems.

The period of turmoil may be about to come to an end. An emerging partnership between the federal government and state and local water project sponsors can forge a new consensus on needed projects and develop strong intergovernmental support for their implementation.

President Reagan, in his January 1984 letter to Senator Laxalt concerning water development, said, "It is time to conclude the discussion and to establish a national water project financing policy so that we can get on with the job of completing projects where commitments have already been made and undertaking new construction starts to meet the country's future needs."

The letter to Senator Laxalt spells out the president's cost sharing and financing policies for water projects. The president states, among other things, that the costs of project planning are to be shared with project sponsors. For project construction and operation, consistency among projects in cost sharing for individual project purposes is to be sought so that all sponsors are treated fairly. Finally, each water agency is to negotiate reasonable project financing arrangements with the sponsors of each project, and cost sharing, financing and cost recovery arrangements are to be sumitted to Congress for ultimate disposition.
The recent series of regional water project financing workshops co-hosted by the Corps of Engineers and the Interstate Conference on Water Problems indicated a widespread interest on the part of the local, state and

federal attendees in forming the kind of partnership necessary. Such a partnership is not new, although the federal government has historically assumed a primary role in project planning, financing and construction. Local and state sponsors have been responsible for providing a share of costs in the form of lands, easements, rights of way and, in some cases, repayment of all or a portion of construction costs and the assumption of operation and maintenance. Sharing planning costs and efforts in the feasibility stage of planning may also create the opportunity to manage the process regarding project sizing, staging and design. This management will more closely match local needs and financing opportunities. Inherent to such shared study management will be a greater effort to identify more specifically the distribution of project benefits in time and space for the identification of revenue recovery possibilities by potential multijurisdictional sponsoring agencies.

Local governments, in providing a valuable experience base for this new partnership, assume their traditional responsibilities for domestic water uses and delivery systems. More and more state governments also are operating financial assistance programs to localities, for water supply planning, drought contingency planning and water conservation. A number of states have initiated water conservation programs, and this trend is likely to grow.

Nationally, diverse uses competing for both our surface and ground waters will test the resilience of our traditional institutions. In many states, water rights are over-appropriated or have little room for future uses. Instream uses, increasingly recognized today, compete with offstream uses during low flow. The growth of the energy sector will require large amounts of water now used for agricultural production. Self-supplied industrial and agricultural users are competing with public and central supply systems, as vendible and nonvendible purposes compete for the allocation of reservoir storage. As locally available sources have been allocated or exhausted, localities and states have begun to compete among themselves for shared or basin-wide resources. Further water development will have increasingly widespread effects and become more difficult to accomplish piecemeal. It is evident that future water development can only be accomplished if it is part of a well planned program as a part of a full intergovernmental partnership.

Demand, competition and financing pressures combine to create a planning and development environment where increased attention will be devoted to cost efficient management of existing water sources. These management decisions will be made to serve more users and to reconsider traditional uses in view of present demands. The management measures are of two types: technical and institutional. Conservation (or demand reduction) opportunities exist in both areas. A great deal of research already has been done on technical management systems; a major need is to implement and effectively use existing knowledge and models. Relatively more work needs to be done in the institutional management areas. Change will be hard in coming but a remarkable amount of change already is occurring. A few selected areas of additional needed research discussed at the February 1985 Universities Council on Water Resources (UCOWR) sponsored National Conference on Water Resources Research are:

1. Improved means to budget, price, finance and manage operation, maintenance, rehabilitation, repair and replacement of water resources systems.
2. Improved methods to identify beneficiaries and to obtain revenues at all levels.
3. Improved knowledge of extreme hydrologic events and risk acceptance strategies.
4. Improved institutional and technical mechanisms for conjunctive use and emergency water management.
5. Impacts of possible future use shifts.
6. Incentives to equalize consideration and analysis of demand and supply management measures by building on the large body of existing conservation research.

I put these management related topics on the table for consideration by the scientists attending this symposium today. I also put to you the prevalent conclusion of the UCOWR which says that traditional federal research dollars for water are likely to decline and researchers should look to the needs of local and state users as part of this emerging new partnership.

PHYSICAL CONSIDERATIONS IN GROUND WATER RECHARGE

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Introduction

Ground water recharge is the amount of water that replenishes aquifers. Because of the balance between recharge, discharge and depletion from aquifer storage, recharge can play a vital role in managing pumpage from ground water basins. Unfortunately, ground water recharge is one of the most difficult components to quantify in the hydrologic budget.

Recharge can occur, for instance, in upland terrain where the amount of precipitation is relatively large, where mountain-front streams cross permeable alluvium, along stream channels and canals, and in agricultural lands. Very little is known about natural recharge by infiltration of precipitation falling over natural arid terrains; however, it is a commonly held assumption that recharge to these areas is negligible. The basis for this generalization is probably the occurrence of near-surface caliche deposits that mark the downward limit of soil-moisture movement in dry climates. These landscapes are only sparsely covered by the hardiest of drought-resistant grasses and shrubs, and mean annual evaporation rates are several times in excess of mean annual precipitation. In arid terrains, most studies of deep-water movement below plant root systems have been conducted in agricultural areas or along stream courses. However, such areas comprise only a small percentage of most deserts.

I will summarize research on recharge mechanisms in a semiarid climate. The two areas of investigation include the southern San Juan Basin, New Mexico, and near Socorro, New Mexico.

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Southern San Juan Basin

The San Juan Basin site is located near Prewitt, New Mexico, where annual precipitation is on the order of 30 cm and gross annual lake evaporation is about 100 cm. The study area extends northward about 16 km toward Casamero Lake (figure 1). Along this transect, sedimentary bedrock units dip north-northeast at approximately 3 to 5 degrees (figure 2). Included in the geologic section is the Westwater Canyon sandstone member of the Morrison formation, one of the principal aquifers in the region. Mudstone and shale members confined conditions and must be dewatered for uranium mining in the Ambrosia Lake district northeast of the study area. Prior to extensive dewatering, water levels in deep wells tapping the Westwater Canyon aquifer, which are located down dip from the outcrop, showed a hydraulic gradient to the northeast in the direction of dip. Cooper and John (1968) and Kelly et al. (1980) indicate that recharge to the Westwater Canyon occurs where the sandstone outcrops. However, the sandstone outcrops on the face of a cliff in most of the area and this affords little opportunity for infiltration of precipitation. Alternative sources of recharge must exist, as will be discussed next.

An investigation of shallow ground water conditions in the alluvium along Casamero Draw, a southerly flowing ephermeral drainage, and adjacent bedrock indicates that ground water flows southward in the direction of topographic slope (figure 3). This direction is opposite to that observed in the bedrock aquifers down dip from the outcrops. The bedrock units lie beneath the alluvial aquifer along Casamero Draw as well as other lowland areas. Here, it is possible for the shallow aquifer to recharge the bedrock aquifer, and the shallow aquifer is recharged by infiltration of ephemeral runoff. However, numerical simulation results suggest that in order for recharge to occur at the subcrop of the bedrock aquifer, the hydraulic conductivity of the bedrock must be several orders of magnitude greater than that in the alluvium (Stephens 1983). Available data indicate this is not the case. Furthermore, only a few valleys similar to Casamero Draw contain saturated alluvium.

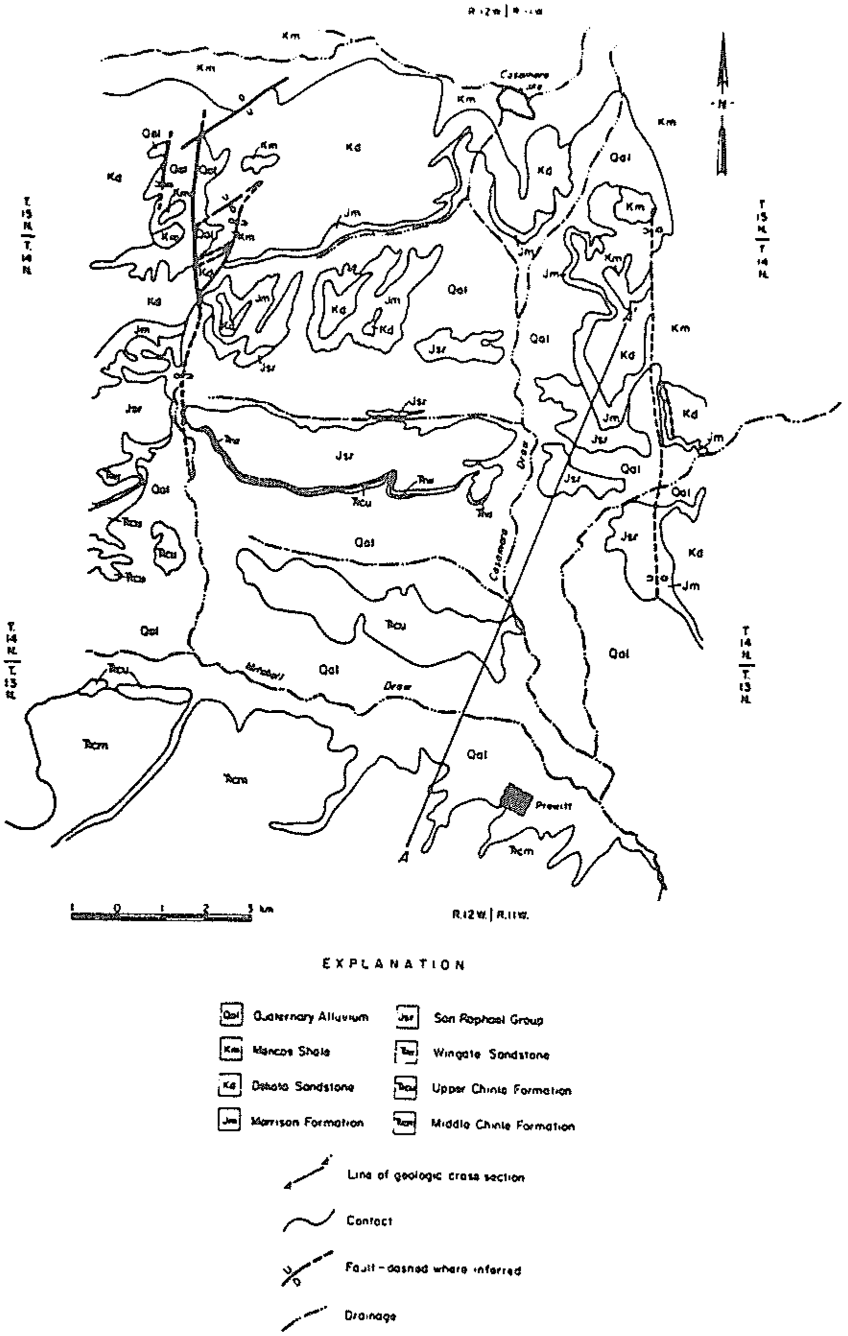


Figure 1. Geologic Map of Casamero Draw, Prewitt, NM.

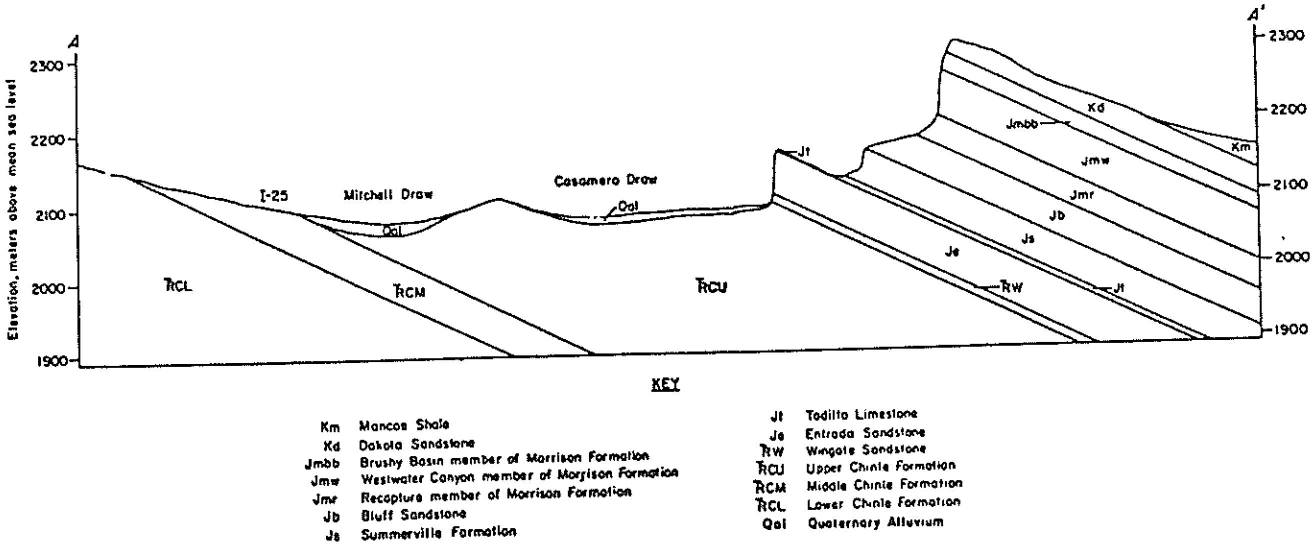


Figure 2. Geologic Cross Section North From Prewitt, NM.

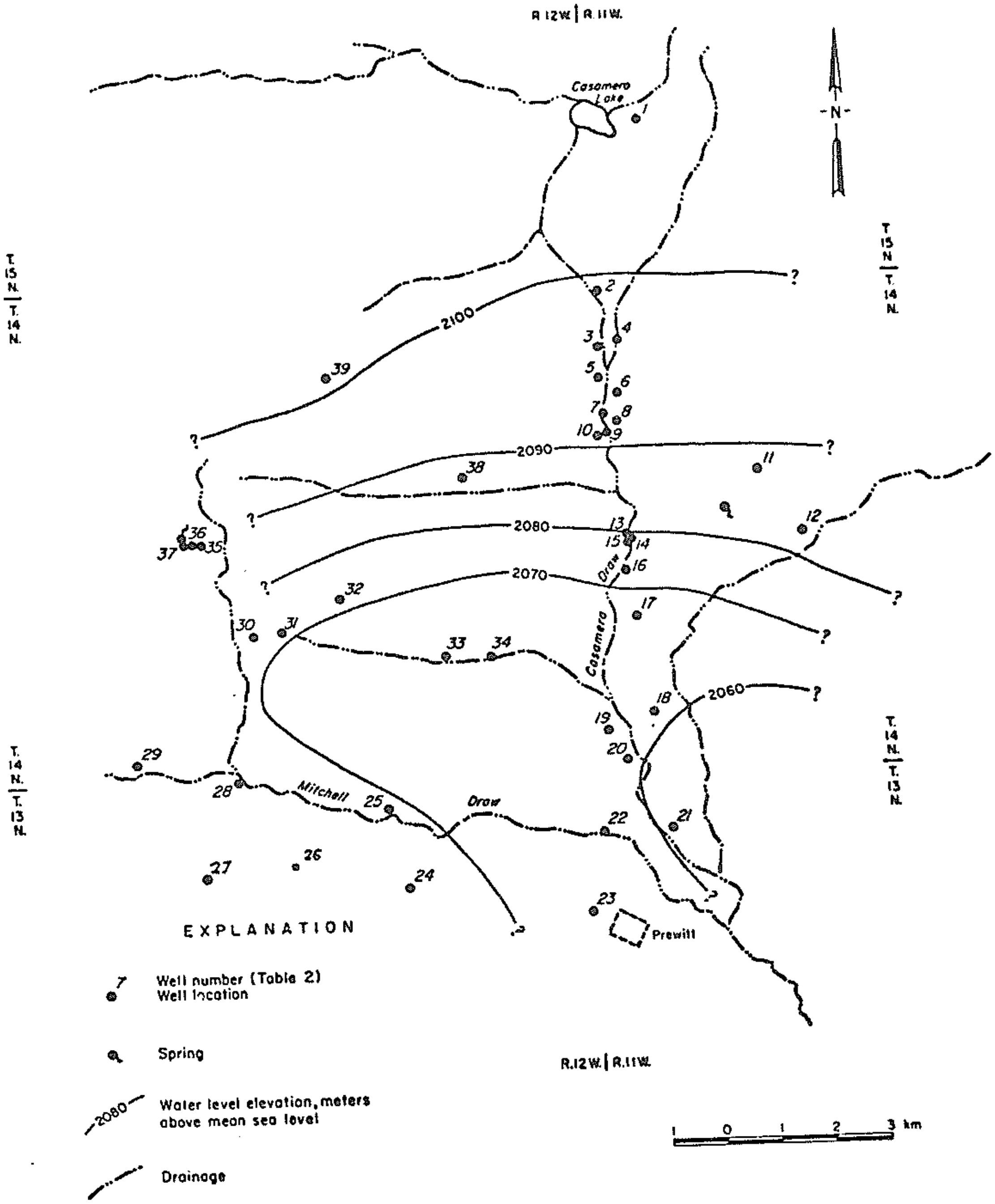


Figure 3. Water Level Elevation Contours in Alluvium and Shallow Bedrock near Casamero Draw.

As an alternative, recharge to bedrock aquifers could occur by leakage across overlying aquitards, which are in turn overlain by saturated alluvium or which transmit infiltration of snowmelt and rain. Numerical simulation results in figure 4 illustrates this recharge mechanism (Stephens 1983). This type of recharge would occur down dip from the outcrop, as well as down dip from the contact with the alluvial aquifer. Recharge across the overlying aquitard would continue along the down-dip directions. At some point in the bedrock aquifer there must be a ground water flow divide between the southerly flowing shallow aquifer system, which is controlled by topography, and the northerly flowing deeper system, which is controlled partly by geologic structure. With this hypothesis, recharge could occur over extensive areas that are covered by fractured bedrock. The Dakota sandstone, for example, forms an extensive dip slope that appears favorable for transmitting infiltrated snow melt to the underlying Morrison formation. This hypothesis for recharge in the southern San Juan Basin appears to be most consistent with observations on ground water movement.

Areal Recharge

This site is located near the southbank of the Rio Salado about 24 km north of Socorro and about five km west of Interstate 25 on the Sevilleta National Wildlife Refuge. Mean annual precipitation is about 20 cm, and gross annual lake evaporation is about 178 cm. The area is sparsely vegetated, and the surficial soils are sandy. Most casual observers would agree that the prospects for significant amounts of recharge at this location are indeed poor owing to the desert-like appearance of the landscape. Nevertheless, an area of about 1.3 square km was instrumented with tensiometers to depths of about 2.5 m and neutron moisture probes access tubing to depths up to 6 m to study soil-water movement. There is also a standard weather station, a second recording precipitation gage, and seven ground water monitor wells. The wells and soil-water monitoring station extend from the active channel of the Rio Salado on the north toward a sandstone on the crest to the south (figure 5). The soil-water instrumentation network, completed in the winter of 1983-84,

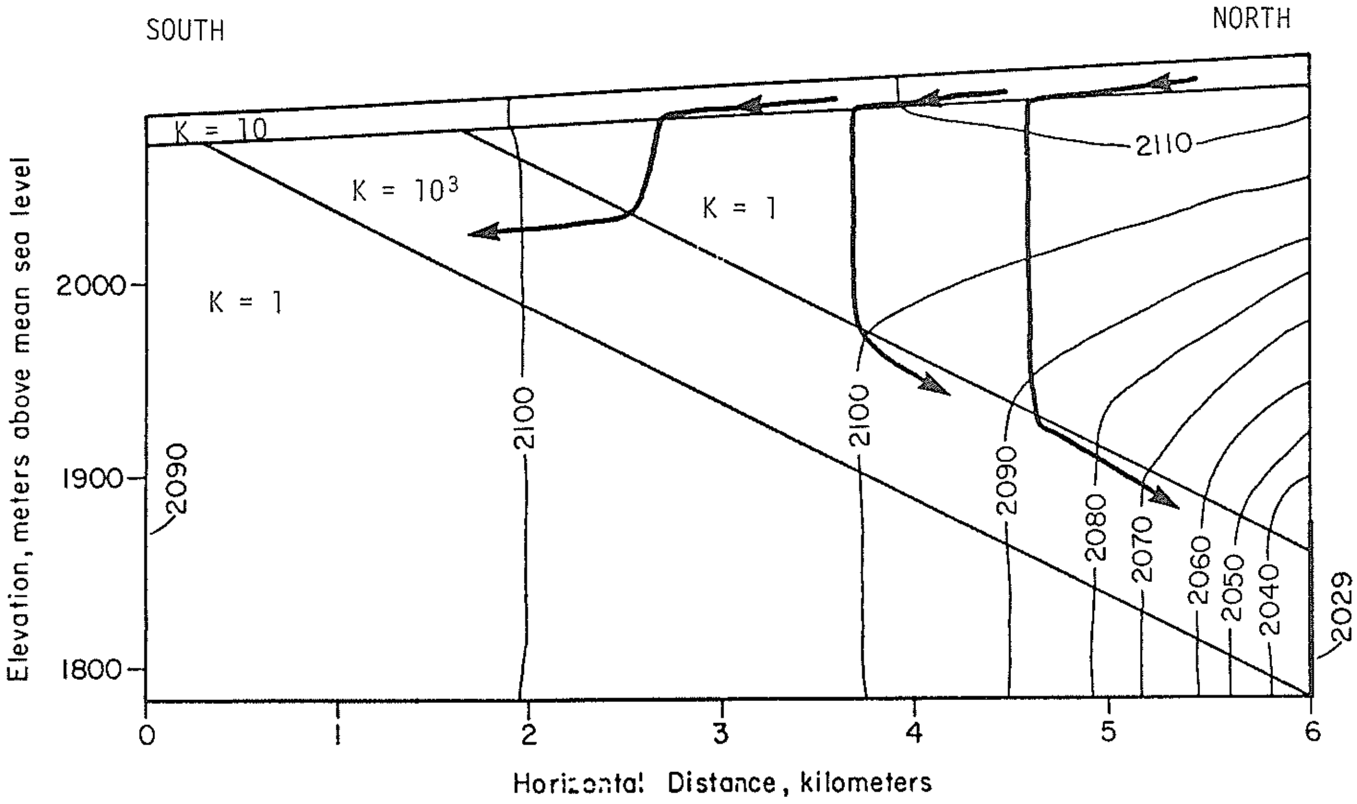
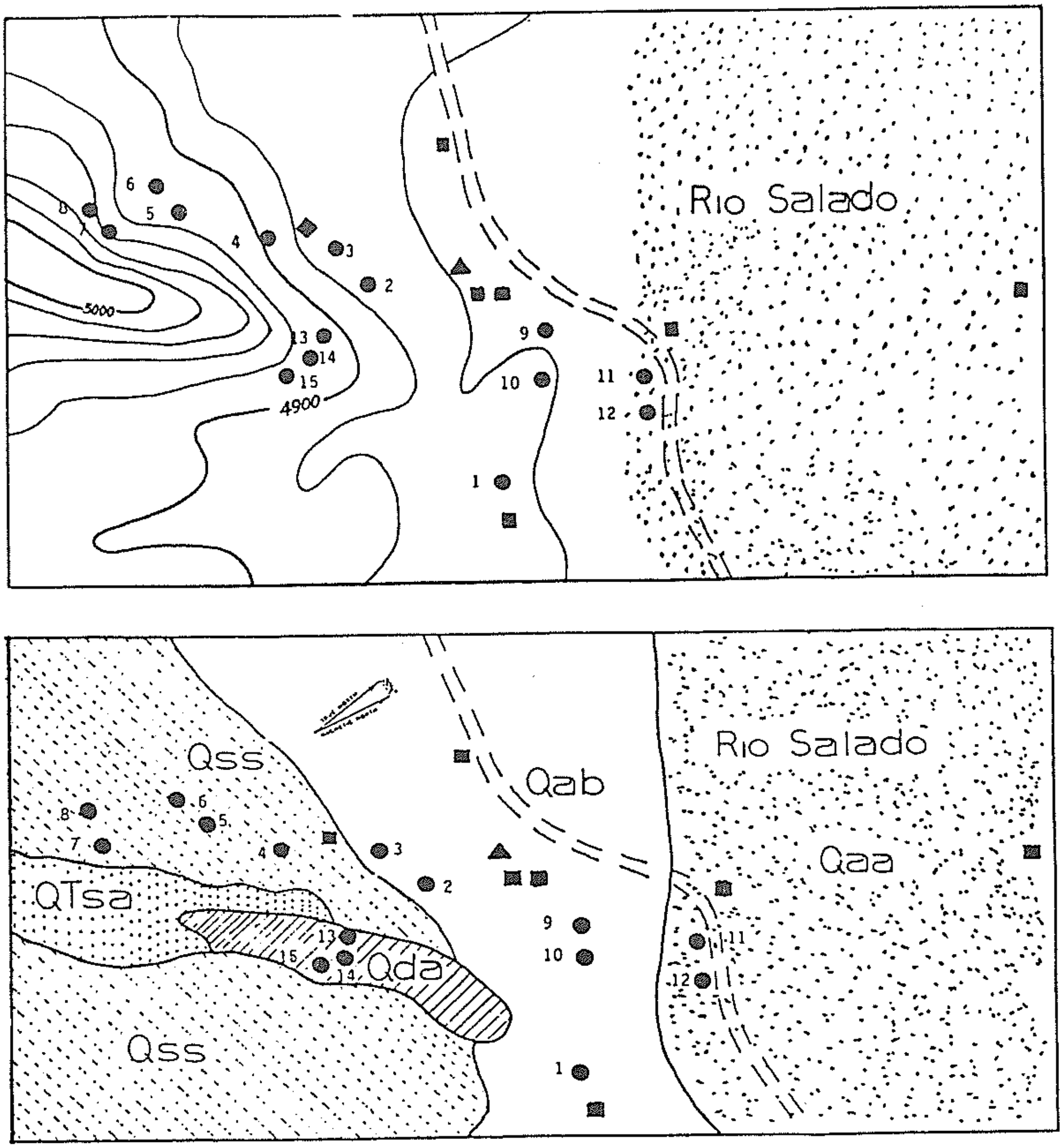


Figure 4. Numerical Simulation of Recharge from Aquitards to a Dipping Sandstone Aquifer, with an Overlying Shallow Alluvial Aquifer.



▲ Weather station

▩ Observation well

● Soil-water station

SCALE: 1" = 500 feet

DESCRIPTION OF MAP UNITS

Surficial deposits are generally 1m or more in thickness where mapped.

ALLUVIAL DEPOSITS- All deposits consist of light-gray or light - brown to reddish-brown silty sand to sandy gravel. Deposits associated with the Rio Salado form cut and fill strath terraces.

Qda Active (upper Holocene) - Surface not stabalized by vegetation. Primarily eolian sand dunes.

Qaa Alluvial unit (Upper Holocene) - Light-brown to light-gray sand and gravel. Includes all active and recently deposited flood plain and tributary alluvium. Thickness usually less than 2 m; thickness of mainstream deposits unknown.

Qab Alluvial unit (Holocene) - Light-brown or light-reddish-brown to light-gray silty sand to sandy gravel. Main stem (Rio Salado) alluvium coarser grained than tributary alluvium. Forms low terrace 1-3 m above top of upper Holocene alluvium (Qaa). Thickness greater than 2 m along main streams.

QTsa Axial stream deposits (Middle Pleistocene) - Light-gray to light-yellowish-brown (oxidized) fine-to-medium grained sand and sandstone cemented by $CaCO_3$. Contains green clay beds and sparse pebbly to gravelly channels. Shows widespread fluvial cross-bedding and cut and fill channels. Thickness greater than 250 m; top eroded.

Qss Stabalized (Holocene) - Forms barchan dunes which are stabalized primarily by mesquite, cresote, grama grass, and saltbush vegetation. Very weak accumulations of calcium carbonate formed as soil in upper part of sand.
Sand dunes - Eolian sand with parabolic and longitudinal dunes; thickness usually 1 -5 m.

Figure 5. Site Topography, Geology and Instrumentation Location, Sevilleta National Wildlife Refuge.

is designed to study the effects of soil texture, vegetation and topography recharge. The wells are intended to determine recharge mostly from stream bed infiltration.

One of the soil-water monitoring stations, station 1, has been monitored since the fall of 1982. Monthly recharge at this unvegetated location is estimated from Darcy's law using average hydraulic gradients calculated from tensiometers at about the 2 m depth and using the geometric mean unsaturated hydraulic conductivity determined insitu by the instantaneous profile method. The results are plotted in figure 6. Annual recharge would be about 20 percent of the precipitation. However, recharge is variable, in response to precipitation. During the winter of 1982-83, a considerable amount of precipitation infiltrated to about the 2 m depth during January. Late summer rains in 1983 also seemed to generate deep percolation. Inasmuch as the water table is only about 6 m deep at site 1 and the rooting depth is less than about 1.5 m, the flux calculated across the 2 m depth eventually should become recharge.

Not all soil-water movement takes place in a vertical direction, especially on a hillslope. To demonstrate this, a bromide tracer was buried on September 22, 1984, in an unconsolidated, poorly vegetated, sandy hillslope at the site near stations 7 and 8 shown in figure 5. There were rains totaling 1.6 cm on September 24, and 2.5 cm on October 3-4; after a 2.4 cm rain on October 22-24, 1984, samples were collected and analyzed by specific ion electrode for bromide concentration. Results are shown in figure 7 for bromide tracer buried at depths 1, 15 and 50 cm. It appears that the bromide moves with a significant lateral component, which is nearly the same direction as both the topographic slope and the direction of stratification dip. To determine whether topography or stratification is primarily responsible for the direction of tracer movement, a similar tracer experiment was conducted at this location in a trench backfilled with the excavated sand. Even though the stratification was destroyed, there was significant lateral movement of the tracer. From these preliminary results, we conclude that topography has a significant influence on unsaturated flow direction on hillslopes.

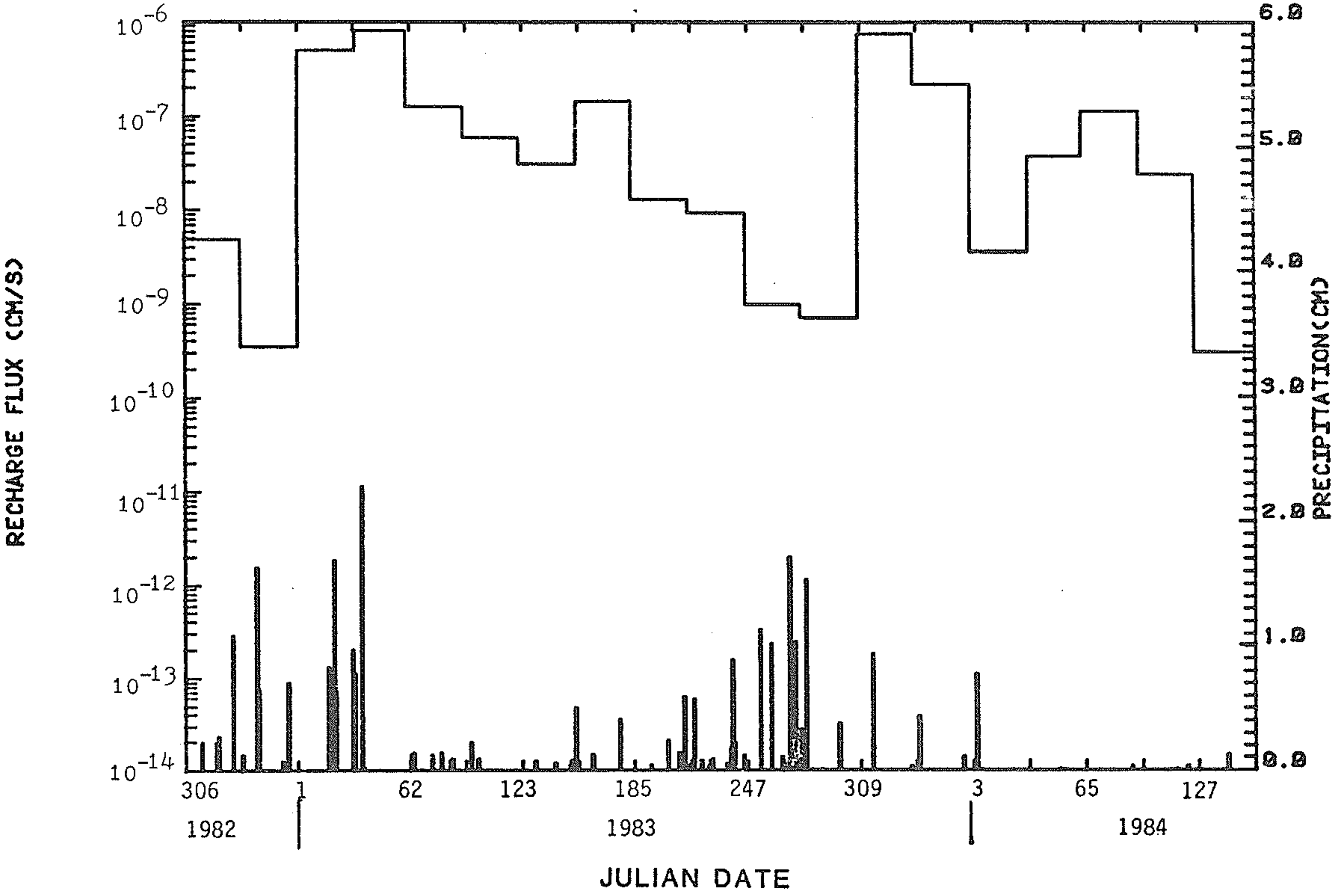


Figure 6. Recharge Flux at Station 1.

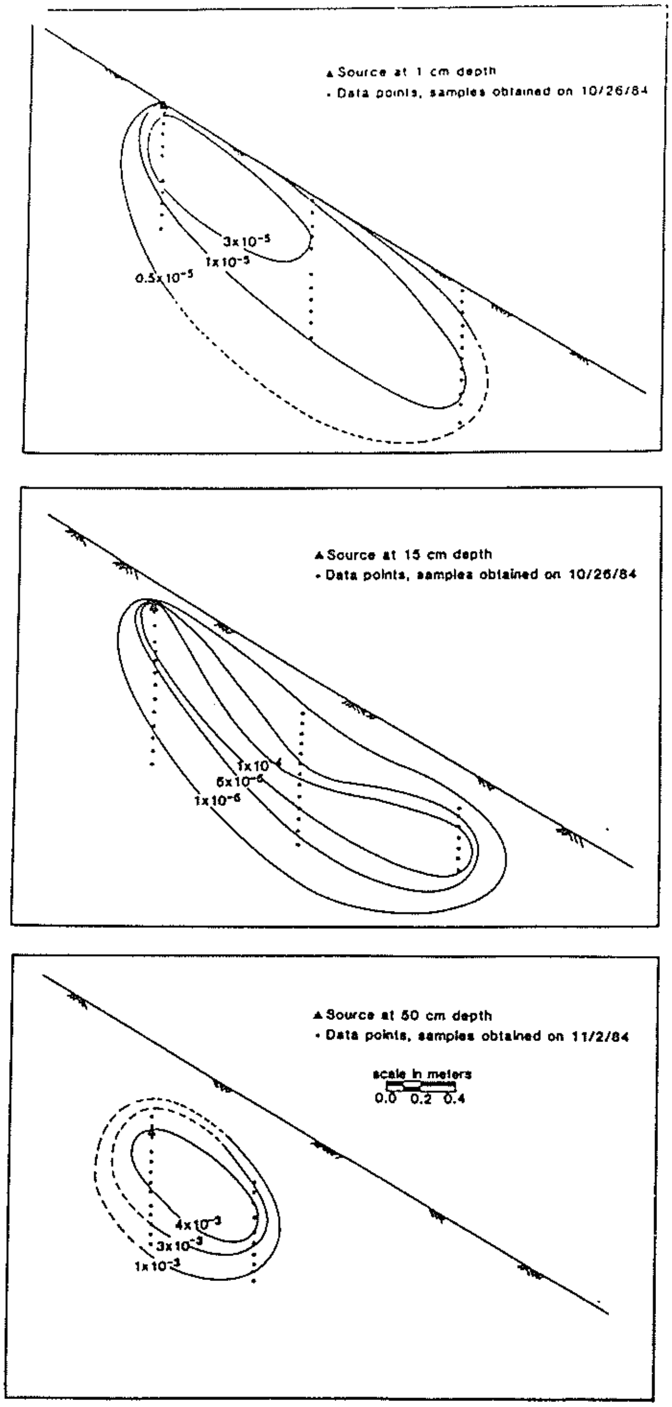


Figure 7. Bromide Tracer Movement on Hillslope near Station 7.

A similar conclusion is inferred from data collected at soil-water monitoring stations 13, 14 and 15 on an active sand dune (figure 5.) Station 13 is located on a steep slope, 14 is on the crest of the dune, and 15 is at a slight depression on the flank of the dune. Figure 8 indicates the cummulative depth of precipitation that fell on October 23-24, 1984, and the subsequent increase in soil-water storage. At the crest of the dune, station 14, only about half of the precipitation infiltrates into the profile. On the slope of the dune, nearly all of the precipitation infiltrated. In the lowland where slopes converge slightly toward station 15, more than twice the amount of water that fell as precipitation appears in the profile. Because there is no evidence of surface runoff, the latter results suggest there are lateral contributions of unsaturated flow from adjacent areas.

Channel Recharge

The ground water monitor wells at the Sevilleta site are screened over 150 cm lengths in the upper part of the water table. One well is located in the center of the broad sandy-bottomed, braided channel of the ephemeral Rio Salado, another is at the southern edge of the channel, another is located at the base of the hillslope to the south about 1000 m from the edge of the channel. The depth to water beneath the channel is less than 2 m. Figure 9 illustrates the aquifer response to runoff. The water table rises due to stream infiltration almost instantly at the channel and begins to rise within two days at a distance of about 1000 m. The stream and aquifer appear to be hydraulically connected during the runoff event, based on the water elevation beneath the channel.

A similar stream-aquifer data collection program was initiated earlier on the Rio Puerco about 37 km to the north by Dr. John Hawley of the N.M. Bureau of Mines and Mineral Resources and his graduate students. The meandering Rio Puerco channel is only a few tens of meters wide and a few meters deep; the sediment load contains a significant percentage of fines. Figure 10 shows the stage, water table configuration, and well hydrographs at the Rio Puerco site. Although there was continuous runoff for about two months, the water table did not intercept the bottom of the channel. Seepage from the channel to the

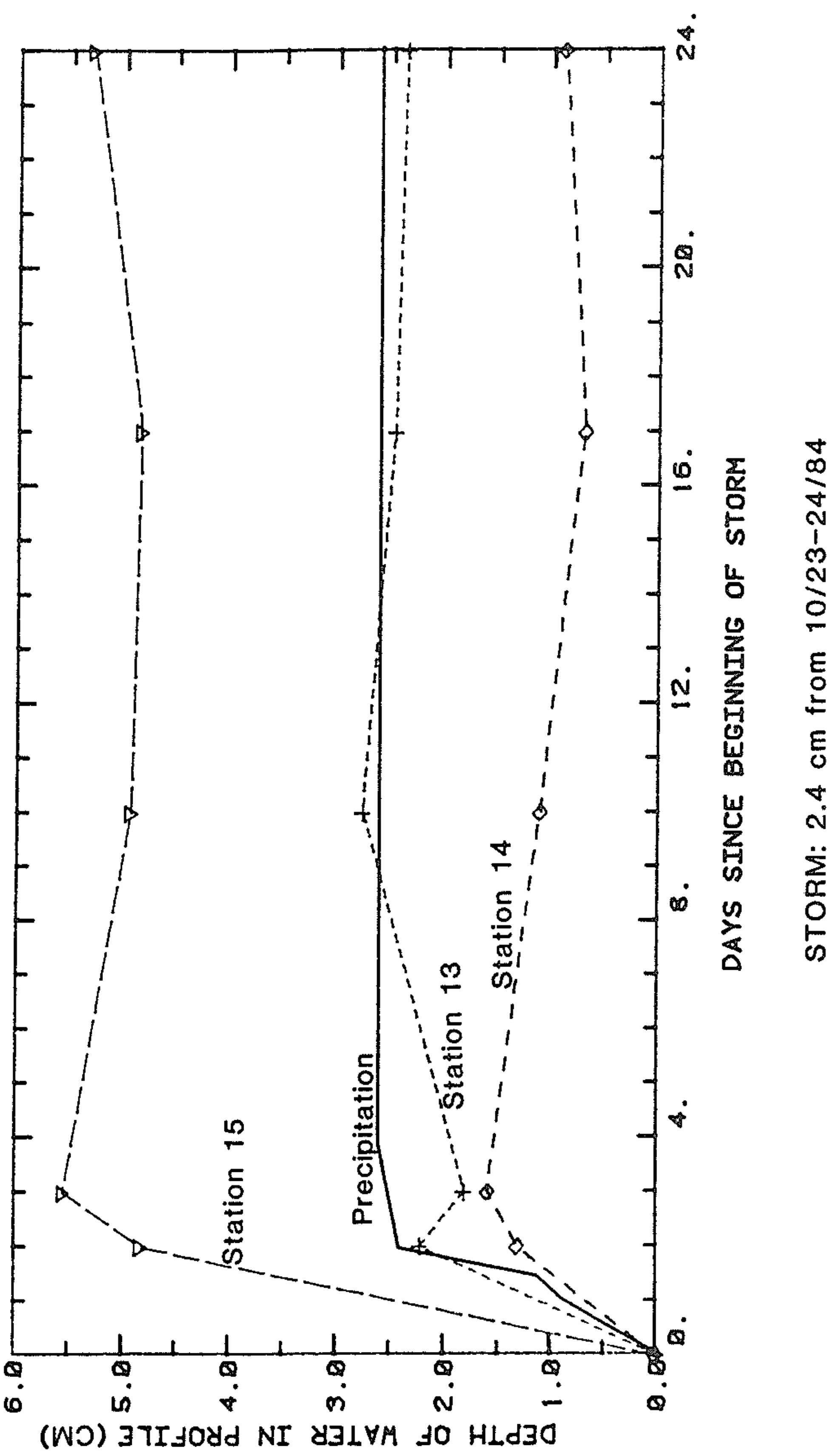


Figure 8. Cumulative Amount of Water Infiltration on Sand Dune: Station 13 (Steep Slope). Station 14 (Crest), Station 15 (Local Depression).

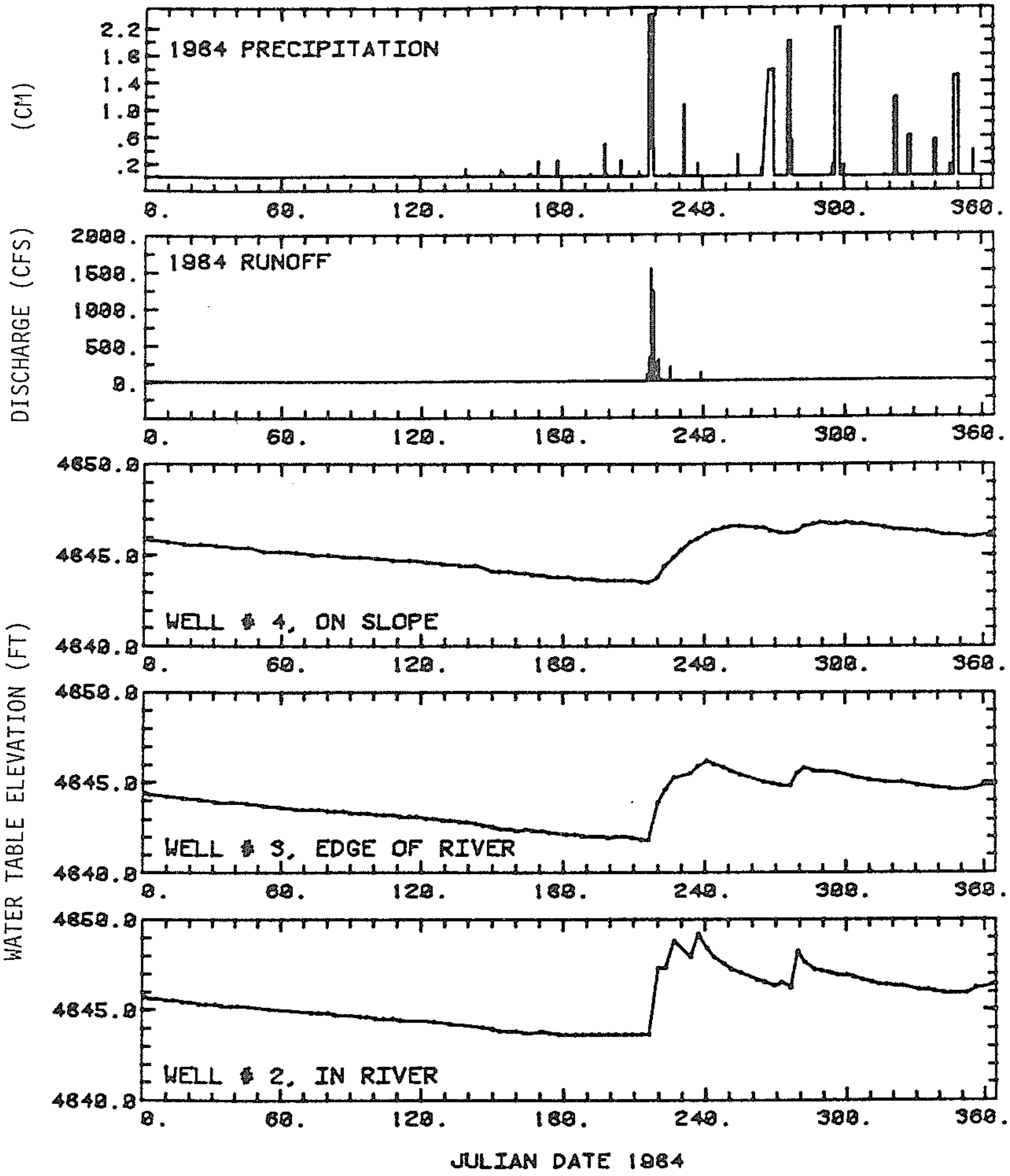


Figure 9. Runoff and Aquifer Response on Rio Salado.

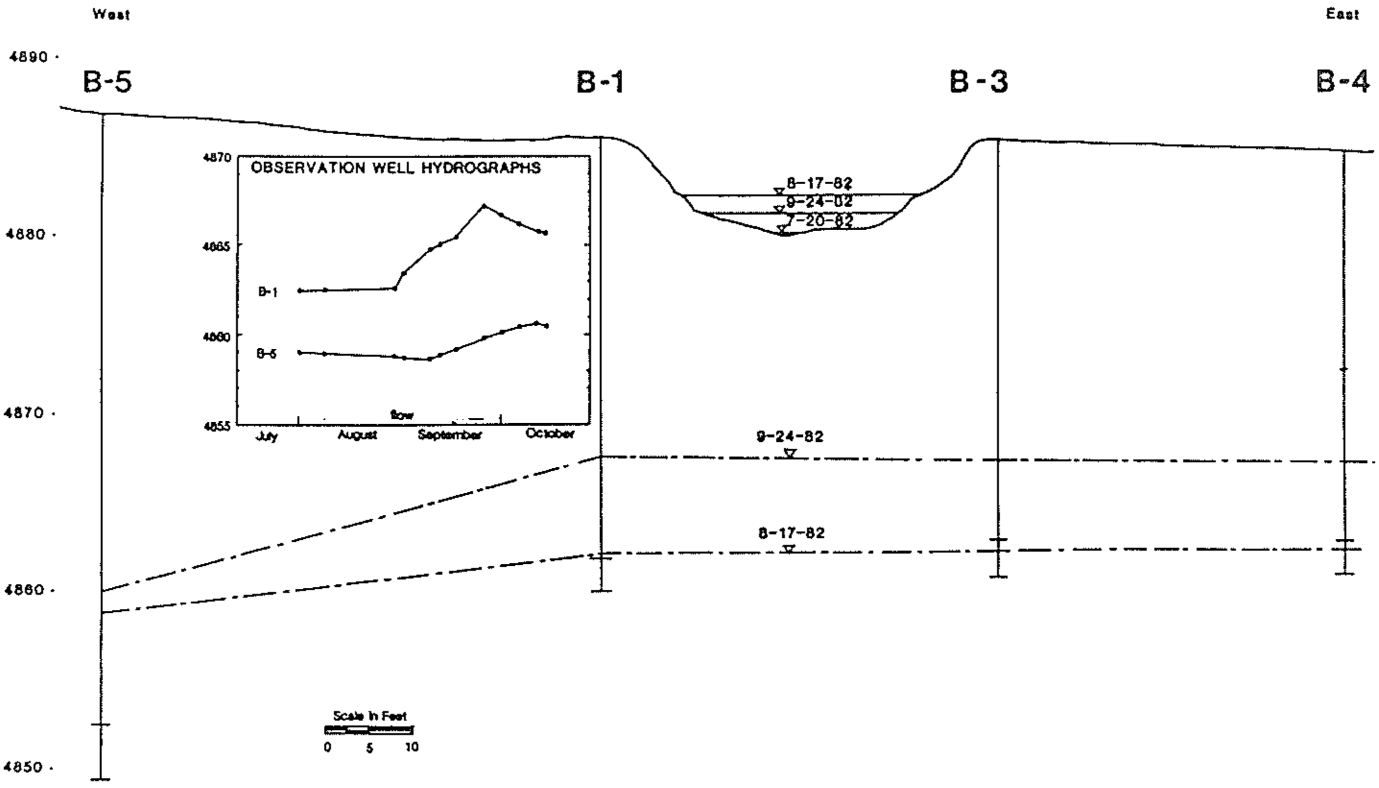


Figure 10. Runoff and Aquifer Response on Rio Puerco West of Belen, NM.

aquifer is delayed on the order of 30 days. These results suggest that there is a clogging layer on the channel bottom that causes seepage to occur under unsaturated conditions. The stream and aquifer are not hydraulically connected. Wells pumping near the Rio Puerco would not induce additional recharge during flow periods such as this, in contrast to the site on the Rio Salado.

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CHEMICAL CONSIDERATIONS IN GROUND-WATER RECHARGE

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New Mexico agriculture, industry, and municipalities are all heavily dependent on ground water. Nearly all available surface water rights have already been appropriated, and thus any further development of water supplies will have to come from additional pumping of ground water. In this context, the recharge rate and quality of ground water recharge in the state assumes great importance.

Traditionally, ground water recharge has been investigated using physical hydrology methods; in particular, water balances and studies of water table fluctuations. However, recent research has shown that various chemical characteristics of soil water and ground water can yield considerable information about recharge processes. In many cases the geochemical techniques can give more information, at lower cost, than the physical ones.

Three techniques will be described in this paper. The first is tracing of a radioisotope produced by nuclear-weapons testing, ^{36}Cl, in the vadose zone. This method is relatively difficult and expensive, but produces unambiguous and detailed results. The second method involves the use of chloride mass balances in the unsaturated zone to infer recharge amounts. This method is simpler, although less detailed. Finally, the use of ^{14}C, ^{2}H, and ^{18}O in ground water to measure long-term changes in recharge will be described.

The Chlorine-36 Method

Chlorine-36 is an unstable isotope of chlorine with a half-life of 301,000 years. Due to its chemical characteristics, chloride moves along

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with ground water and soil water, typically being neither absorbed nor precipitated. It thus constitutes an excellent hydrologic tracer. Chlorine-36 has been widely used prior to the last five years due to its low natural abundance, usually in the range of one ^{36}Cl in 10^{12} atoms stable chlorine to one ^{36}Cl in 10^{15} atoms stable chlorine. This low abundance renders standard radioisotope counting methods impractical. However, the recent development of a new analytical technique, tandem accelerator mass spectrometry, has allowed relatively routine analysis of ^{36}Cl (Elmore et al. 1979).

Chlorine-36 was produced by nuclear weapons testing in the 1950s and injected into the stratosphere. This process created a "pulse" of enhanced ^{36}Cl fallout over the globe between 1954 and 1964. The shape of this pulse is known (Bentley et al. 1982, Elmore et al. 1982). By measuring the depth to which the pulse has penetrated in the soil, the rate of net soil-water movement may be inferred.

In order to demonstrate this application, soil samples were collected from a vertical auger hole near Socorro, New Mexico. The experimental procedures are described in Phillips et al. (1984). The profile of the measured ^{36}Cl/Ca ratio with depth is shown in figure 1. The known bomb-^{36}Cl pulse is included for comparison, the peak of the bomb was found at a depth of about one meter. From this penetration depth, and the measured water content of the soil, the annual moisture flux to this depth may be calculated to be 2.5 mm/yr. or 1.2 percent of the mean annual precipitation. This relatively small water flux is consistent with other determinations of recharge in New Mexico. In addition to the recharge flux, fundamental transport properties of the soil were also calculated from the ^{36}Cl pulse, as described in Phillips et al. (1984).

Cloride Mass Balance

Recharge may also be determined using a mass-balance approach based on the chloride content of vadose water in the unsaturated zone. In the chloride method, recharge is determined from the relationship $R = Clp/Clsw.\ P$, where R = recharge (mm/yr), Clp = average annual chloride input from precipitation (mg/L), Clsw = average chloride content

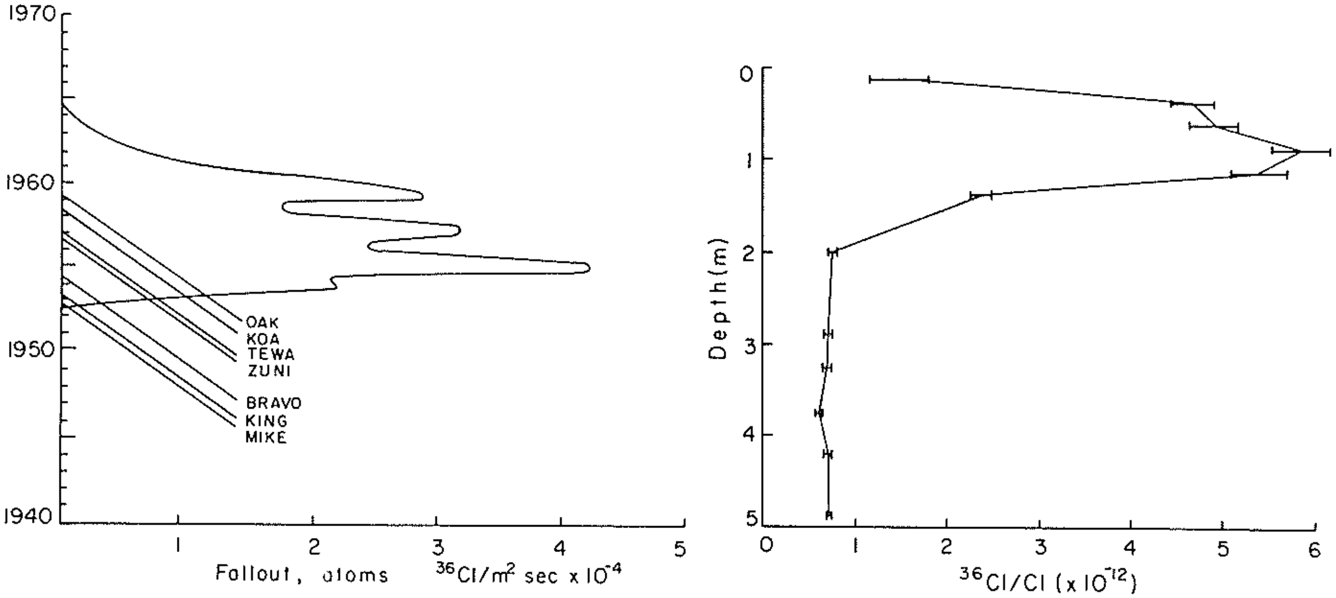

Figure 1. Fallout of ^{36}Cl from nuclear-weapons testing compared with $^{36}Cl/Cl$ of soil water, with depth, at Sevilleta National Wildlife Refuge, New Mexico.

of the soil water (mg/L), and P = average annual precipitation (mm/yr). Clp and P are either obtained from the literature or measured. Clsw is determined from plots of cloride content versus depth. Recharge is inversely proportional to Clsw; for example, the higher the Clsw, the lower the recharge.

The chloride method assumes: (1) precipitation is the only source of chloride, (2) recharge is by piston flow, (3) precipitation has been constant through time, and (4) chloride in precipitation has been constant through time. Because these are not always valid, results are considered to be estimates of recharge. However, recharge results from the chloride method compare favorably with results of other chemical methods. A plot of recharge from chloride versus recharge from tritium gave a straight line (Allison and Hughes 1978). Recharge based on the chloride method also has been corroborated by stable-isotope data (Allison et al. 1985).

In order to test the validity of this method, we compared the soil-water ages obtained from the chloride mass-balance method with the position of the bomb-^{36}Cl peak. The distribution of soil-water ages from the chloride mass-balance method is illustrated in figure 2. The timing of the ^{36}Cl peak, between 20 and 30 years ago, is known precisely. This interval therefore has been indicated on the soil-water age graph and converted to a depth interval using the age-depth relationship. This depth interval is shown to correspond exactly to the observed position of the bomb-^{36}Cl peak, thus validating the chloride mass-balance method. Application of the chloride mass-balance method in New Mexico are described below.

Recharge vs Landscape Setting. The chloride method has been applied to determining local recharge to the Ogallala Formation (Miocene and 22iocene) in major upland landscape setting in Curry County, New Mexico (Stone 1984a). Three settings were deemed typical of the region: cover sand, sand hills, and playas. Cover sand is the broad sheet of eolian sand overlying the Ogallala and formally known as the Blackwater Draw Formation (Pleistocene). The sand hills are deposits of younger dune sand (Holocene). Playas are shallow depressions where runoff periodically ponds.

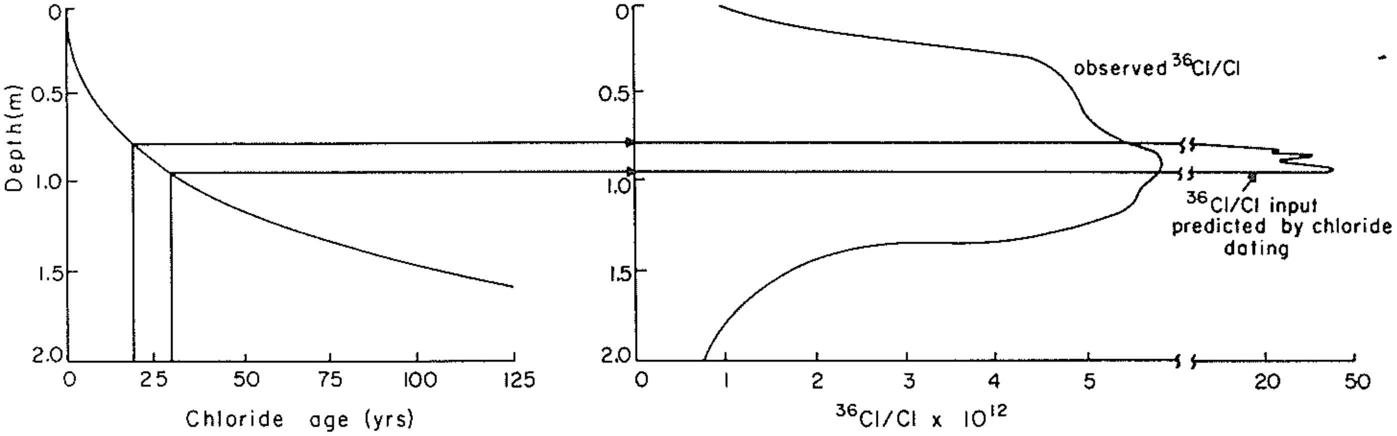

Figure 2. Soil-water infiltration times, calculated by the chloride mass-balance method, as a function of depth. Predicted position of the ^{36}Cl peak is compared with the observed position.

Recharge was found to be highest in the playas (2.8 mm/yr), intermediate in the sand hills (1.25 mm/yr), and lowest in the cover sand (0.21 mm/yr). Irrigation return flow is evident in the shallow part of the profile for the irrigated cover sand site (figure 3).

These local or point recharge rates have been modified and converted to volumetric fluxes for: (1) the areas covered by each landscaping setting, and (2) the entire county by Stone and McGurk (1985). A total upland recharge value of 4,232 acre-feet was obtained. An additional unknown volume of recharge is supplied by valley settings. Of the upland recharge, cover sand accounts for 54 percent, sand hills contribute 37 percent, and playas produce 9 percent.

Impact of Mining. The chloride method has also been applied to determining impact of coal strip mining on recharge at the Navajo Mine in northwest New Mexico (Stone 1984b). Local or point recharge values for undisturbed and reclaimed settings were compared as a measure of mining impact. Recharge in all areas was found to be low (less than 1 mm/yr), because of the low rainfall (145 mm/yr). This preliminary study shows premining recharge rate is 0.01 mm/yr, whereas, post-mining recharge rate is 0.02 mm/yr (figure 4). Although a twofold increase is indicated, both recharge values are of the same order of magnitude and very low. Additional work is planned to obtain more local recharge values and convert them into areal and regional volumetric recharge fluxes.

Paleohydrology. Application of the chloride method to the Salt Lake Coal Field, an area of potential mining north of Quemado, New Mexico, unexpectedly provided some insight into the paleohydrology of the area (Stone 1984c). In this study, chloride was observed to decrease with depth at all settings (figure 5). This was interpreted as evidence that the recharge rate had been greater at some time in the past. This was checked by making lots of cumulative chloride versus cumulative water content. Such plots should yield a straight line if precipitation, chloride input, and recharge have been constant. The plots for the Salt Lake Coal Field are characterized by convex-upward curves (figure 6). Points between straight-line segments in the curves are age dated, based

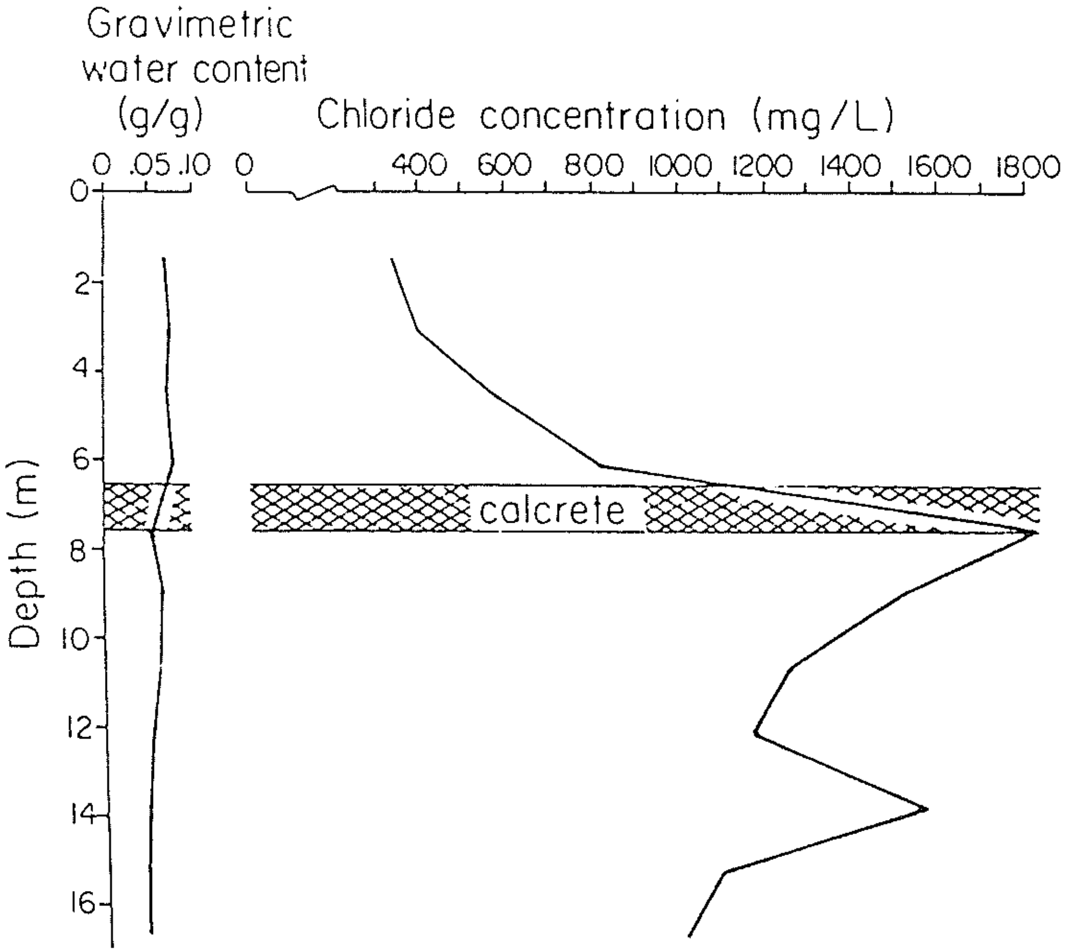

Figure 3. Chloride and moisture profiles for irrigated cover sand settings, Curry County (Stone 1984a).

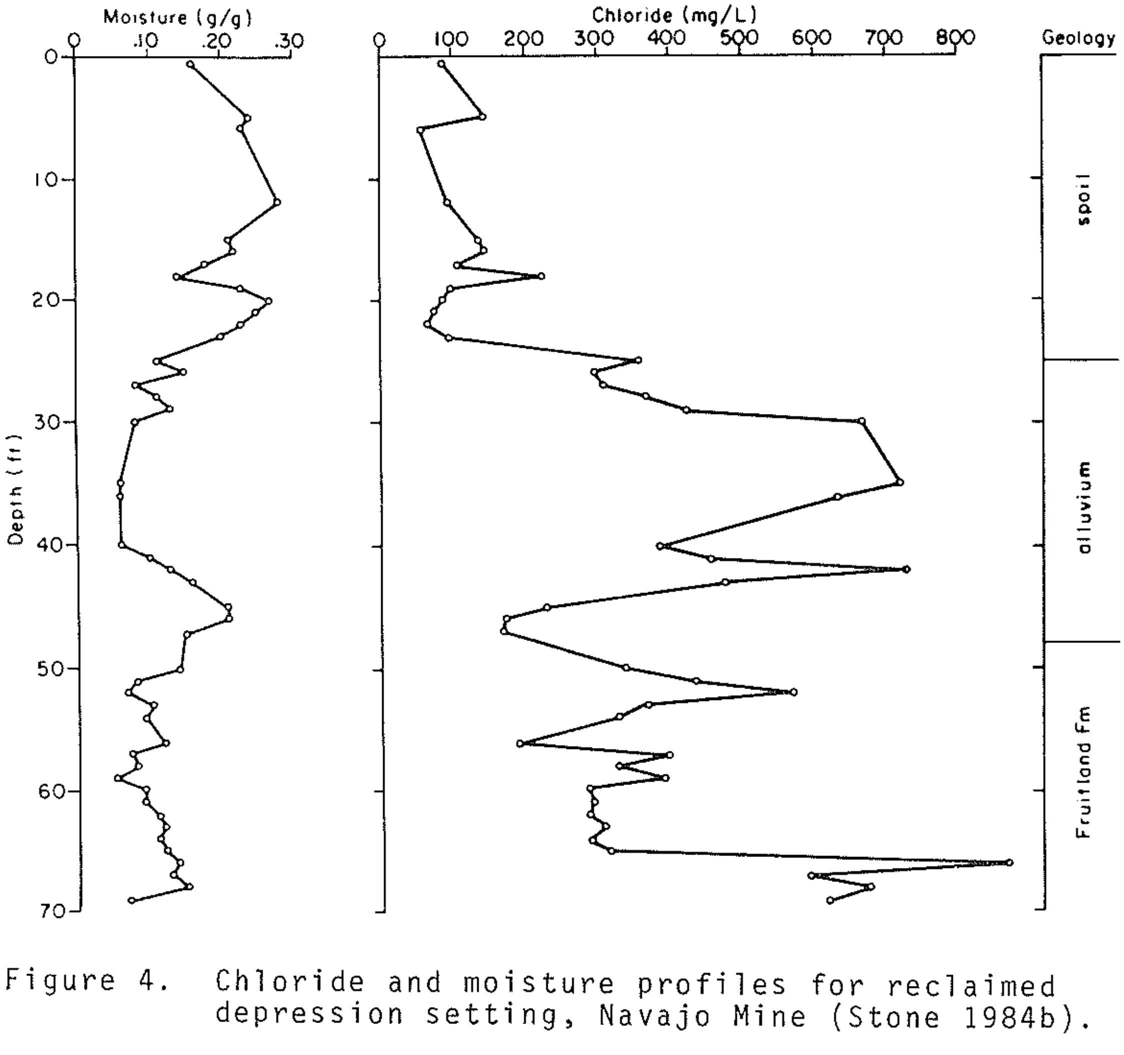

Figure 4. Chloride and moisture profiles for reclaimed depression setting, Navajo Mine (Stone 1984b).

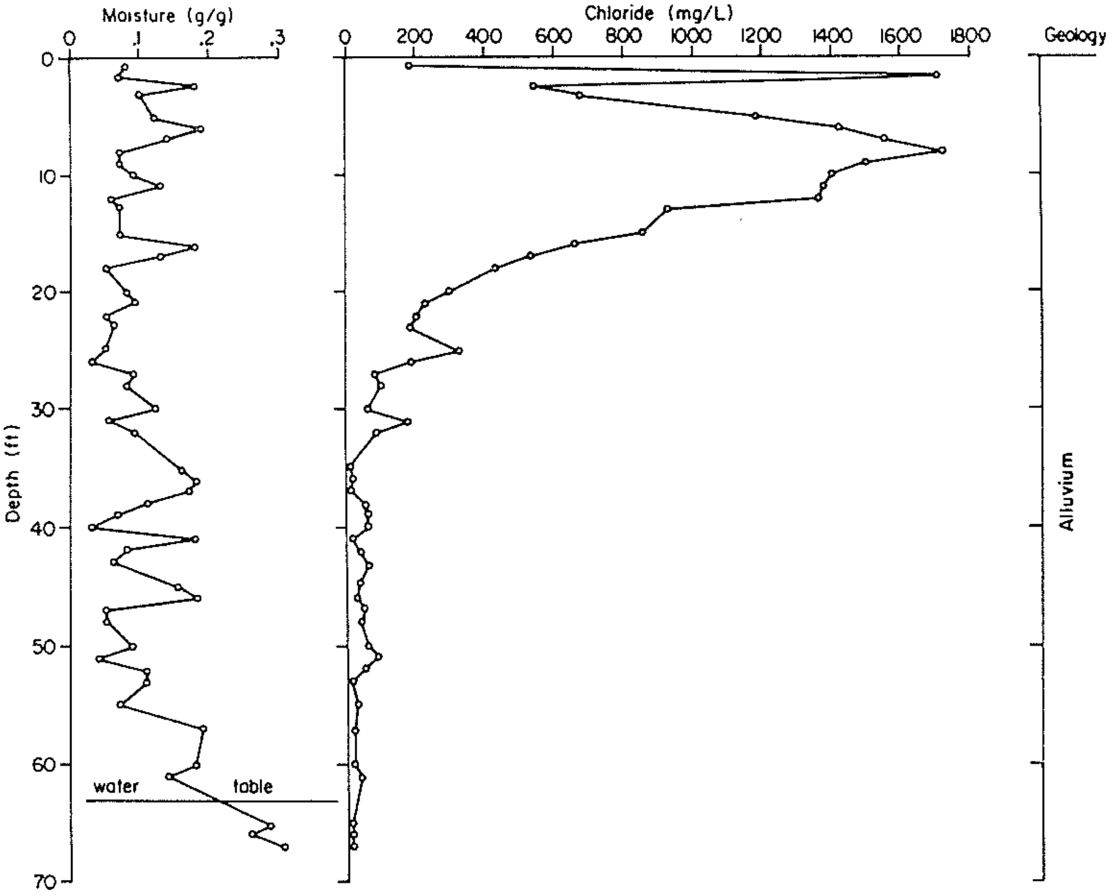

Figure 5. Chloride and moisture profiles for thick alluvium setting, Salt Lake Coal Field (Stone 1984c).

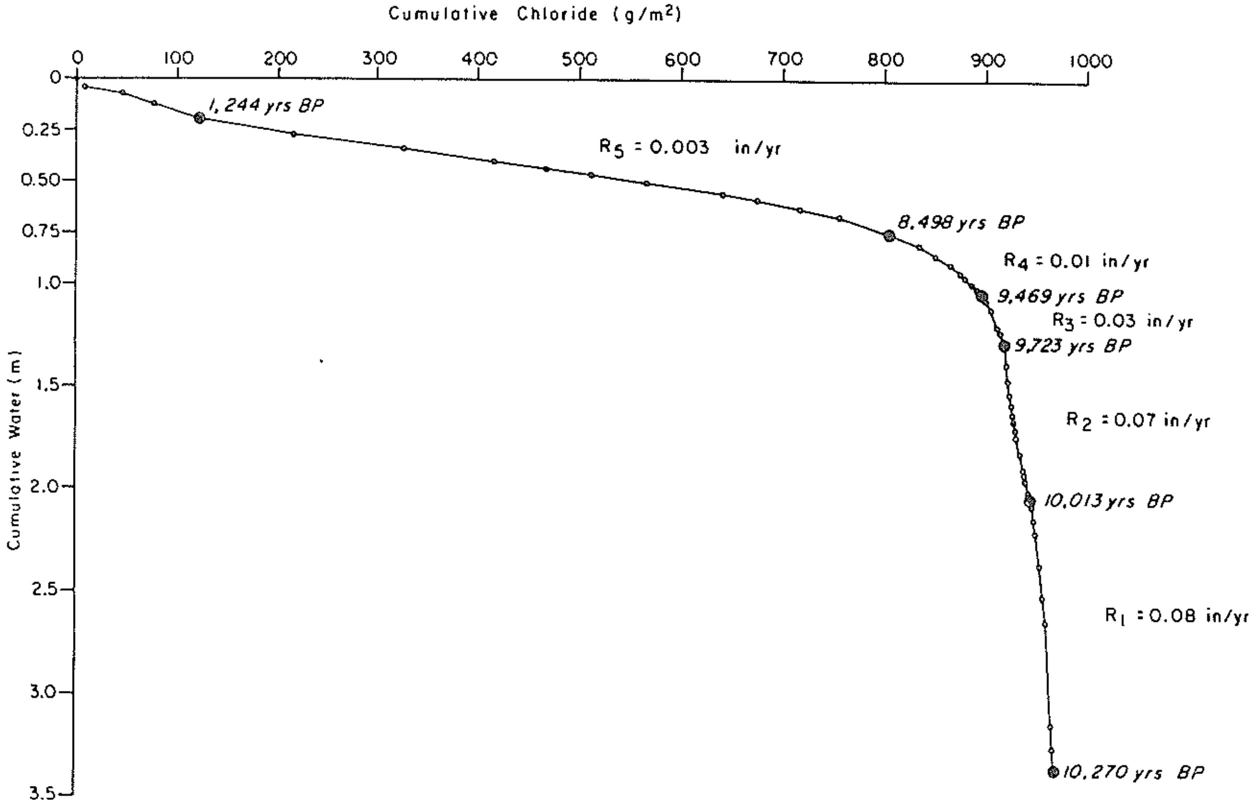

Figure 6. Cumulative chloride vs cumulative water plot for thick alluvium setting, Salt Lake Coal Field (Stone 1984c).

on cumulative chloride content at that point (g/m^2) and modern values for Clp (g/m^3) and P (m/yr). Recharge rates between such points were determined in the normal way (relationship above). Higher recharge rates were found to be associated with the older (lower) parts of the profiles. The timing of the apparent changes in recharge are reasonable in view of Quaternary paleoclimate reconstructions for the region.

Such paleorecharge rates are not merely of academic interest. They represent worst-case values for consideration in waste-disposal site evaluations. In other words, they approximate recharge during the wetter climates of the recent past.

An alternative explanation of the chloride versus depth profiles from the Salt Lake Coal Field would be that they represent a ground water discharge situation through capillary rise and evaporation. Analysis of stable-isotope data from the unsaturated zone would be necessary to determine which interpretation is correct.

Recharge Inferences from Isotopic Studies of Deep Ground Water

Results from the chloride mass-balance study in the Salt Lake area, described above, implied that soil-water fluxes below the root zone may have been substantially greater during the last glacial episode than they are today. This conclusion is supported by isotopic studies of the ground water in the San Juan Basin of northwestern New Mexico.

Ground water in the Ojo Alamo aquifer of the central basin was dated using ^{14}C (Phillips and Tansey 1985). This dating produced a coherent set of ages ranging from modern to more than 30,000 years old. The same water samples also were analyzed for their stable isotope content: The ratios $^{18}O/^{16}O$ and $^{2}H/^{1}H$ in the water molecule. Lesser concentrations of ^{18}O and ^{2}H in precipitation are well known to be correlated with colder climate (Dansgaard 1964). Indeed, we found that water dating to before 10,000 years (the end of the last glacial episode) did have lower concentrations of these isotopes (figure 7).

Not only temperature, but also amounts of recharge (i.e., the soil-water flux below the root zone) can be inferred from the stable-isotope contents of ground water. Using a relation developed by

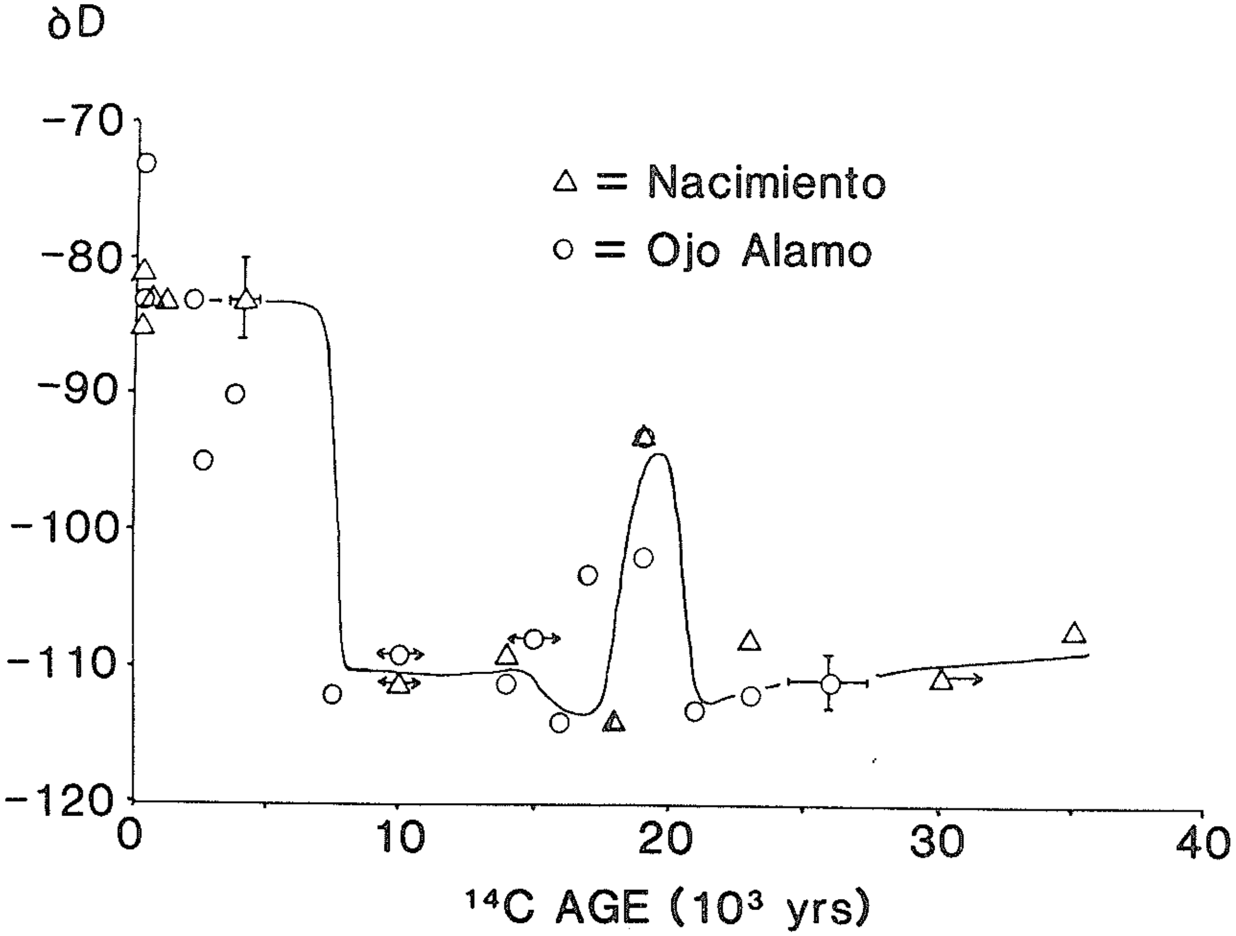

Figure 7. Variation of δD (deuterium concentration) with ^{14}C age of ground water in the central San Juan Basin. More negative δD indicates colder climate.

Allison et al. (1984), we calculated the amount of recharge as a function of ^{14}C age, illustrated in figure 8. Significant variations with time were found. Intervals of enhanced recharge occurred at about 3,000 years before present (B.P.), 15,000 B.P., and between 20,000 and 25,000 B.P. These intervals of high recharge are corroborated by independent paleoclimatic evidence of moist conditions, such as high water levels in closed-basin lakes (Smith and Street-Perrott 1983).

In order to investigate whether larger soil-water fluxes actually resulted in larger amounts of water entering aquifers, we measured the distribution of ^{14}C dated water within the Ojo Alamo aquifer study area in the San Juan Basin. Flowlines were used as boundaries for the measured area. The measurements did reveal a correspondence between the recharge inferred from the stable isotopes and the amount of water in the corresponding age range actually present in the aquifer. The amount of water dated to the driest period (5,000 to 10,000 years) was approximately half the amount dated to the wettest period (20,000 to 25,000 years).

This result implies that recharge rates calculated from water balances in large aquifers may seriously overestimate the present recharge rate. A disproportionately large fraction of the water may have been recharged during wet periods in the geological past. Furthermore, it implies that the aquifer is not truly in a hydraulic steady state. In order to perform accurate numerical simulation of the ground water flow, transient boundary conditions may have to be included.

Conclusions

Several geochemical methods for investigating the ground water recharge process are available. These include tracing of the bomb-^{36}Cl pulse, chloride mass balance, and ^{14}C, ^{2}C, and ^{18}O in ground water. Application of these methods at various locations around New Mexico has yielded concordant results. The methods have all demonstrated that at most places in New Mexico, the ground water recharge rates are low, typically on the order of millimeters per year, or less. The

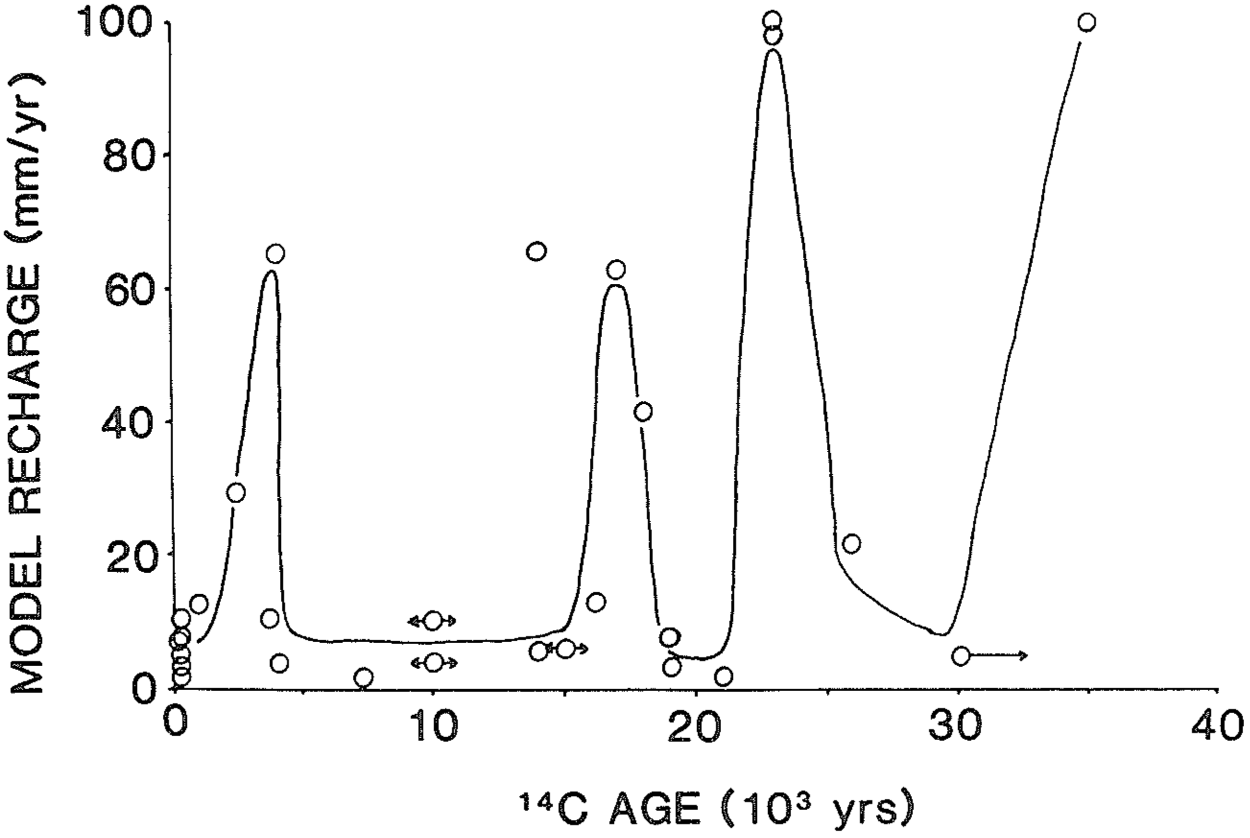

Figure 8. Variation of calculated ground-water paleorecharge with ^{14}C age in the central San Juan Basin.

recharge rate varies significantly depending on soil texture and geomorphic setting. The recharge rate also has varied significantly through geologic time. Recharge to the water table may have been more than an order of magnitude greater during the last ice age. Further application of these techniques should be a major aid in quantifying amounts and distribution of ground water recharge in New Mexico.

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ARTIFICIAL RECHARGE RESEARCH--A PERSPECTIVE

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Artificial recharge of ground water has been practiced on a modest scale as a water management tool for about the last 100 years. Research on artificial recharge has been quite active, and will remain so with funding of the recently enacted Ground Water Recharge Demonstration Act. Artificial recharge research generally addresses one or more of three topics:

1. Development of guidelines for site selection.
2. Development of methods to maximize operational efficiency.
3. Demonstration of feasibility.

Two general methods are used to recharge ground water--surface spreading and well injection. Site-selection guidelines for both techniques were investigated by the U.S. Geological Survey as part of a study conducted in the Southern High Plains of Texas. Three case histories indicate that neither intuitive wisdom nor the results of core analyses are adequate to predict the success or failure of artifical recharge.

An experiment involving the spreading of water was conducted at a site at the Lubbock, Texas, airport. The depth to water at this site is about 38 meters. The experiment showed that a fossil caliche layer occurring at a depth of 20 meters was quite permeable, contrary to historical assumptions. In addition, a continuous 2- to 3-meter thick clay layer at about a 27 meter depth proved to be much more permeable on an areal basis than core analyses indicated, although the permeability of the layer to air, as determined by a field technique, proved reliable (Weeks 1978).

In the other two case histories, the experiments involved the injection of sediment-laden playa-lake water into wells. Both of these also provided counterintuitive results. In one experiment, water was injected into a well, tapping a layer of fine gravel, which was expected to accept even sediment-laden water relatively freely. Instead, the well clogged severely after 10 hours of injection, and its yield was restored only to 60 percent of its original value by subsequent pumping (Brown and Keys 1985). A second experiment involved measurements made during well injection by a farmer, who had been injecting sediment-laden playa lake water into his well at a rate of about 40 to 50 liters per second for several years whenever water was available. Cores indicated that the aquifer materials consisted of fine to medium sand, an improbable medium for successful injection of playa lake water. However, the zones that were accepting water were identified by temperature logging, and core examination indicated "worm-hole" type secondary porosity in the relatively friable sand (Brown and Keys 1985).

The above experiences indicate the difficulties involved in developing reliable guidelines for selecting suitable sites for artificial recharge, and indicate that all such guidelines be viewed with a healthy degree of agnosticism.

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